Late orogenic structural control on the regional geometry of basement massifs: An example from the Jeseník Mountains, Czech Republic

Vliv pozdně orogenních struktur na regionální geometrii basementu: příklad z krystalinika Hrubého Jeseníku, Česká republika (Czech summary)

(6 text-figs.)

SIMON TESTA - WES GIBBONS

Department of Earth Sciences, University of Wales, Cardiff, CF1 3YE, UK

During a visit to the Jeseník Mountains in the summer of 1993, Radek Melka and Wes Gibbons became interested in anomalous steep zones along the eastern margin of the Desná Complex. At this time, the origin and significance of these steep zones remained unclear. It was their hope and intention to continue and develop this work during 1994. Sadly, due to Radek's untimely death, this was not to be so. The present authors returned to the area in the summer of 1994 to further the study of this problem. This paper presents their findings and discusses possible broader implications drawn from their conclusions. Variscan metamorphic rocks in the Jeseník Mountains, (NE Czech Republic) include a prominent asymmetric dome-like structure known as the Desná antiform. This regional fold exposes a core of pre-Devonian basement (Desná Complex) flanked by metasediments of probable Devonian age. Both basement and cover within the area are pervaded by a "top-to-southwest" main mylonitic fabric of probable Variscan age, which in the basement rocks transposes an earlier migmatitic foliation thought to be of Cadomian age. The main mylonitic fabric on the northwestern side of the antiform dips gently or moderately to the northwest and is parallel to the regional sheet dip. In contrast, within both the hinge region and southeastern limb of the antiform the main mylonitic fabric is folded about southeasterly verging folds with associated steep to moderate northwest dipping axial planar crenulation fabric. Local overturning of the steepened mylonitic fabric around these late folds reverses the apparent sense of mylonitic shear from sinistral (top-to-southwest) to dextral (top-to-northeast). The presence of near-vertical fold limbs along this southeast side of the Desná Complex has produced local steep zones which, like the domal geometry of the Desná Complex itself, are a product of the late southeasterly-directed compression. The outcrop pattern of the Desná Complex and its metasedimentary cover is therefore attributed neither to early antiformal nappe stacking nor core complex collapse, but to late orogenic cross folding.

Key words: basment and cover relationships, steep shear zones, cross-folding

Introduction

The Jeseník Mountains are situated in the Czech Republic at the northeastern margin of the Bohemian Massif which represents the easternmost part of the Variscan orogenic belt in Central Europe (Fig. 1a). The Jeseníky region is positioned approximately between the NW-SE trending Elbe and Sudetic Marginal Fault Zones, with its western margin represented by the Ramzová thrust and its eastern margin by the contact with a detached Culmian basin. This area lies at the northwestern edge of the Moravian terrane of Matte et al. (1990) which corresponds to the Moravo-Silesian Zone of Suk et al. (1984) (Fig. 1b). The Jeseníky region exposes a series of tectono-metamorphic units that are broadly subdivided from west to east into: a high grade gneissic complex (Staré Město belt), low grade Devonian metasediments (Branná Group of Zapletal 1950), followed by greenschist and amphibolite-grade metasediments, metagranitoids, and reworked migmatites (Keprník and Desná complexes) (Fig. 2). The structural, metamorphic and tectonic history of the eclogite-bearing Staré Město nappe is in strong contrast to that of both the Keprník and Desná basement and their associated cover. Both the Keprník and Desná complexes show an elongate gneissic and metagranitoid core which is overlain by metasediments of probable Devonian age (Pouba in Svoboda 1966). The Desná Complex lies immediately SE of the Keprník Complex, and is separated from it by a zone of highly deformed and sliced Devonian and pre-Devonian metasediments (the Červenohorské sedlo belt). Along the eastern margin of the Jeseníky region, a wide belt of Devonian low grade metasediments (Vrbno Group) borders the Desná Complex. Further east lies a Devonian-Carboniferous detached Culmian basin (Fig. 2). The four main tectono-metamorphic units (Staré Město, Branná, Keprník, and Desná) that comprise the Jeseníky region occur as belts running NNE-SSW, with all contacts being tectonic.

Becke (1892), Suess (1912, 1926), Kossmat (1927), Kölbl (1930), and Bederke (1935) considered the structure and metamorphism of this region to be a product of Alpine-type (crustal stacking) tectonics. The application of thrust stacking concepts to the Bohemian Massif has been used to underpin several plate tectonic models for the Variscan belt (e.g. Franke 1989, Matte 1986, 1991). This view of compressional nappe tectonics was emphasised by Fediuková et al. (1985) and Cháb et al. (1992) for the eastern part of the Jeseníky region. However, more recently, Sidorinová (1988, 1990) and Cháb et al. (1994a), have pointed out the apparently extensional nature of some aspects of the regional architecture. This view of extensional tectonics playing a major role in the construction of the orogen is supported by the present

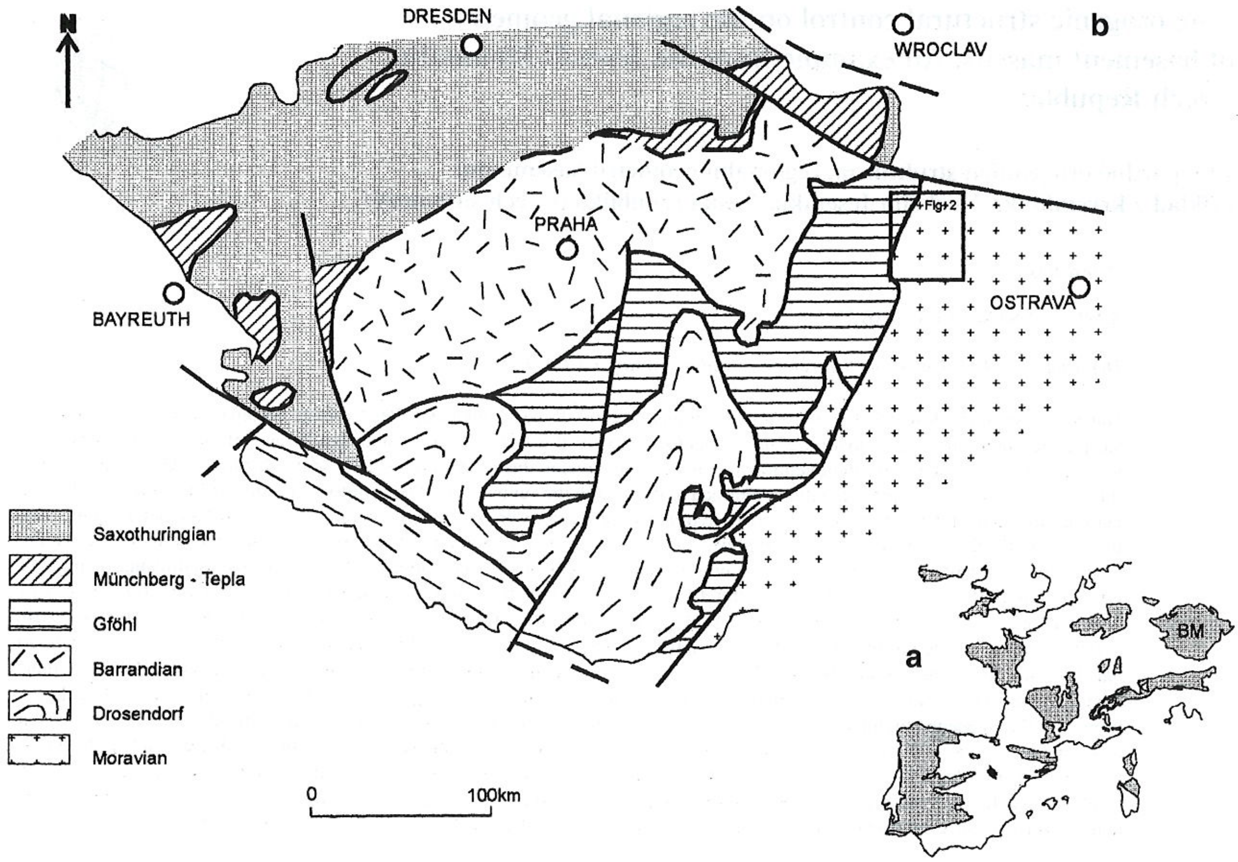


Fig. 1. (a). Massifs of the Variscan belt in Europe. BM = Bohemian Massif
(b). Displaced terranes within the Bohemian Massif (after Matte et al. 1990). Saxothuringian terrane = Late Precambrian to Late Carboniferous metamorphic complex with metapelite, arc basalt, blueschist, ophiolite and granulite. Münchberg - Teplá terrane = Palaeozoic metamorphic complex with meta-ophiolite. Barrandian terrane = Late Precambrian supracrustal and Palaeozoic marine sediments. Gföhl terrane = High grade lower crustal/upper mantle Palaeozoic basement. Drosendorf terrane = ?Late Precambrian to Late Palaeozoic mostly pelitic metasediments. Moravian terrane = Reworked Late Precambrian (Cadomian) basement and Upper Palaeozoic metamorphic cover. All terranes affected by Variscan (430-300 Ma) tectono-metamorphic events. All terrane boundaries are tectonic. Gföhl and Drosendorf terranes formerly grouped into Moldanubian zone

authors. Particularly in favour of this interpretation is the fact that the highly deformed but very low grade Branná metasediments now lie above amphibolite-grade schists and metagranitoids of the Keprník Complex, suggesting crustal thinning after nappe stacking. The dominant foliation of the entire metamorphic belt is most commonly northwest dipping and concordant with the boundaries of the main tectonometamorphic units. However, an exception to this is provided within the Desná Complex which displays a broadly antiformal geometry with the main foliation arching over a central core of reworked migmatitic and metagranitoid rocks. The Keprník Complex also appears to display a dome-like structure, although domains with southeast dipping foliations are less frequently observed. For these reasons the complexes have commonly been referred to as the Keprník and Desná domes. Such dome-like basement structures are common in orogens elsewhere around the world and are variously ascribed to antiformal stacking during compression, to the uplift of metamorphic core complexes during extensional unroofing, or to the dome-and-basin style folding of a pre-existing sheet of foliated rocks. This paper offers a description of the structures of the region and examines the origin of the antiformal geometry for the Desná region. Emphasis is placed on the eastern margin where the boundary between the metamorphic Desná rocks and the Devono-Carboniferous detached Culmian basin further east is marked by a zone where the dominant fabrics are commonly sub-vertical.

Desná Complex

The Desná Complex consists of an elongate core of reworked basement rocks. It is flanked to the northwest and southeast by a cover of metasediments of probable Devonian age and by low-grade metasediments of the Vidly Brook Group in the north (Fig. 2), with both basement and cover rocks showing the same mylonitic fabric. The basement rocks consist of mylonitised migmatites, opthalmic gneisses and metagranitoids, and grey quartzo-feldspathic mylonitic and ultra-mylonitic schists and gneisses of uncertain protolith.

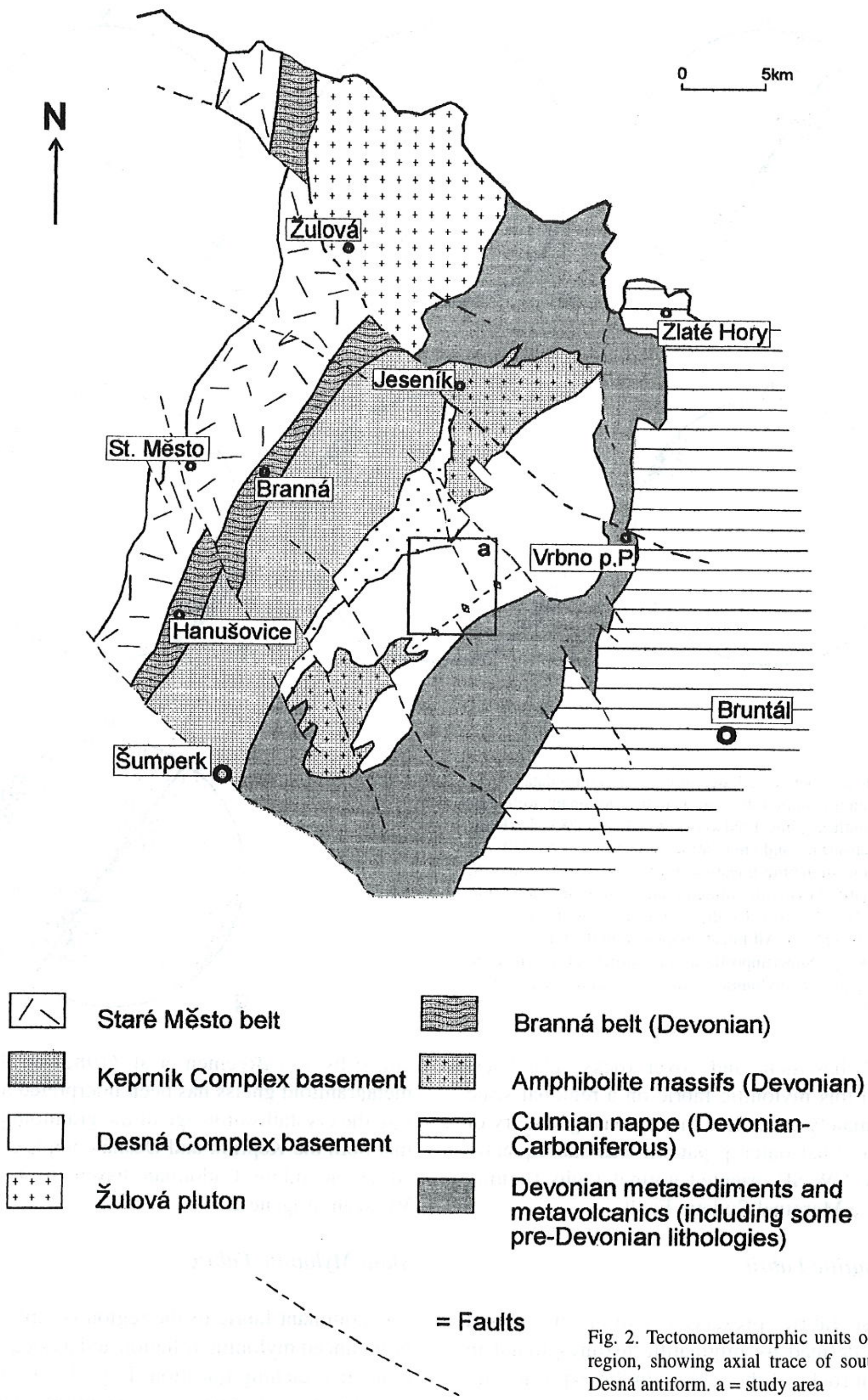
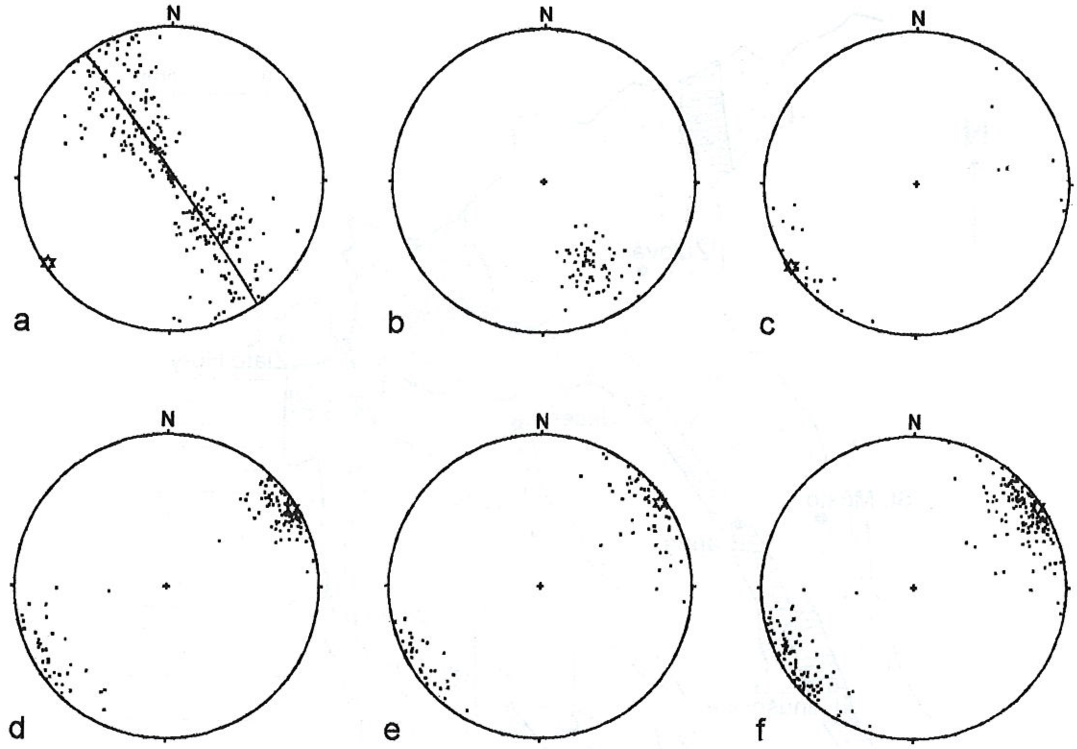


Fig. 2. Tectonometamorphic units of the Jeseníky region, showing axial trace of southeast vergent Desná antiform. a = study area

These mylonitised basement rocks also contain muscovite±tourmaline meta-pegmatite and amphibolitised meta-basic intrusions. On the northwest side of the complex these mylonitised basement lithologies are overlain by an equally deformed cover sequence of quartzites, black feldspathic schists, acid and basic volcanics, calc-schists and mica schists (the Červenohorské sedlo belt). These metasediments are similar to and correlate with some members of the Vrbno Group which have been ascribed a Devonian age by Květoň (1951) and Hladil (1987). The structure of the Desná Complex records three main ductile tectonic events. The earliest event produced a migmatitic fabric which is only observed in the basement rocks. A subsequent event produced the main fabric of the region, and is represented by a heterogeneous mylonitic foliation pre-



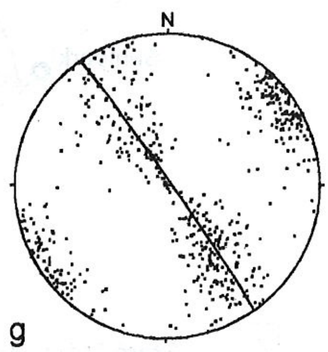


Fig. 3. Lower hemisphere equal area plots of structural data (a). Poles to main mylonitic foliation. Including dominant northwest and localized southeast dips. Fold axis = 02/235. n = 283. (b). Poles to late fold axial surface and crenulation. Orientation = 57/330. n = 72. (c). Mylonitic stretching lineation. Fold axis = 02/236. n = 25. (d). Late crenulation/mylonitic foliation intersection lineation. Fold axis = 04/058. N = 121. (e). Undifferentiated lineation data. Fold axis = 05/055. n = 82. (f). All lineation data combined. Fold axis = 04/057. n = 228. (g). Superimposition of all structural information, showing coaxiality of mylonitic and late folding deformation events. n = 583

sent in both basement and cover rocks. The latest event folded this mylonitic fabric on a regional scale and has ultimately controlled the regional geometry of the area. The final outcrop pattern was subsequently modified by NW-SE oriented normal faults running parallel to the Marginal Sudetic Fault.

Early Migmatitic Fabric

The earliest fabric preserved within the Desná Complex is defined by migmatitic textures found in the basement rocks of the region. In the exposures least overprinted by later deformational events, anatectic textures are well preserved, most commonly defined by a stromatic migmatitic foliation with leucosome and semi-pelitic mesozome banding alternating on a <1 cm scale. In some areas a sub-anatectic opthalmic gneiss texture shows Otswald-ripened augens of feldspar, whereas other exposures display an intermediate stage of migmatization where patches of granitoid melt have developed in proximity to mafic rich selvedges. A U-Pb zircon age of 546+6/-8 Ma obtained by van Breemen et al. (1982) on the Keprník metagranitoid gneiss has been interpreted as representing the crystallisation age of the granitoid protolith so that both the Keprník and Desná complexes are viewed as including Cadomian basement reworked by Variscan orogenesis.

Main Mylonitic Fabric

The dominant fabric of the region is represented by a pronounced mylonitic foliation and associated SW-NE mineral stretching lineation (Figs. 3a,c) formed under amphibolite and greenschist conditions. This fabric is discernible throughout the region within all the exposed rocks of the Desná Complex and its metasedimentary cover, and is present across an observable thickness of approximately 650 m. The whole of the Desná Complex and its cover may therefore be viewed as part of a crustal-scale shear zone. The dominant dip of this mylonitic foliation of the region is most commonly gently or moderately to the northwest. However, locally this foliation can be sub-vertical or

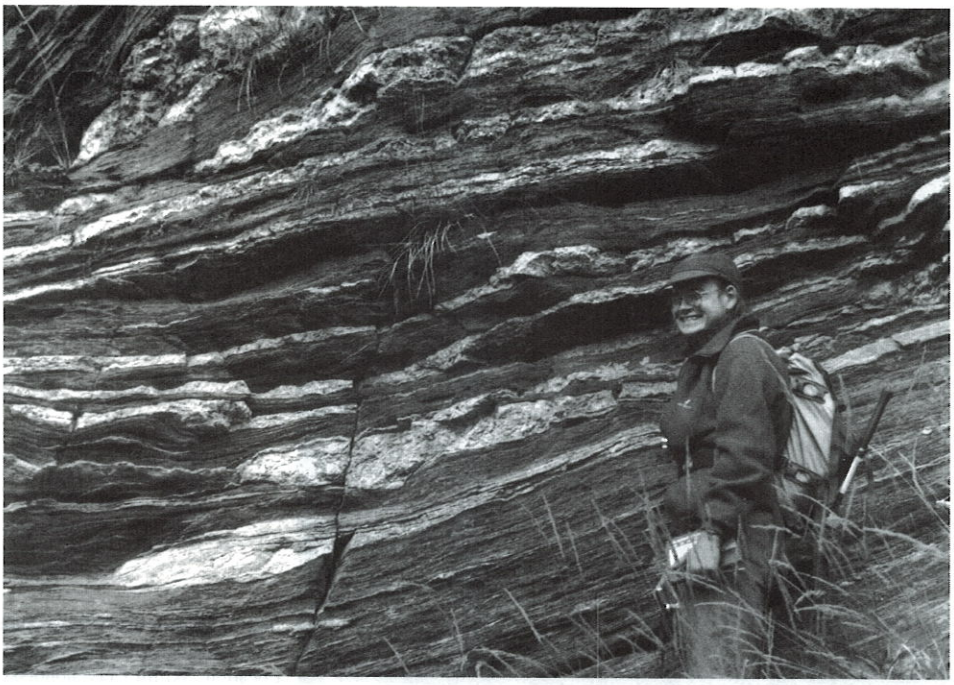


Fig. 4. Highly extended and boudinaged pegmatite intrusions parallel to main mylonitic foliation (Desná Complex basement), emphasising low dip of mylonitic fabric on NW limb of Desná antiform. Location: ridge section from Medvědí Hora parallel to Borový Potok

southeast dipping due to later folding. Strain partitioning within the region has produced localised zones of more intense shear, with an especially prominent belt of mylonitisation occurring in the structurally lowest exposed basement rocks. The mylonitic overprint varies from this intense ultra-mylonite to low strain domains in which the earlier migmatitic foliation is best preserved. The pronounced stretching lineation is defined by micas and chlorite on the mylonitic foliation surfaces. Abundant asymmetric kinematic indicators denoting non-coaxial (i.e. rotational) deformation contained within this mylonitic foliation, show top-to-southwest shear sense and include S-C fabrics, C' shear bands, mica foliation fish, and sigma-type porphyroclasts clasts. Displaced fish hook folds and extensional quartz veins also denote top-to-southwest shear sense. This mylonitic reworking has been interpreted to be of Variscan age (Sidorinová 1988, 1990).

The migmatitic banding is best preserved in low strain domains in which it is commonly tightly folded by folds associated with mylonitisation. In places, typically along the long limbs of these folds, heterogeneous strain has produced a mylonitic fabric which is oriented sub-parallel to the fold axial planes, with fold axes oriented sub-parallel to the mylonitic mineral stretching lineation. In regions of higher strain the mylonitic fabric dominates, with only sparse relics of folds occurring as rare hinges isolated within the foliation. The coaxiality of the fold axes and stretching lineation and the parallelism of the fold axial surfaces and mylonitic foliation, as well as the transposition of the folds by the foliation, all indicate progressive shear in which the folds are interpreted as a precursor to the main mylonitic foliation. Folds are also present in deformed quartz veins within the basement and cover rocks of the region. These folded quartz veins reveal progressive fold development and transposition from relatively undeformed quartz veins to transposed rootless isoclinal hinges. The development of these quartz veins is interpreted to have been associated with mylonitisation during which they may have formed orthogonally to the extension direction and then were progressively folded, rotated and transposed during the shearing. In some cases, the meta-pegmatite intrusions can be seen to have been highly extended and boudinaged (Fig. 4) and are variably overprinted by the mylonitic fabric, especially at their margins. Otherwise several exposures show these pegmatites to have remained relatively unaffected by the mylonitisation, probably due to their compositionally controlled rheological strength under the mylonitic greenschist/amphibolite facies conditions. The meta-pegmatitic bodies are thus interpreted having been intruded prior to mylonitisation, most likely being associated with the earlier migmatization event, then rotated into parallelism during shearing. The meta-basic intrusions within the basement rocks are highly friable and contain an intense fabric. It has proven difficult to assess whether this fabric is a representation of the mylonitic foliation or the cleavage associated with the subsequent cross folding deformational event. Meta-basic intrusions often appear to lie parallel to the main fabric, but are also seen to cross cut the mylonitic foliation in places. For these reasons the exact timing of the basic intrusions still remains unclear.

The same main mylonitic fabric is seen in the metasedimentary cover rocks to the Desná Complex. The strong variation in lithology, from quartzite to pelite, together with the heterogeneous nature of the mylonitic event, has produced a pronounced variation in the manifestation of this deformation. The quartzites show heterogeneous strain and typically contain a weak mylonitic fabric with localised intense shear zones, whereas calc-schists show a homogeneous intense

Fig. 5. Mica schist (Červenohorské sedlo Belt) displaying late axial planar crenulation cleavage and folding of mylonitic fabric. Location: Ski lift Červenohorské sedlo

mylonitic foliation and intra-foliation boudinage. Graphitic phyllites and micaschists also typically show an intense mylonitic foliation as a response to shearing deformation. The degree of mylonitic deformation was to become an important control on the manifestation of the later compressional structures as discussed below.

Later Folding and Crenulation

A late compressional event has folded the mylonitic foliation to produce NE-SW oriented folds with sub-horizontal axes and with axial planes and associated axial planar crenulation cleavage dipping from near vertical to moderately to the northwest (Figs. 3a,b,d). The folds range from open to near-isoclines and vary in scale from regional (km-scale), through parasitic folds (m- to cm-scale), to crenulation of the mylonitic foliation (mm-scale). The folds have axes oriented sub-parallel to the earlier mylonitic stretching lineation so that their hinges are coaxial with the extension direction of the previous mylonitisation (Fig. 3). This cross folding event has previously been recognised by Bederke (1935), Orel (1973, 1975) and Rajlich (1974). This late folding event commonly causes a departure from the dominant regional northwest dip of the earlier mylonitic foliation, with the steep limbs of the southeasterly verging folds typically dipping steeply southeast.

The expression and intensity of the late compressional deformation varies across the region. This variation is most marked in the Devonian metasedimentary cover rocks of the Červenohorské sedlo belt where some quartzites are virtually unaffected but mica schists commonly display a strong crenulation cleavage (Fig. 5). A variation in late fold type can be observed between metasedimentary lithologies to the southeast of the Desná Complex basement where basic meta-volcanics in proximity to graphitic phyllites show rounded decimetre-scale open folds, whereas phyllites show tight centimetre-scale chevron folding and in places transposition by the crenulation cleavage.

The mylonitised basement rocks only rarely show the late crenulation cleavage but the main mylonitic fabric is commonly folded by southeasterly verging folds with steep to moderate northwest dipping axial surfaces. An expression of the late crenulation cleavage can sometimes be seen as a spaced cleavage in the pegmatite intrusions. Quartz veins present in both basement and cover metasediments folded during the prior deformation are often refolded by the late compressional event. It is clear that there was a drop in temperature and confining pressure between the main mylonitic event and the later cross folding event (Cháb et al. 1984, 1992, Fediuková et al. 1988).

The coaxiality of the axes of the late folding with the earlier stretching lineation (and therefore extensional direction) is interpreted as being a result of either:

(1) inherited rheological anisotropy produced by the strong planar fabric and pervasive stretching lineation formed during the main mylonitic event controlling the fold axial direction of the later folding event. In such a case the principal compressive stress direction of the later event need not be oriented perpendicular to axes of the produced folds (Watkinson - Cobbold 1981).

(2) the principal axes of stress and strain during the deformation history remain constant in direction but change in relative magnitude. In this model a switch from SW-NE extension during the main mylonitic event to later SE-NW compression may have been produced during either progressive deformation or two quite separate events.

Desná Antiform and the Structure of the Eastern Steep Belt

Both the sheet dip of the main mylonitic fabric and the intensity of late folding vary across the Desná antiform. The northwest limb of the antiform is characterised by a dominant northwest dip of the mylonitic foliation. Here mylonitic Devonian metasediments consisting of quartzites and black feldspathic schists outcrop above equally mylonitised basement rocks. The mylonitic foliation is virtually unaffected by late folding, with the exception of the black feldspathic schist in which minor upright folds are common. The moderate northwesterly sheet dip that is displayed by this limb of the Desná antiform conforms to the regional dip that characterises much of the Jeseníky area. In marked contrast to this is the sheet dip of both the hinge region and southeast limb of the Desná antiform which commonly shows an anomalous steep dip and localised steep dips of the main mylonitic fabric respectively. These anomalous steep dips are directed to the southeast as well as to the northwest. It is the existence of these steep dips within a region supposed dominated by relatively flat-lying structures that first stimulated interest in this area.

The lithologies and structures of the hinge and southeast limb of the Desná antiform are best exposed along a NW-SE traverse starting from the high ground immediately east of the hydro-electric power station reservoir southeastwards to the prominent source confluence of Divoká Desná. At the northwestern end of this traverse, typical mylonitic basement rocks lie within the Desná antiformal hinge and contain numerous late parasitic tight folds of decametre-scale (Fig. 6a). In this region the previous mylonitic foliation locally dips both steeply to the northwest and southeast on the opposing limbs of these tight folds. Locally the folding is intense enough to rotate the steep southeast-dipping limbs through the vertical and into a northwest dip. This overturning of the steepened mylonitic fabric induces an apparent reversal of the shear sense from sinistral (top-to-southwest) to dextral (top to northeast) (Fig. 6b).

The southeast limb of the Desná antiform is best exposed along and between the streams of Divoká Desná, Sviní Potok, and Velký Dědův Potok to the east of Zámčisko Quarry, and is characterised by a dominant southeast dipping mylonitic fabric, often folded by open folds so that both limbs still dip to the southeast. Grey quartzo-feldspathic mylonitic and ultramylonitic schists and gneisses of uncertain protolith make up most of the area between the reservoir and high ground between Velký Dědův Potok and Sviní Potok. These basement lithologies exhibit the typical southeastward dip of the mylonitic foliation folded by late open folds, and also locally show a steep to moderate northwestward dipping axial planar late crenulation cleavage. The north facing slope of the Sviní Potok valley exposes sheared metagranitoid basement with a southeasterly dipping strong mylonitic fabric showing top-to-southwest shear sense. Zones of weakly developed late folds with an open style are separated by regions of intense heterogeneous deformation in which cascades of folds producing steep zones locally dipping to the northwest. It is the abundance of these fold cascades that produce localised steep dips on the southeastern fold limb. The strong development

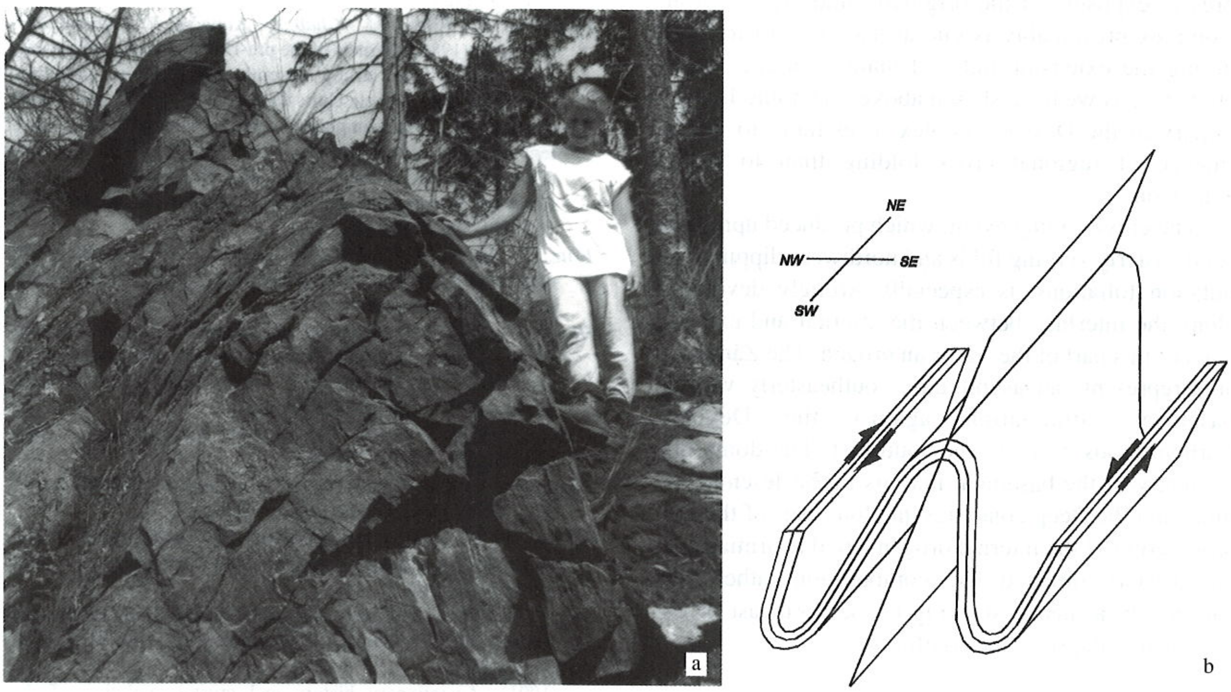


Fig. 6. (a). Typical late fold geometry in hinge region of Desná antiform emphasising the steep dip of the mylonitic fabric. Location: high ground immediately east of the hydro-electric power station reservoir (Desná Complex basement)
(b). Schematic diagram of typical late foldb in the hinge region of the Desná antiform, showing apparent reversal of mylonitic shear sense from sinistral (top-to-southwest) to dextral (top-to-northeast) on overturned fold limb

of the late upright fold-generating deformation may be traced southeast from the Sviní Potok valley where steeply dipping quartzite and intensely crenulated graphitic phyllite are exposed. Thus in this region it is the late overprint of upright to southeasterly verging folds that now dominates the orientation of an earlier flat-lying mylonitic regional fabric. The dome-like geometry of the Desná Complex is a response to NW-SE compression of previously mylonitised rocks.

Conclusions

Both the Desná and Keprník complexes represent antiformal regions separated by a steep synformal region of the Červenohorské sedlo belt metasediments. Kölbl (1930) and Pouba in Svoboda et al. (1966) have similarly interpreted the Červenohorské sedlo belt as a synformal region (Cháb et al. 1994b). Such basement dome-like structures elsewhere in the eastern Bohemian Massif have been interpreted as resulting from antiformal nappe-stacking during early east or northeast directed displacements (Schulmann et al. 1991, Fritz - Neubauer 1993). The dominantly southwestward-directed kinematics of the Desná Complex is hard to reconcile with northeasterly nappe stacking (suggested as possibly related to back-thrusting by Cháb et al. (1992). An alternative explanation is that the dome-like antiforms are core complexes produced in response to extensional uplift during the main mylonitic event. Certainly the influence of large-scale crustal extension on Variscan orogenic geometry was very great, as is being recognised in many parts of the orogen (e.g. Cháb et al. 1994a, Pitra et al. 1994). The present exposure of the originally mid-crustal Desná Complex presumably is due at least in part to uplift during the extension-induced main mylonitic event. However, as we have shown above, the dome-like geometry of the Desná Complex owes more to the influence of regional cross folding than to earlier extension.

The cross folding event, which produced upright to southeasterly verging folds and northwest-dipping crenulation foliations, is especially strongly developed along the interface between the internal and external parts of this part of the Variscan orogen. The Zámčisko area represents an asymmetric southeasterly verging basement culmination against the Devono-Carboniferous rocks to the southeast. The dome-like geometry of the basement massifs in the Jeseníky region, and the steep zone present along part of the eastern margin of the internal orogen, are due primarily to southeasterly-directed late compression rather than earlier crustal nappe stacking to the northeast or extensional collapse to the southwest.

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Vliv pozdně orogenních struktur na regionální geometrii basementu: příklad z krystalinika Hrubého Jeseníku, Česká republika

Krystalinikum Hrubého Jeseníku zahrnuje významnou asymetrickou dómovitou strukturu známou jako desenská klenba. Tato regionální vrása je tvořena předdevonskými basementovými horninami v jádře a devonskými metasedimenty ve vrásových křídlech. Jak basement, tak i horniny pokryvu jsou v této oblasti postiženy jz.-vergentní hlavní mylonitovou stavbou pravděpodobně variského stáří, vedoucí k transpozici starších migmatitických foliací kadomského stáří. Hlavní mylonitická stavba na sz. okraji antiformy zapadá mírně k SZ a je rovnoběžná s regionálním zapadáním příkrovových desek. Naproti tomu, v zámkové oblasti a jz. křídle antiformy je mylonitová foliace vrásněna jv.-vergentními vrásami, doprovázenými na SZ zapadající osně-plošnou foliací krenulační. Lokální přetočení zestrměných mylonitových staveb okolo těchto pozdních vrás způsobuje otočení zdánlivého smyslu tektonického pohybu ze sinistrálního na dextrální. Přítomnost téměř vertikálních vrásových ramen podél jz. okraje desenského komplexu se projevuje jako lokální strmé zóny, které jsou, podobně jako geometrie celého desenského komplexu, produktem jv. orientované komprese. Současná stavba desenského komplexu a jeho metasedimentárního pokryvu není tudíž přisuzována ani antiformálnímu příkrovovému naskládání, ani kolapsu jaderného komplexu, nýbrž pozdně orogennímu příčnému vrásnění.