Late-Variscan Extensional collapse of the thickened Moldanubian crust in the southern Bohemia

Pozdně orogenní extenzní kolaps moldanubické zóny v jižních Čechách (Czech summary)

(8 text-figs.)

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Lithotectonic structure of the Moldanubian Zone, resulting from Variscan overthrusting of analogues of the Gföhl Unit over Montonous and Varied Groups, has been affected by NW-vergent late-extensional tectonics on a crustal scale. Major intramoldanubian extensional fault - the Podolsko detachement - as a part of the Vodňany-Týn nad Vltavou fault zone, has exhumed the Monotonous Group, and juxtaposed the Gföhl and Monotonous Units which were originally separated each from other by the Varied Group. Estimated minimum throw along this late fault is about 5 km. The intrusion of granitoid magmas could have been partly synchronous with the extensional movements which continued after emplacement of the granite intrusives.

Microstructural study of small granitic bodies located along shear zone boundary reveals transition from deformed granites with C/S fabric, through C/S orthogneiss, banded orthogneiss to ultramylonites. Sharply localized ultramylonitic shear zones display transition from amphibolite facies conditions to greenschist facies under the same kinematic regime.

Quartz C-axis analysis shows that prism <a> slip system was dominant for all stages and intensities of deformation. C-axis pattern is controlled by finite strain geometry rather than by kinematical framework at least during early stages of deformation. This indicates that the development of C/S planes could not be synchronous and that determination of kinematics using quartz microfabric should be interpreted with care.

Key words: Crustal extension, Moldanubian Zone, normal ductile shear zone, deformation microstructures, quartz microfabric

1. Introduction

The tectonic evolution of orogenic belts is often terminated by extensional collapse. Two types of extensional processes in the European Variscan belt have been distinguished: a late-Visean-Westphalian extension, which is nearly parallel to the orogenic belt and is the result of persistent compressive forces, and a late-Stephanian to early-Permian extension caused by changes in extension direction accommodated by crustal faults. The late-Visean to Westphalian extension was accompanied by deep erosion of the central part of the orogen and coincides with the development of large fluviodeltaic basins (Burg et al. 1994a, b). This extension was accompanied by the ascent of granites, which were emplaced in bodies parallel to the belt (Faure - Pons 1991).

This general scheme for the Bohemian Massif has been proposed by Burg et al. (1994b). The extensional tectonics controlled by compressive forces have been described in the external parts of the Moldanubian region by Zulauf (1994), Schulmann et al. (1994), Scheuvens et al. (1995). However, within the central part of the orogen, in the most deeply eroded part of the Moldanubian crust, the pattern of extension has not yet been described in detail. The structural development of the internal part of the Moldanubian Zone of the Bohemian Massif has been explained in terms of convergent tectonics and large-scale nappe emplacement (Tollmann 1982, Franke 1989, Matte 1991).

In this paper we present geometrical, kinematical and microstructural data relating to extension in a broad area (Fig. 1), which can be subdivided as follows; between České Budějovice and Týn nad Vltavou, from NW edge of the Prachatice and Křišťanov granulite bodies to the NW contact of the Sušice Varied Group with the Central Bohemian Pluton, and the last and most important part lies along the northern part of the Vodňany-Týn nad Vltavou shear zone (e.g. Vrána 1979) as far as to Strakonice (Fig. 1). These new observations provide evidence of tectonic extension of the upper parts of the Moldanubian crust. An attempt is made to explain modification of the relative position of the main Moldanubian lithotectonic units in terms of extension during the final stage of tectonic evolution.

2. Pre-extensional framework

The Moldanubian Zone of the Bohemian Massif is characterized by large-scale nappe tectonics. This concept was first proposed by Kober 1938, and later elaborated on by Vrána (1979), Tollman (1982), Matte (1986), Franke (1989, 1990), and Matte (1991). The presence of high-pressure rocks in the uppermost position in the structural sequence proves that tangential compressional tectonics affected most of the Moldanubian Zone (Carswell 1991, Carswell - O'Brien 1993). Evidence for both early- and late-Variscan HP-HT metamorphic events is provided by geochronology (Carswell -

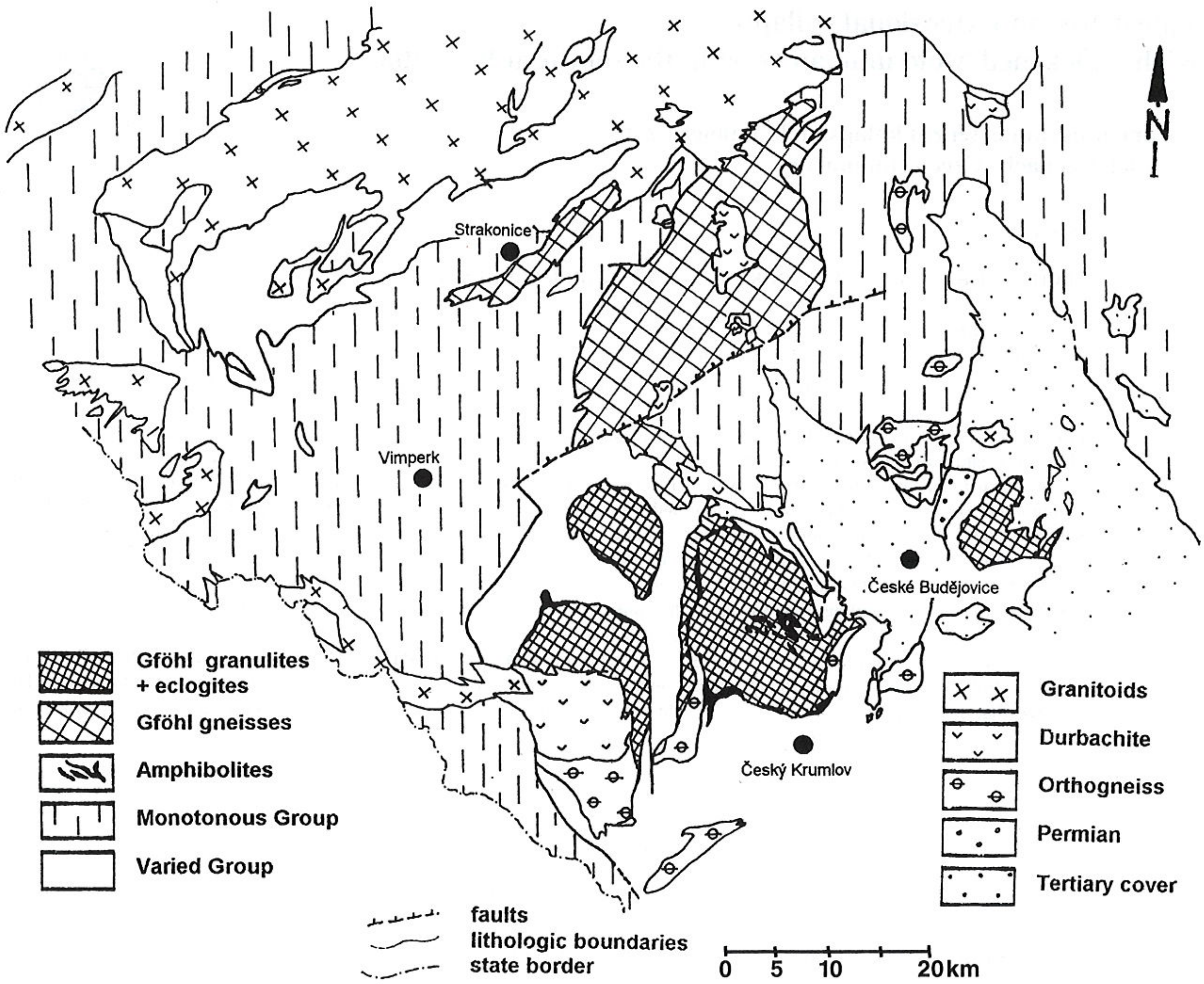


Fig. 1. Geological sketch of the studied part of the Moldanubian zone showing the position of the Gföhl Unit and the Vodňany-Týn nad Vltavou shear zone in the area studied. According to Zeman et al. (1979, set of unpublished maps 1:200 000) and Vrána (1992)

Jamtveit 1990, Wendt et al. 1994). LP-HT metamorphism overprinted most of the pre-existing metamorphic record during the Late-Variscan.

Tectonostratigraphy

Three main tectonostratigraphic units have been distinguished in the Moldanubian Zone: the Monotonous Unit, the Varied Unit and units considered to be parts of the Gföhl Unit. The Monotonous Unit and the Varied Unit are characterized by amphibolite-facies metamorphism (720-760 °C and 7-9 kbar in Petrakakis 1986, Petrakakis - Richter 1991). The Monotonous Unit consists mainly of partly migmatized pelitic and psammitic gneisses, in which the characteristic assemblage is bt-pl-sil-grt-Kf-qtz±crd. Intercalations of quartzites, calc-silicate rocks, amphibolites and orthogneisses occur locally. In contrast, the Varied Unit contains a higher proportion of other rock types, e.g. calcite and dolomite marbles, graphitic gneisses, calc-silicate rocks, and amphibolites. Chlupáč (1992) suggested lithostratigraphic correlation between the Sušice Varied Group and the Palaeozoic in the roof of the Central Bohemian Pluton. This would mean that this local unit may be distinct from other occurrences of the Varied Group in southern Bohemia.

The Gföhl Unit, as defined by Fuchs and Matura (1976) and Franke (1989), consists chiefly of leucocratic anatectic "Gföhl gneisses" (Dudek et al. 1974) with minor intercalations of other rocks, together with major granulite bodies. These lithological and tectonic units together form an allochthonous tectonic sequence. The presence of high pressure rocks, such as HP granulites, eclogites, and peridotites, in addition to paragneisses and amphibolites, is characteristic of this unit. Peak conditions of metamorphism are 1000 °C, 16 kbar for granulites and 1060 °C and 20 kbar for eclogites (Beard et al. 1989, Carswell - O'Brien 1993). The granulite facies metamorphism is dated at 345±5 Ma (Rb/Sr) (Van Breemen et al. 1982, Wendt et al. 1994).

Metamorphism during the thrusting of the Gföhl Unit over the Drosendorf Units was predominantly of amphibolite facies and has been dated at 340-320 Ma by van Breemen et al. 1982, Matte et al. 1985, and Teufel 1987. The Podolsko Complex (Fig. 1) consists chiefly of orthogneisses and leucocratic migmatites and also contains small patches of granulite. The Podolsko Complex has been correlated with the Gföhl

Unit (Kodym 1966, Kodym - Suk 1958, Franke 1989, and Matte et al. 1990). Compared to the relatively clear position of the Gföhl Unit high in the Moldanubian crustal stack in Lower Austria and western Moravia, the granulites and the Podolsko Complex now form separate bodies, some of which have significant subsurface extension.

Pre-extensional tectonic pattern

The oldest foliation recognized in some parts of the Monotonous Unit is the compositional banding and schistosity typical of the metasediments. This foliation has been identified as S1 attributed to D1 by Vrána (1979, 1992). Two main directions of mineral lineati-

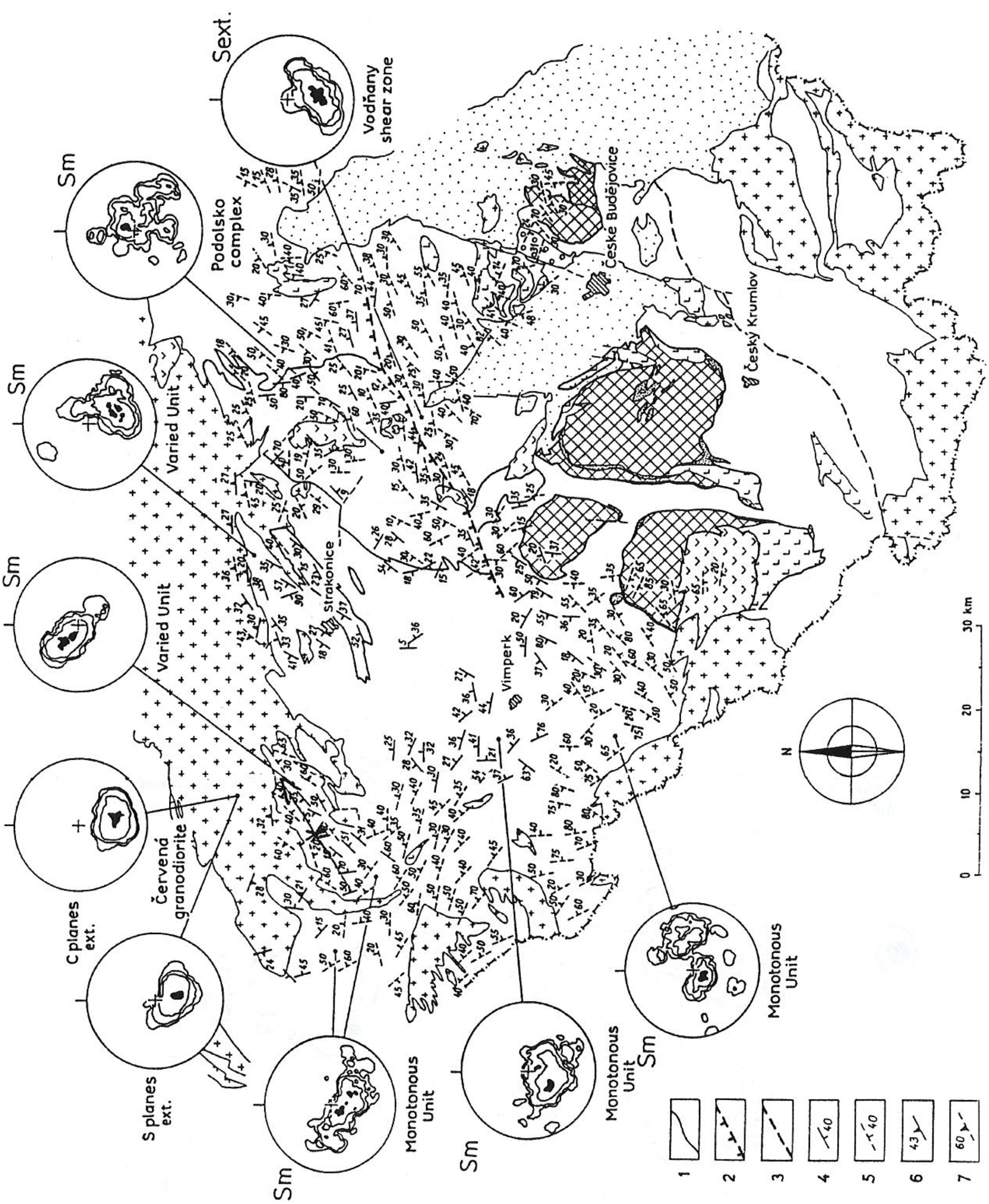


Fig. 2. Map of rock foliations in the area studied. Diagrams of poles of foliation planes in lower hemisphere, equal area projection, contoured at multiples of uniform distribution, show orientation of measured foliation planes in individual subareas. About 100 measurements per diagram. The measured foliation planes formed under several stages of deformation

1 - lithologic boundaries; *2* - Podolsko detachment normal fault; *3* - boundary between the Kaplice and Monotonous Units; *4* - structures measured by the authors of this paper; *5* - measurements from publications and maps; *6* - magmatic foliation measured; *7* - magmatic foliation taken from literature on occur - NW-SE (max. 324/24) and NNE-SSW (max. 15/15). However, lineation is often absent even in the high-strain zones and S-fabrics prevail. South of Vimperk and near Týn nad Vltavou in the southern part of the Moldanubian region, sets of north-south trending vertical planar fabrics are observed in both the Monotonous and Varied Groups (Fig. 2). These have been attributed by Vrána to the second recognizable Moldanubian deformation S2 (D2). The prevailing S3 (D3) shear foliation is developed in most parts of the region, with the exception of the Šumava area where it was obliterated during superimposed deformation and amphibolite-facies recrystallization. The older structural fabrics are recognizable in some subareas which have not been so strongly affected by younger pervasive refoliation. Poles to foliation planes in the Sušice

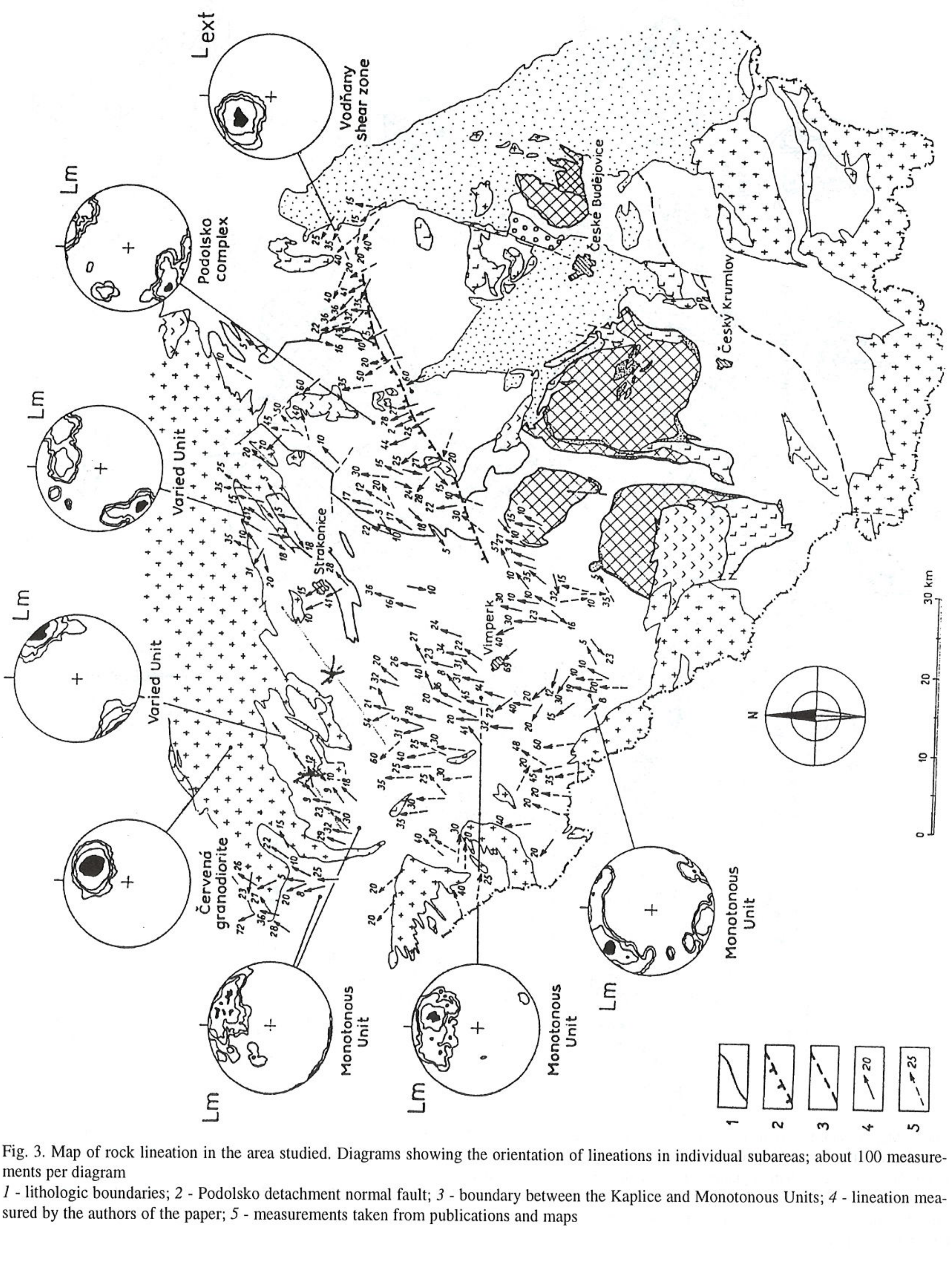


Fig. 3. Map of rock lineation in the area studied. Diagrams showing the orientation of lineations in individual subareas; about 100 measurements per diagram

1 - lithologic boundaries; *2* - Podolsko detachment normal fault; *3* - boundary between the Kaplice and Monotonous Units; *4* - lineation measured by the authors of the paper; *5* - measurements taken from publications and maps

Varied Group display a fan-like distribution, arranged around the SW-NE axis, which corresponds well with the trend of the main fold axes and with the general megasyncline structure of the Sušice Varied Group (Fig. 2). Moderate monoclinal dips towards the SE predominate in the case of the Strakonice Varied Group.

Prominent stretching lineations in the Varied Group near Strakonice, locally emphasized by an L-fabric, plunge gently towards the NE or SW (max. 45-50/10; resp. 225°) (Fig. 3). The stretching lineation is marked by rodding of quartz-feldspar aggregates and alignment of metamorphic minerals. The compositional banding is refolded by synschistose recumbent and isoclinal folds with hinges parallel to the main stretching direction (cf. Rajlich et al. 1986).

Migmatites of the Podolsko Complex rocks display banding defined by alternation of leucosomes and mesosomes. Although the foliations vary widely in trend, maxima of poles are clustered around the center of the orientation diagram (Fig. 2), indicating a very low dip of the planes (5-30°). In most cases the foliation planes show a prominent SW-NE stretching lineation seen as rodding of quartzo-feldspathic aggregates, oriented growth of sillimanite in the foliation planes, and integrowths of biotite and sillimanite in pressure shadows around the boudinaged garnet porphyroclasts (Figs. 3, 4a).

The general sense of displacement of the Podolsko Complex over the Monotonous and Varied Units during the compressional tectonic stage has not yet been determined unambiguously, but Vrána (1979) and Rajlich et al. (1986) deduced southeastward transport for this part of the Moldanubian domain. Conversely, Matte et al. (1985, 1990) and Schulmann et al. (1994) suggest eastward movement of the Gföhl granulites in Lower Austria and in the easternmost part of the Moldanubian Zone. The chronology of these movements within the Variscan processes remains uncertain.

3. Late-Variscan extension

Tectonic activity did not cease after the main allochthonous units were assembled. Evidence of this is provided by large-scale intramoldanubian shear zones and detachments which affect all the main Moldanubian tectonostragraphic units (Vrána 1979, 1992, Rajlich et al. 1986).

Intramoldanubian shear zones

Several shear zones of variable scales have been detected within the Moldanubian Zone in southern Bohemia. Some of them are of a regional scale cutting across the boundaries of internal Moldanubian nappes (Suess 1926, Vrána 1981, Rajlich et al. 1986). In the area studied, such a main shear zone has been recognized by Vrána (1979) and Machart (1987) who intepreted the Týn nad Vltavou-Vodňany shear zone as a major discontinuity between the Podolsko Complex and the underlying Monotonous Group. This zone separates the major NW part of the Podolsko Complex at its south-eastern margin from the underlying Monotonous Unit (Fig. 1) and can be traced from Týn nad Vltavou in the NE to the area east of Vimperk in the SW. The shear zone extends several tens of kilometers in length (Vrána 1979, Machart 1987). A zone of intense low-temperature mylonitization which varies in width from several metres up to hundreds of metres is present at the north-west edge of the regional shear zone. It runs parallel to the older amphibolite-facies shear foliation which affects the paragneiss complex over a thickness of more than ten kilometres. The late mylonitic zone marks a crustal-scale normal fault along NW margin of the polyphase shear zone and, together with petrological information, serves as an evidence for late-orogenic collapse in this part of the Moldanubian Zone.

The Podolsko part of the Týn nad Vltavou-Vodňany shear zone

Our structural studies support an interpretation in which the original sole-thrust contact of the NW part of the Podolsko Complex with the underlying Monotonous and Varied Units is cut-off by the normal-fault shear zone. Because the complex was transported along this normal fault, the authors refer to this part of the Týn nad Vltavou-Vodňany shear zone as the Podolsko detachment. Deformation of the Moldanubian metamorphic rocks caused by extensional shearing resulted in intense reworking of the older metamorphic fabrics. Relics of earlier mineral assemblages in low-strain domains indicate that retrograde shear deformation affected originally high-grade rocks of the Podolsko Complex (Fig. 4a, b, c).

The mylonitic foliation planes are defined by mylonitic layering, the preferred orientation of phyllosilicates, alignment of feldspar clasts, and are locally emphasized by quartz ribbon aggregates. This foliation cuts across the older compositional foliations. It is curved and deflected but generally tends to be parallel or subparallel to the Podolsko detachment margins and dips to the north or northwest at moderate angles (Fig. 2).

S-fabrics generally predominate. Strong mineral lineations, marked by streaking and alignment of feldspar clasts and recrystallized quartz ribbons, plunge uniformly towards the NW (Fig. 3). However, locally intense L-fabrics, defined by preferred orientation of rock-forming minerals or by local perturbation of foliation, results in development of rodding parallel to the regional stretching lineation.

Heterogeneous deformation leads to the development of lens-shaped low-strain domains surrounded

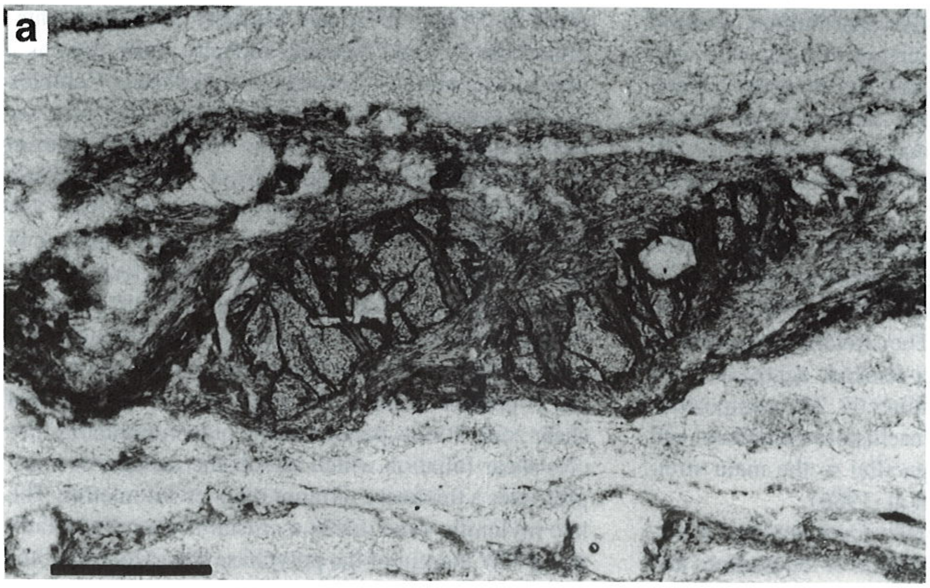
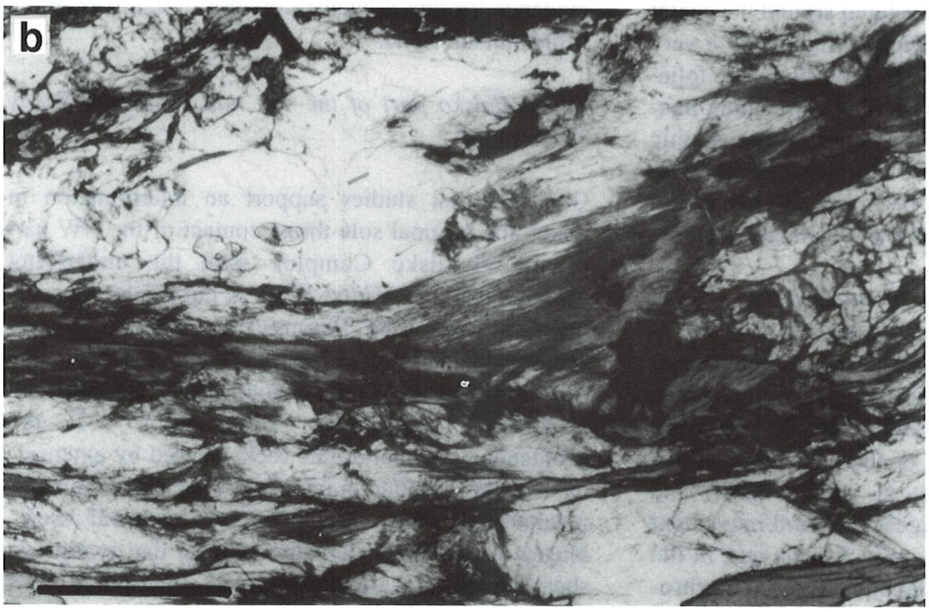


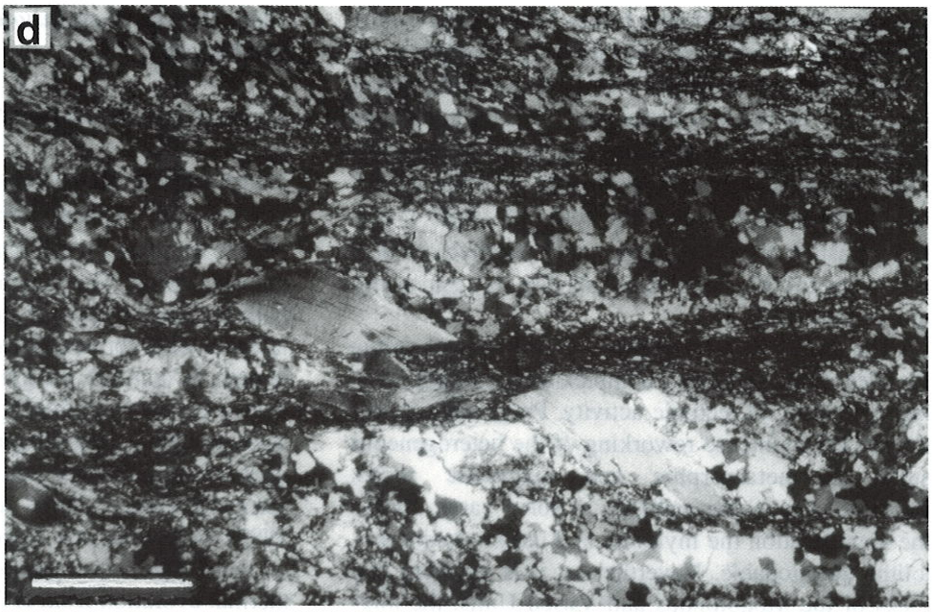
Fig. 4. Photo-micrographs from sheared rocks of the Podolsko Complex, illustrating superimposed deformational microstructures in sheared granitoids (e-f) and changes in metamorphic grade (a-d)
Scale bars equal to 1 mm

a - Asymmetrically boudinaged garnet in the main metamorphic foliation, surrounded by intergrowths of sillimanite and biotite in pressure sheadows (migmatite of the Podolsko Complex);

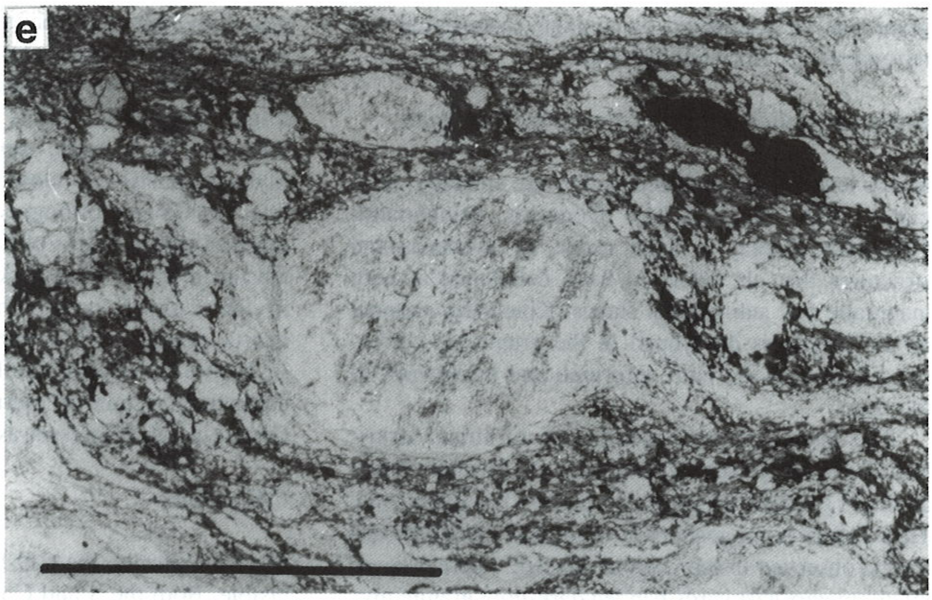


b - Growth of sillimanite along the main foliation planes of the Podolsko migmatites, typical of the decompressional regime;

c - Relics of hypersolvus alkali feldspar in mylonitized Podolsko migmatite, indicating granulite facies metamorphic history;



d - Biotite mica-fish sense-of-shear indicator associated with the development of extensional shear-bands in deformed granitoids;



e - Delta-porhyroclasts of feldspar, greenschist facies deformation of granite;

f - Asymmetric microfolds refolding mylonitic layering in the greenschist facies ultramylonites by sigmoidal ultramylonite bands. This pattern is typical of the strain-path partitioning described by Choukroune and Gapais (1983). The spatial distributions of the mylonite foliation and stretching lineation suggest down-dip movements along the shear zone. This conclusion is also supported by several sense-of-shear criteria such as an ubiquitous C/S fabric, ?-porphyroclasts in the orthogneiss and ∂-porphyroclasts in the mylonites (Fig. 4d), mica-fish (Fig. 4e), and asymmetric folds (Fig. 4f).

The wide range of microstructures formed within the shear zone suggests a complex and probably long-lasting history of tectonic activity. Progressive deformation led to intense reworking of the heterogeneous suite of metamorphic and magmatic rocks. Retrogressive metamorphism, in some cases, makes the identification the mylonite and ultramylonite protoliths questionable. Nevertheless, it is apparent that rocks of the Monotonous and Varied Units, the migmatites of the Podolsko Complex and the Variscan granitoids were affected by a single extensional and retrogressive deformational event.

Granitoid bodies occurring along the shear zone

Minor leucocratic granitoid bodies are spatially associated with the Podolsko Complex detachment. Granitoids display a wide range of deformational structures that are likely to have developed at both magmatic and sub-solidus stages. Kinematic patterns of the structures developed in the granitoids correspond well with the bulk deformational framework of the zone.

The inhomogeneous distribution of strain described above led to the development of variable deformational gradients in particular parts of the shear zone. Thus rather homogeneously deformed orthogneisses can be observed in the Čavyně Massif, whereas several kilometers eastwards banded dark-grey granite mylonites and ultramylonites alternate with almost undeformed rock in the Záboří quarry.

Magmatic rocks with little or no sign of ductile deformation are trapped within the undeformed pods surrounded by mylonite foliation or they are present as minor intrusions along the shear zone. The boundary between the C/S granites in low strain domains and the surrounding mylonites and ultramylonites is always sharp and distinct. The mylonite foliation planes within the granitoid bodies generally dip very uniformly, except at sites where they wrap around low-strain domains. Protomylonites are rare, and all the mylonitic rocks can be allocated to end-members on the descriptive scale of Heitzman (1987).

A strong mineral lineation gives way to brittle striations within the same kinematic framework, suggesting a decrease of temperature during fault evolution. The lineation plunges uniformly towards the NW (Fig. 3).

Microstructural evolution and deformational mechanisms

Microstuctures in distinct types of deformed rocks

Deformational microstructures, mineral assemblages, and inferred deformational mechanisms have been used to decipher the thermal and mechanical history of the shear zone. The metapelitic rocks, heterogeneous both in composition and structure, do not provide suitable material for detailed systematic study of the strain path. In contrast, the granitoids record the complete deformational evolution from protomylonite to steady-state structures. The behavior of granitoids during progressive deformation has recently been described comprehensively (Burg and Laurent 1978, Handy 1989). Moreover, the supposed syntectonic character of small intrusions provides information about the thermal evolution from HT to LT fabrics.

With respect to the degree of deformation, four stages of mylonitization have been distinguished: (1) C/S granite, (2) C/S orthogneiss, (3) - banded orthogneiss, (4) - mylonite (Fig. 5). Deformed C/S granites occur in minor leucocratic bodies several tens of metres in thickness, or in pods, surrounded by mylonite/ultramylonite bands e.g. close to Vodňany. In contrast to this, the Čavyně orthogneiss body generally displays more advanced stages of deformation. The three more advanced stages of reworking were therefore studied in the Čavyně body. The metagranitoids contain quartz, perthitic microcline, albite and sodic oligoclase, biotite and muscovite. In muscovite-rich varieties, columnar crystals of tourmaline up to 5 cm occur. Garnet is locally present as an accessory.

C/S granites

Macroscopically, the C/S fabric of the rock is clearly visible. Both the S and C planes dip towards the NW at an angle of about 30°. Slightly curved C-planes bear a strong mineral lineation plunging to the NW. The spatial distribution of these planes is indicative of normal-fault movements. However, at the microscale, it forms the dominant structure within the rock, with C-planes heterogeneously crosscutting the rock and playing a subordinate role (Fig. 5a). Micas and feldspar porphyroelasts are aligned in the S planes. The tips of mica porphyroclasts are recrystallized and deflected into the C-planes (Fig. 6a). Plagioclase and K-feldspar grains locally display euhedral shapes, most of them being modified by extensive fracturing. K-feldspar grains also show variably developed microcline twinning and undulatory extinction. Dynamic recrystallization starts at the mutual contacts between individual feldspar grains and along internal microshear zones and kinks (Figs. 5, 6a).

Quartz is present as pockets wraping around feldspar porphyroclasts. Rare relict quartz grains within

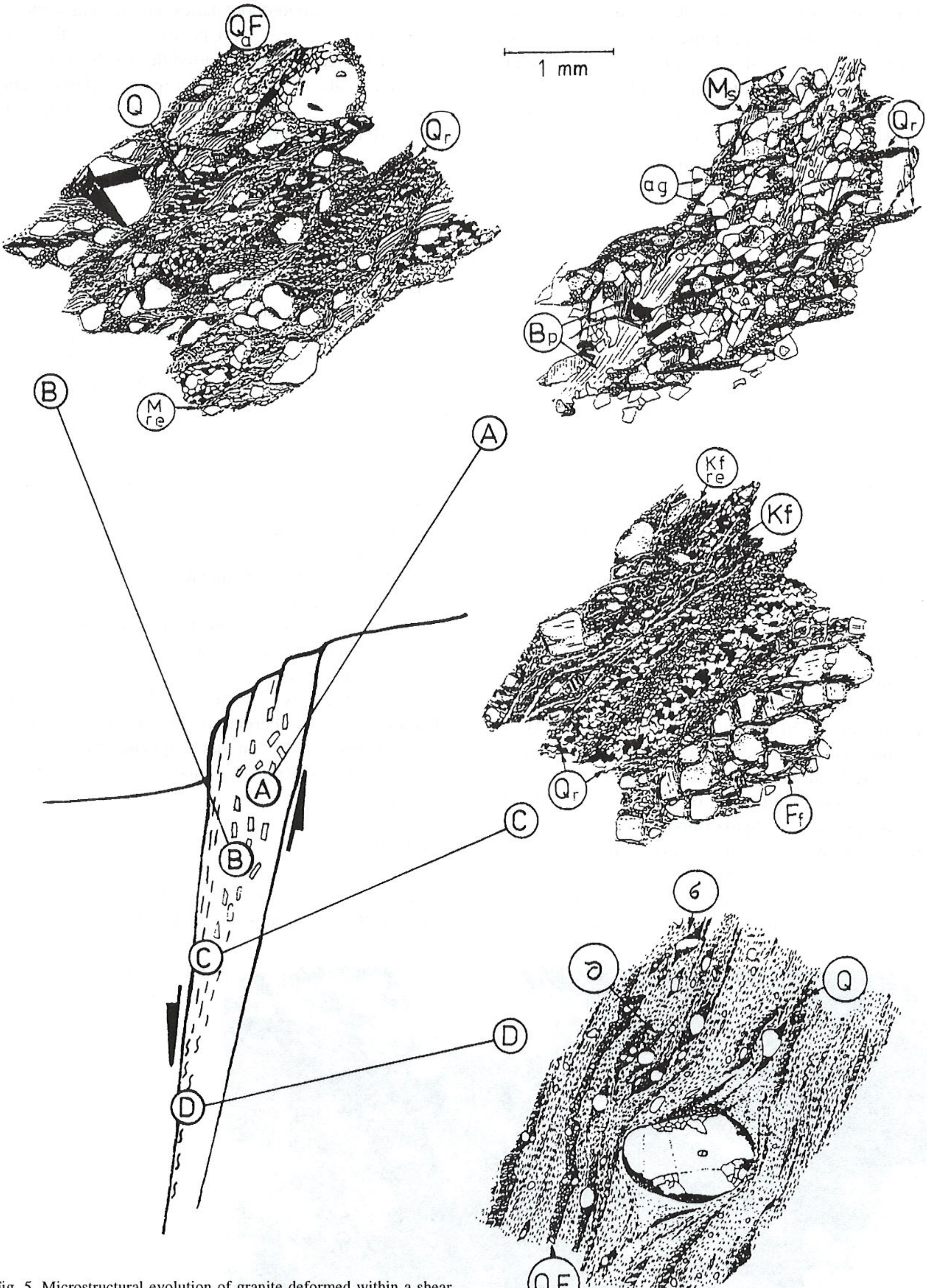


Fig. 5. Microstructural evolution of granite deformed within a shear zone during the extension. Four stages of progressive deformation within the shear zone:
A - C/S granite is the first stage of deformation. The angle between S and C planes approximatelly 35°; B - C/S orthogneiss. The angle between S and C planes is about 25-30°; C - Banded orthogneiss; D - Ultramylonite, Q - quartz, Qr - quartz ribbon, QFa - quartz-feldspathic aggregate, Ms - muscovite, B - biotite, Mre - recrystallized micas, Bp - primary biotite, F - feldspar, Kfre - K-feldspar recrystallized, δ - delta clasts, θ - sigma clasts, ag - angular grains

the pockets form larger irregular clasts showing internal features, such as prismatic subgrains. These large grains are surrounded by colonies of small, almost equant, strain-free grains typical of mantle-and-core microstructure (White 1976). In the case of complete recrystallization of quartz in pockets, the grains are subequant, 0.2 mm in size with serrated boundaries indicating grain-boundary migration (Guillopé - Poirier 1979). The large pockets are locally interconnected by narrow strips of small recrystallized quartz grains parallel to the C surfaces. Grains within these proto-ribbons show a low aspect ratio (5 : 1), are dominantly equant, strain-free and 0.1 mm in size.

C/S orthogneisses

In the C/S orthogneiss, the C-planes are well developed, and the S and C planes are in spatial equilibrium (Fig. 5b). Shear bands, marked by alignment of micas, are locally developed. The fine-grained matrix forms more than 70 vol. % of the rock. Mica porphyroclasts form abundant foliation fishes, with their tails elongated to the C-planes.

Feldspars are present in the form of individual porphyroclasts or aggregates; plagioclase predominates over K-feldspar. They display strong undulatory extinction. K-feldspars are affected by abundant myrmekite growth (Fig. 6b) at high-pressure sides of the feldspar grains (Simpson - Wintsch 1989). Biotites and small, almost equant, strain-free quartz grains crystallized in the pressure shadows of the feldspar clasts. The C mica-rich planes are locally emphasized by polycrystalline quartz aggregates often composed of individual thin ribbons, separated by micas. Quartz ribbons are formed by large irregular grains 0.3-0.7 mm in size with serrated boundaries and undulatory extinction. No significant grain-size variations in individual ribbons have been observed. Elongated grains form often oblique fabrics with repect to ribbon boundaries. Grain shapes and internal strain features indicate that dominantly grain boundary migration has occurred during the recrystallization. Locally, in the vicinity of feldspar clasts, highly flattened quartz ribbons showing no grain size reduction are developed (Fig. 5b).

Banded orthogneisses

The banded orthogneiss consists of quartz ribbons, alternating with a fine-grained matrix containing feldspar porphyroclasts (Fig. 5c). The matrix is made up predominantly of quartz and phyllosilicates, with subordinate small feldspar grains. Matrix phyllosilicates display strong shape preferred orientations parallel to the mylonitic foliation. Perturbed zones occur in the vicinity of large feldspar porphyroclasts, where the matrix phyllosilicates are deflected.

Polycrystalline quartz ribbons with a high aspect ratio dominate the banded structure of the rock. Ribbon thickness is typically fairly uniform. Individual grains 0.3-0.5 mm long also show a uniform grain size distribution. Grains are subequant with irregular and serrated boundaries, sometimes a weak shape preferred orientation is developed (Fig. 6c).

Most porphyroclasts are individual feldspar crystals or crystal fragments; composite aggregates do not occur. Porphyroclasts display dominantly oval shapes, with the longest axes aligned parallel to the stretching lineation (Fig. 5c). Perturbed zones between individual fragments suggest that they originated from one crystal which was fractured and pulled-apart in the X-direction.

Mylonites

The protolith of the mylonites/ultramylonites can be inferred from the composition of rocks within the low-

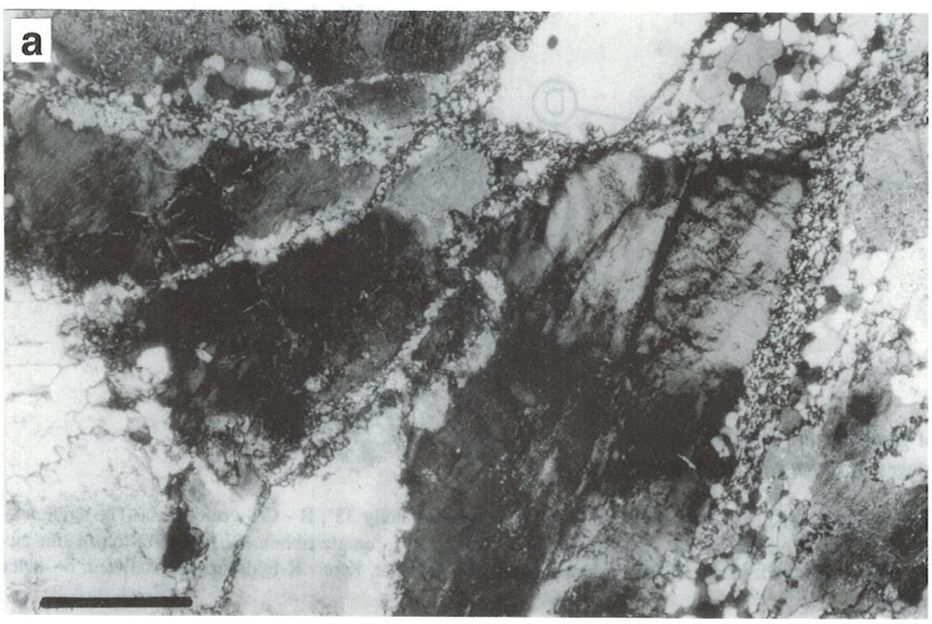
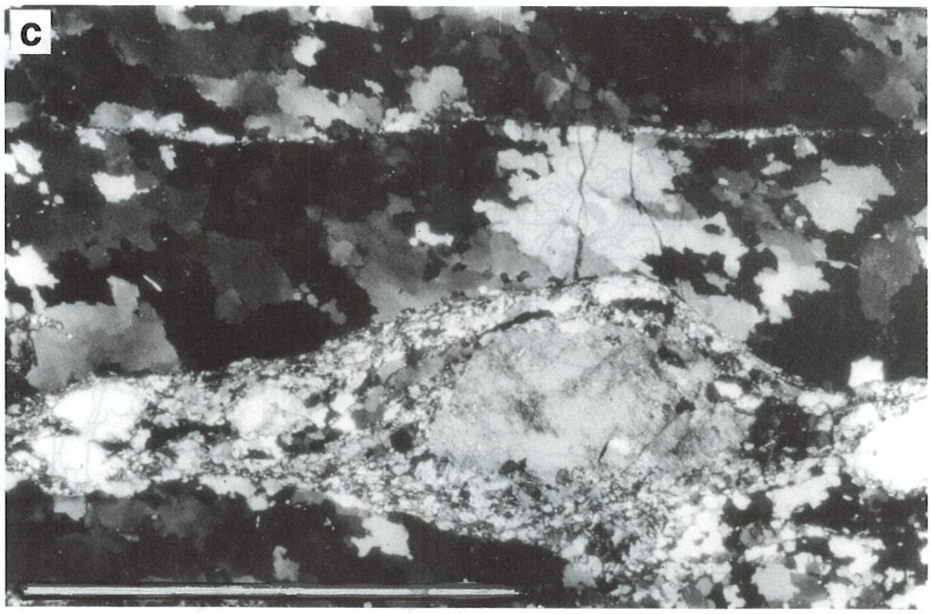


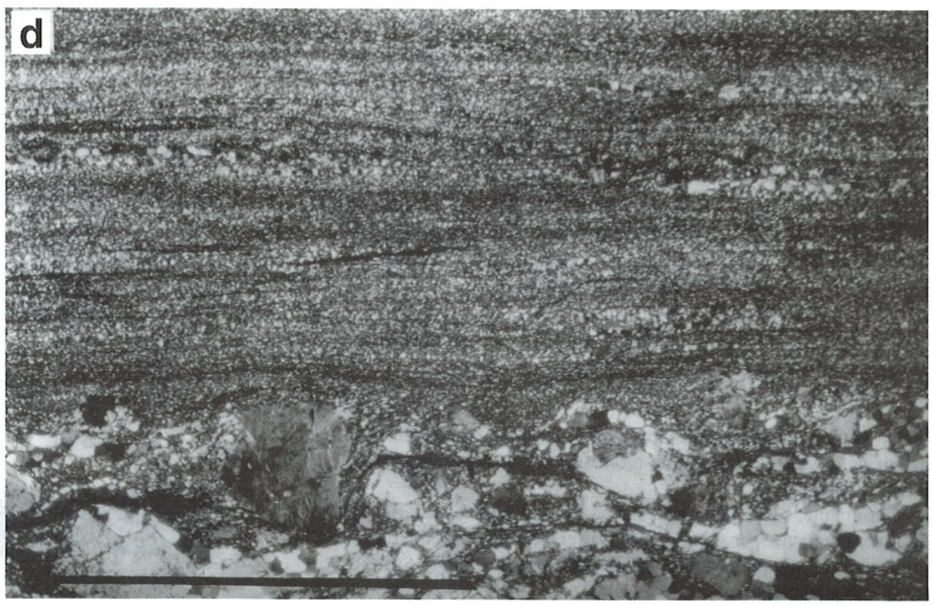
Fig. 6. Photo-micrographs of structures of the deformed granites
Scale bars equal to 1 mm

a - Dynamic recrystallization of K-feldspar clasts along microshear zones and kink-bands, weakly deformed granite;

b - Pressure-induced growth of myrmekites along a foliation plane at the rim of K-feldspar clast in C/S orthogneiss;



c - Asymmetric grain shape and grain-boundary migration in recrystallized quartz bands, banded orthogneiss. Note the relict feldspar clast surrounded by quartz matrix;



d - Ultramylonite with some relics of feldspar clasts and quartz ribbons in lower part of the photograph.

strain domains. Mylonites, which locally occur in the central part of the shear zone, consist of an ultrafine-grained matrix formed of the breakdown products of feldspars, primary micas, chlorite, sericite and quartz grains (Figs. 5d, 6d).

Quartz is concentrated mainly in scarce elongated, ribbons reaching tens of centimeters in length. Polycrystalline ribbons are composed of several thin quartz layers, mutually parallel and separated from each other by very thin micaceous bands. They progressively thin around the feldspar porphyroclasts. Individual quartz grains 0.1 mm in size show both crystallographic and shape preferred orientation. The angle between the ribbon boundary and the long axes of orientated small grains varies from 10° to 45°. All grains display serrated and sutured boundaries indicating grain boundary migration. Some of the quartz grains in the thinner ribbons meet locally in triple-point junctions thus suggesting a certain degree of equilibration.

Lenticular or angular feldspar porphyroclasts are preserved in the matrix (Fig. 6d). Deformation of feldspar is dominantly brittle, however, some recrystallization occurs in the necks of the feldspar grains. Greater deformation leads to the progressive grain-size reduction of feldspars and thus to the relative enrichment of fine-grained matrix. The feldspar clasts are surrounded by perturbed mylonitic foliation defined by preferred orientation of phyllosilicates. Feldspar porphyroclasts are mostly subrounded, rounded and oval in shape. Such a shape is attributed by O'Hara (1988) to pressure solution acting in addition to the cataclasis process, which by itself could not produce the oval shape of the porphyroclasts.

C-axis fabric analysis

C-axes of approximately 200 quartz aggregates have been measured using a U-stage, and the results display-

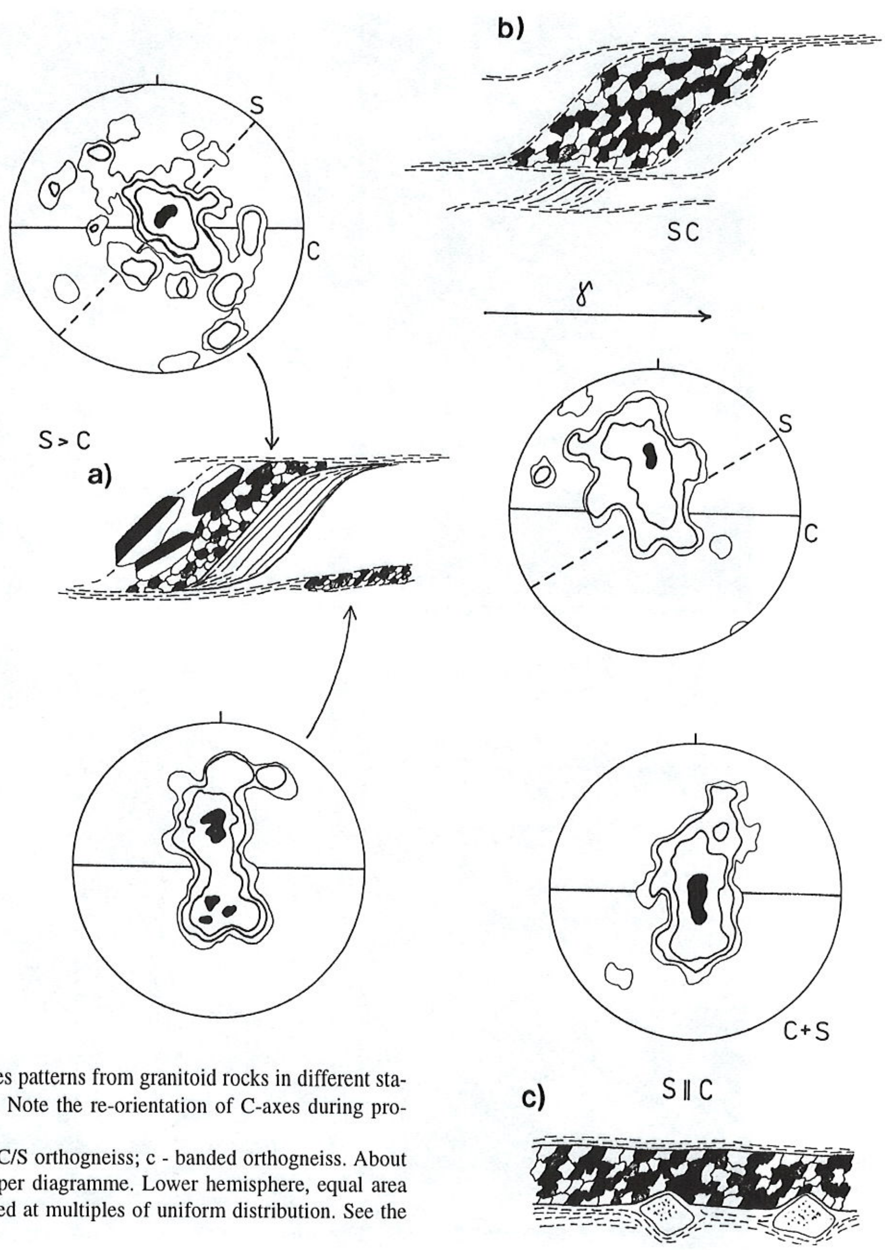


Fig. 7. Quartz C-axes patterns from granitoid rocks in different stages of deformation. Note the re-orientation of C-axes during progressive shearing
a - C/S granite; b - C/S orthogneiss; c - banded orthogneiss. About 200 measurements per diagramme. Lower hemisphere, equal area projection. Contoured at multiples of uniform distribution. See the text for explanation

ed on lower hemisphere equal area projections (Fig. 7).

In C/S granites, the quartz ribbons generally tend to be arranged parallel or subparallel to S planes, that are defined by preferred orientation of micas and feldspars. The quartz ribbon boundaries are deflected 40-50° from the C planes. C-axes of most of the small grains compounding the ribbons are clustered around the center of the diagram. C-axes that are inclined from the Y-axis of the finite strain ellipsoid form a single girdle. This girdle is 45° apart from the C-plane which is perpendicular to the S planes (Fig. 7a). The C-axis distribution suggests activity of the prism <a> and rhomb <a+c> glide systems during development of quartz-fabric in simple shear regime (Lister - Hobbs 1980). Angles between the quartz ribbon and the kinematic frame-work slightly vary from ribbon to ribbon, depending on the particular angle between the S and C planes.

Narrow quartz ribbons are also developed along the C-planes. They are composed of significantly smaller recrystallized grains. These grains exhibit strong C-axis preferred orientation pattern forming a unique girdle perpendicular to the C-plane (Fig. 7a). The girdle is usually formed by two symmetrically distributed maxima along a trace of the C-plane suggesting combined prism <a> and rhomb <a+c> glides.

The fabrics with pre-existing S-planes and subsequently formed C-planes are attributed to the tectonic event that, according to microstructural evolution of rock-forming minerals, began already in the sub-magmatic stage of rock formation, and that continued untill a solid state was reached.

The C/S orthogneisses display C-axes projected in a well defined, unequally populated single girdle. The girdle is always inclined in an opposite sense than the imposed deformation defined by the C planes (Fig. 7b). In the projection, the angle between the girdle and the Z axis varies between 20° and 35°. It is always considerably lower than in case of the C/S granites. The decreasing angle between the S and C planes is associated with development of one single broad girdle in a position almost perpendicular to the C plane. However, at this stage it is still oblique to the C planes.

In the banded orthogneisses, the C-axis fabric is dominated by a well developed and more or less equally populated single girdle, that is slightly inclined according to the imposed shearing. The S planes show evidence of being totally reworked by the C planes, so that both systems form a unique planar fabric. Quartz is present exclusively in the form of recrystallized mosaic of small grains forming ribbons parallel to the mylonite foliation. The C-axes are clustered about the Y axis of the strain ellipsoid, forming a short girdle perpendicular to the XY plane (Fig. 7c). This indicates an activity of unique prism <a> glide system parallel to the shear plane.

In the mylonites, the quartz c-axis patterns are weaker than those in the banded orthogneisses. Moreover, the fabric is strongly domainal, with intensity strongly varying from ribbon to ribbon (Fig. 8). The c-axes are clustered around the centre of the diagram indicating a dominant activity of a prism <a> glide. This weakening of the quartz c-axis fabric is attributed to a concentration of a flow stress in the ultra-fine grained matrix.

Interpretation of the c-axis fabric analysis

Our study shows that the C-axis girdles are not perpendicular to the kinematic framework defined by the C-planes from the beginning of plastic deformation but instead, the C-axis patterns are governed either by the geometry of S-planes or C-planes giving two mutually inclined girdles (cf. Vrána 1959). This result is in contradiction with the generally accepted concept of kinematic control of the quartz c-axis pattern in shear zones (Berthé et al. 1979, Lister - Williams 1979, Bouchez - Pécher 1981). In early stages of granite deformation the quartz C-axis girdle orientation is not consistent with the sense of shear within the shear zone. This development can be attributed to two different models. The first one implies a contemporaneous sliding along the quartz ribbon boundaries parallel to both the S and C-planes. The smaller grain size of quartz grains and stronger preffered orientation of the C-axes suggests a higher shear stress concentration

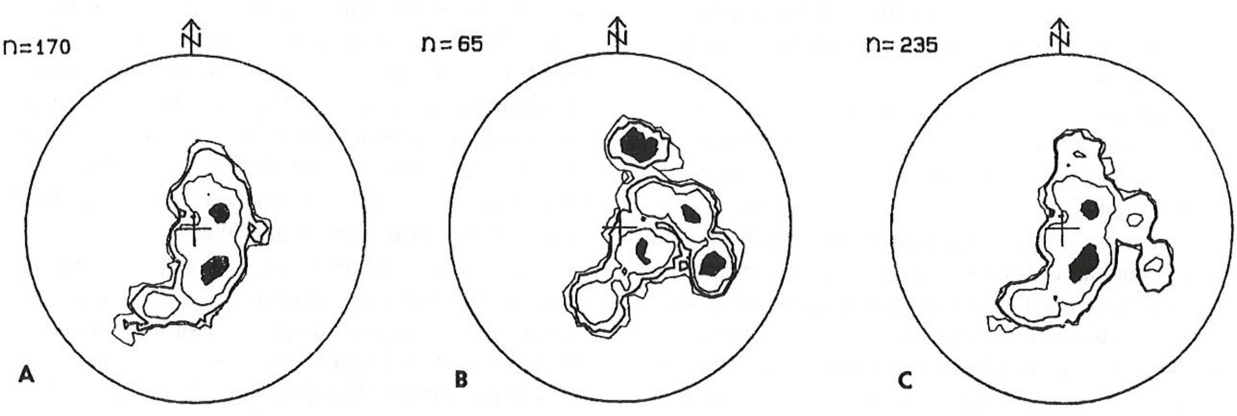


Fig. 8. Quartz C-axis patterns from greenschist facie mylonites and ultramylonites. Lower hemisphere, equal area projection. Contoured at multiples of uniform distribution. See the text for explanation

along the C-planes. In this model the S-planes have a ramp-geometry, while the C planes a flat geometry of a small-scale duplex structure. The second model suggests a polyphase development; the fabric is related to the S-planes during its first stage, and the C-structures prevail and overprint the former S-fabric in the second stage. This fabric can originate during a progressive cooling and deformation of granite in which weak quartz blebs are elongated parallel to the shear direction. The quartz C-axis fabric is controlled by the geometry of the S-planes in this stage. Shear deformation concentrated in the C-planes in later stages of progressive cooling and deformation. None of those models is compatible with the generally used C/S theory of Berthé et al. (1979). The girdle orientation is consistent with the generall sense of shear only in case of a banded orthogneiss where the quartz ribbons are parallel with the flow planes.

4. Tectonic evolution

Our investigations confirm that major NE-SW sub-horizontal stretching was imposed on both the Varied and Monotonous Groups and the "Gföhl" Podolsko Complex during early to late compressional tectonics. Thrust movements have already been recognized by Vrána (1979) on the basis of the relative position of the Podolsko Complex and the underlying units and the associated refoliation and mylonitization. The same character of tectonic style has been confirmed by Machart (1987) and Urban and Synek (1992). The structural pattern in the area studied has been affected by NW-vergent late-extensional tectonics on a crustal scale. The extensional instabilities, developed predominantly in domains with a NW dipping foliation, have exhumed the Monotonous Group, and juxtaposed the Gföhl and Monotonous Units which were originally separated by the intervening Varied Group. This geometry is developed along that part of the Týn nad Vltavou-Vodňany shear zone, here defined as the Podolsko Complex detachment, which appears to be one of the dominant intramoldanubian extensional faults. The intrusion of granitoid magmas could have been partly synchronous with the extensional movements which continued after emplacement of the granite intrusives.

Amphibolite facies shear deformation of granitoids at low-strain intensities is marked by development of C/S fabric which passes into high-strain banded orthogneiss. This deformational sequence shows a progressive transition from the heterogeneous deformation throughout large volumes of rocks characterized by the well-developed C instabilities towards the homogeneous deformational fabrics localized in shear zones. Progressive development of shear zone leads to decrease of the C/S angle and to the uniformity of quartz grain size resulting from more homogeneous flow stress and strain rate distributions within the core of the shear zone. This strain gradient has been established under constant temperature conditions and led to steady state flow and an increase of the viscosity contrast between shear zone and the wall rock (Handy 1989). Continued deformation led to crustal uplift and, consequently, a decrease of geothermal gradient during cooling. The P-T path of the shear zone separating the Podolsko Complex from the underlying Monotonous Group intersected the reaction curve of destabilization of plagioclase and micas and resulted in a reaction-enhanced transition to grain-size sensitive creep in mylonites (Handy 1989). These sharply localized ultramylonitic shear zones display continuous transition from amphibolite facies conditions to greenschist facies under the same kinematic regime.

The thermomechanical evolution of mylonite zone is compatible with the thermal evolution of extended litosphere (Thompson - Ridley 1987). The Podolsko Complex exhibits HP metamorphism during compresive movements that were followed by a subsequent decompression associated with widespread MP anatexis (sill, grt, Kf) and an extensional reactivation under amphibolite to greenschist facies. The lower Monotonous Group shows MP-MT metamorphism (Petrakakis 1986) overprinted by HT-LP metamorphism during which cordierite-bearing anatexites (crd, sill, Kf) related to intrusion of the Central Moldanubian Pluton were formed (Vrána 1992). The contact of both units was strongly modified by the late extensional deformation under amphibolite to greenschist facies conditions.

In order to estimate the throw along the extensional intramoldanubian zones, we can take into account the present area of the Podolsko Complex on both sides of the Vodňany-Týn nad Vltavou shear zone. Based on this relation, the minimum throw along this late fault is about 5 km. According to pressure differences estimated for the Gföhl Unit and the underlying Drosendorf Unit s.l. (4-6 kbar, Petrakakis 1986), the total vertical throw along the shear zone could be as great as 12-18 kilometres. However, this estimate is based on absolute difference in depth of these two units during metamorphism related to crustal thickening in the southernmost part of the Moldanubian Zone. The timing of the extensional tectonics is bracketed by the age of intrusion of the Central Moldanubian Pluton 330 Ma (van Breemen et al. 1982) and the fact that the extensional tectonics affects also the granitoids of Central Bohemian Pluton and Gföhl migmatites in which anatectic event was dated at 339 Ma (van Breemen et al. 1982).

The tectonic interpretations of the Moldanubian Zone of the Bohemian Massif is usually based on a model of convergent mountain building processes (Matte et al. 1990, Franke 1989). Our case study of various parts of the Moldanubian Zone in southern Bohemia shows that the geological fabric of these parts is strongly modified by late-extensional processes. Parts of the Gföhl Unit (if we accept this term for the high-grade bodies studied) can no longer be interpreted purely as "klippen" resulting only from compressional tangentional movements and, according to the results of this study, their recent position is modified by the late-orogenic gravitational collapse. Thus, on the basis of field and microstructural evidence, the Gföhl relics are inferred to fill structural "grabens" in the underlying units during late stages of tectonic evolution. This conclusion is in accord with a general model proposed by Burg et al. (1994a,b) for the final structural pattern of the Variscan belt.

Results of gravimetric survey provide new data on the depth of the Podolsko Complex and Prachatice granulite body, the base of which may lie 10 km below surface (Šrámek et al., in press). These results contradict our hypothesis if the subsurface occurrence of light granitic bodies is discounted. Moreover, the amount of extension proposed by Burg et al. (1994b) should be the subject of further investigation in the Bohemian Massif. It seems probable that the Central Moldanubian Pluton in the Moldanubian Zone played an essential role in the extensional process in a way similar to the large magmatic bodies described from the French Massif Central (Faure - Pons 1991).

Acknowledgment. The authors thank Dr. Stanislav Vrána from the Czech Geological Survey for his very helpful notes to manuscript and review, and Dr. Vladimír Tolar for his help with figure drawings. The research was funded by project of the Ministry of Environment of the Czech Republic "Geological model of the western part of the Bohemian Massif in relation to the deep borehole KTB in FRG", coordinated by Czech Geological Survey, Dr. S. Vrána coordinator". The funding is acknowledged.

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Pozdně orogenní extenzní kolaps moldanubické zóny v jižních Čechách (Czech summary)

Litotektonická stavba moldanubika, vzniklá v důsledku nasunutí tzv. gföhlské jednotky na monotónní a pestrou skupinu, byla modifikována během sz. orientované extenze korového měřítka. Pozdně extenzní intramoldanubický podolský zlom podél sz. okraje variské duktilní střižné zóny mezi Vodňany a Týnem nad Vltavou zdůraznil tektonické rozhraní mezi exhumovanou monotónní skupinou a podolským komplexem. Monotónní skupina byla relativně vyzdvižena podél střižné zóny a tohoto poklesového zlomu do úrovně gföhlského alochtonu. Minimální odhad vertikální složky polyfázového poklesu je 5 km, maximální odhad až 18 km.

Malá tělesa granitoidů intrudovala pravděpodobně synchronně s poklesovými pohyby, přičemž extenzní deformace pokračovaly i po zchladnutí a vmístění granitů. Mikrostrukturní výzkumy některých granitoidních těles ukazují na plynulý přechod od C/S granitů, přes C/S ortoruly, páskované ortoruly až po ultramylonity. Deformace probíhaly převážně za podmínek amfibolitové facie a za poklesu do facie zelených břidlic.

Analýza mikrostaveb křemene dokládá aktivitu prizmatického <a> kluzného systému pro všechna stadia a intezity deformace. Křemenné stavby jsou řízeny spíše geometrií konečné deformace nežli kinematickým rámcem deformace přinejmenším během počátečních stadií, a vývoj C/S staveb tedy nemusí být synchronní. Univerzální určování kinematiky pohybů za použití asymetrie obrazců křemenných C os je v tomto případě problematické.