Evolution of Lugosilesian Orocline (North-eastern periphery of the Bohemian Massif): Kinematics of Variscan deformation

Vývoj lužicko-slezské oroklíny (severovýchodní okraj Českého masívu): Kinematika variské deformace (Czech summary)

(11 text-figs. 2 plates)

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The north-eastern periphery of the Bohemian Massif was consolidated during long-lasting Variscan s.l. (Caledonian-Variscan) orogeny, in the conditions of the subequatorial oblique collision of more inner zones of the Variscan accretion wedge with the Brunovistulian terrane. This foreland corresponds to a mosaic of units most probably sutured, and jointly accreted, to the Baltica during the Caledonian orogeny.
Regional kinematic analysis of the more internal domains (the Orlice-Sněžník Unit and its footwall envelope) proved the early-Variscan top-to-N lower crust synmetamorphic (higher rank of amphibolite to granulite-eclogite facies) nappe shearing. The Lower Devonian collision caused ENE-WSW transtensional stretching – oblique rifting of the Brunovistulian foreland brittle crust. The top-to-N thrusting of the Variscan orogenic front is recorded by an a-type of stretching lineations in the gneiss of the Orlice-Sněžník Unit. Due to the NW-SE trend of the western indented edge of the Brunovistulian foreland, an oblique dextral wrench collision in the Moravosilesian Zone occurred. The mentioned NNW-SSE transpressional shortening resulted in crustal overthickening and the top-to-SE back thrusting, especially in the Zábřeh Unit and Silesicum. The late-Variscan transtension, with an ENE trend of stretching lineations, followed above mentioned crust overthickening. The gravitational collapse and out-ward lateral escape in the inner and deeper domains was contemporaneous with wide-spread intrusions of S-type granites and the growing of subperpendicular half-grabens, e.g. Boskovice and Orlice furrows.
The dextral late-Variscan, and post-Variscan strike-slip kinematics along the Sudetic WNW trending transcurent faults resulted in a typical bend of orogen – the Lugosilesian orocline.

Key words: Bohemian Massif, Moravosilesian Zone, oblique collision, transpression, transtension, crustal overthickening, crustal extension

Introduction

The continental crust of the NE periphery of the Bohemian Massif was consolidated during the long-lived polyphase Variscan s.l. (Caledonian-Variscan) orogeny. In this area the Variscan orogenic belt seems to have a form of an orocline (orogenic bend – Figs. 1 and 2) as a consequence of a complex dextral oblique collision between the early consolidated cratonic foreland of the Baltica and accretion wedge of the Variscan front.

In spite of the recent NNE trend of the Moravosilesian branch of above mentioned orocline, which by most authors is interpreted to be the result of a simple W-E acting late-Variscan compression, we present the idea of a subequatorial long-termed oblique collision regime (Grygar 1988, 1992) in which the orocline was formed. From a dynamic viewpoint (the Variscan NW-SE to NNW-SSE maximal compression), the findings of our regional structural studies are consistent with the results published by e.g. Le Gall and Darboux (1986), Eisbacher et al. (1989) etc. from the west European part of the Variscan orogenic belt. The complicated structural framework (bending) of the studied eastern domain of the Variscan collision belt – Lugosilesian orocline – resulted, amongst other things, from the complex structural role of the subducted Brunovistulian (Havlena 1976, Dudek 1980) foreland terrane. During the late Variscan tectogenic stages it was gradually detached and wrenched from a position adjacent to Baltica (Grygar 1991, 1992), especially from its elevated and towards south projected edge – the Ukrainian shield. Here we discuss the kinematics of the whole group of Lugosilesian orocline allochtoneous units in relation to its Brunovistulian foreland terrane.

Field studies were conducted in the area of Orlice-Sněžník Unit and its peripheral units: the Silesicum and the Zábřeh Unit, the Moravosilesian flysch foredeep, and the Upper Carboniferous coal-bearing molasse (all on the Czech territory only).

Geological setting

The area of Lugosilesian orocline exhibits the juxtaposition of some regional units separated by systems of faults of a different type, magnitude and polyphase activity. First, all NW-SE striking faults, mostly of Variscan origin, with post-Variscan rejuvenation, create the recent „block-like" framework of the orogen. These faults interferred with the NNE-SSW trending thrust-fold system

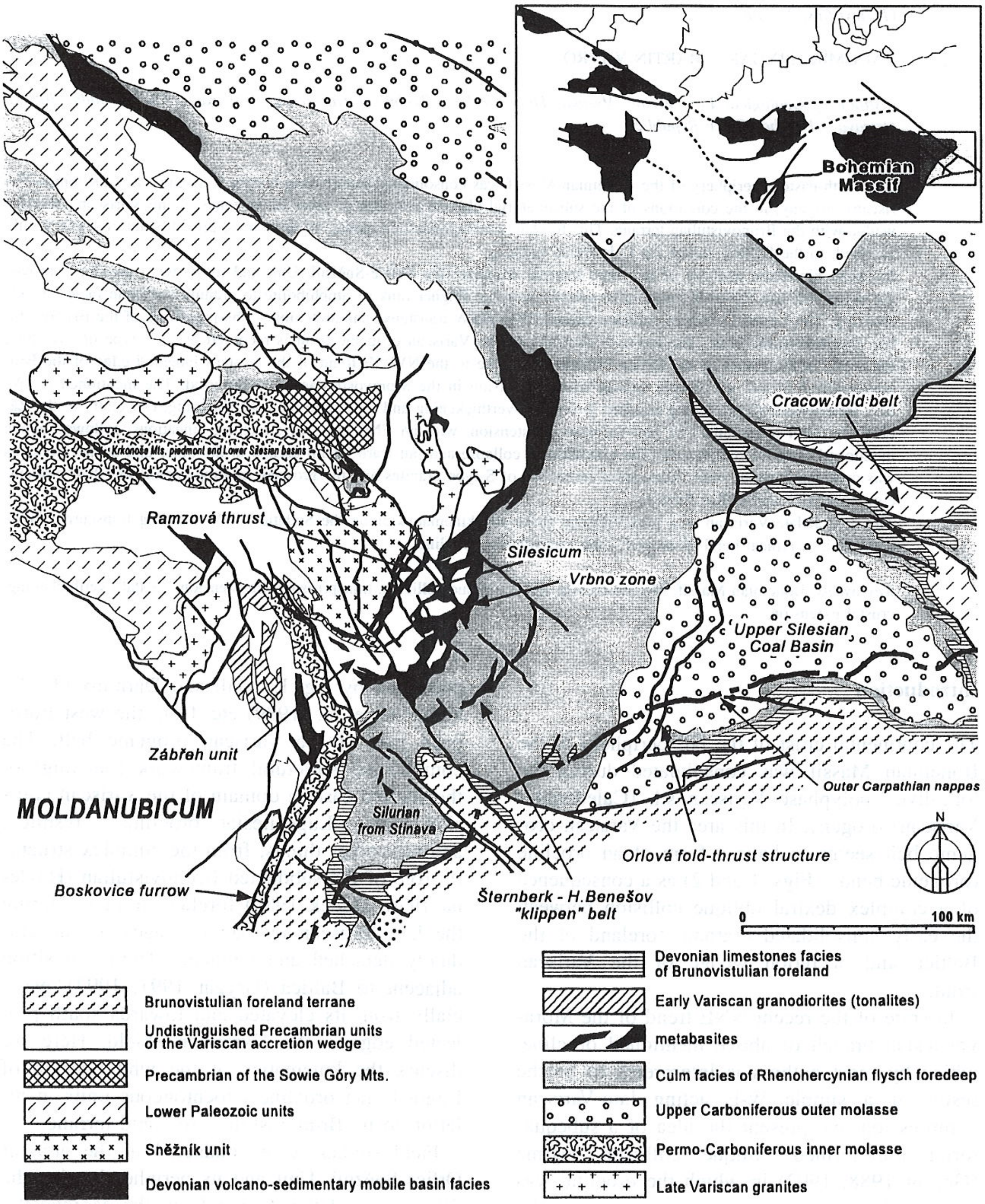

Fig. 1. Uncovered geological sketch map of the Lugosilesian orocline (pre-Mesozoic units – Epivariscan platform)

(so-called Moravosilesian trend), which is the most significant feature of the eastern flank of the above mentioned orocline. The Ramzová thrust, or according to Skácel (1979) the Nýznerov dislocation zone, separates two main regional units: Lugicum (West and Middle Sudetes) on the west, represented in the studied area by the Orlice-Sněžník Unit, and the Silesicum, as a part of the Moravosilesian Zone (East Sudetes) further east. Both mentioned main regional units are sutured by an HT-HP ophiolite-like assemblage, preserved in the Staré Město belt (e.g. Mísař et al. 1983), whose equivalent rocks crop out also in the northern-most zone of the Zábřeh Unit along the southern boundary of the Orlice-Sněžník Unit.

The oldest unit at the NE border of the Bohemian Massif corresponds to the Góry Sowie crystalline (e.g. Żelaźniewicz 1990). It is situated in the inner zone of the Lugosilesian orocline. The late Riphean – early Cambrian (Gunia 1981) succession of pelitic to psammitic sediments (also U-Pb 1750±270 Ma for paragneiss – van Breemen et al. 1988 – interpreted by authors as sedimentary provenance age) was consolidated by a complex polydeformation and polymetamorphic development during long-persisting Caledonian-Variscan (Variscan s.l.) orogeny. The deformation D_3 and the retrograde metamorphism M_{2-3} in low-amphibolite facies conditions (Żelaźniewicz 1990) is dated at ~ 380-360 Ma (van Breemen et al. 1988). Other evidence for the Caledonian (Early Variscan) tectonothermal activities from the neighbouring Kłodzko Unit and the Orlice-Sněžník Unit were presented by Borkowska et al. (1990). However, data of Oliver et al. (1993) indicate a pre-Caradoc Ordovician age for the synmetamorphic granite of the Góry Sowie crystalline (it corresponds also to the data of Kröner et al. 1994a). The same authors considered as very likely two tectonothermal events (Ordovician and Devonian).

The presence of pre-Devonian (early-Paleozoic) strata in the Lugicum with affinity to the Saxothuringian zone of the Variscan orogen is well documented (e.g. Grocholski 1986, Chaloupský et al. 1989, Haydukiewicz 1990, Don and Żelaźniewicz 1990, Franke et al. 1993, Chlupáč 1993 etc.). But east of the Ramzová and Nýznerov thrust zones, in the Moravosilesian area, the situation is more complicated because such members are metamorphosed and strongly tectonized. Therefore, stratigraphic and also tectonic position of pre-Devonian metamorphosed sequences has not been clearly established. Only in the southern axial zone of the Moravosilesian flysch foredeep in the Drahany Upland, near the

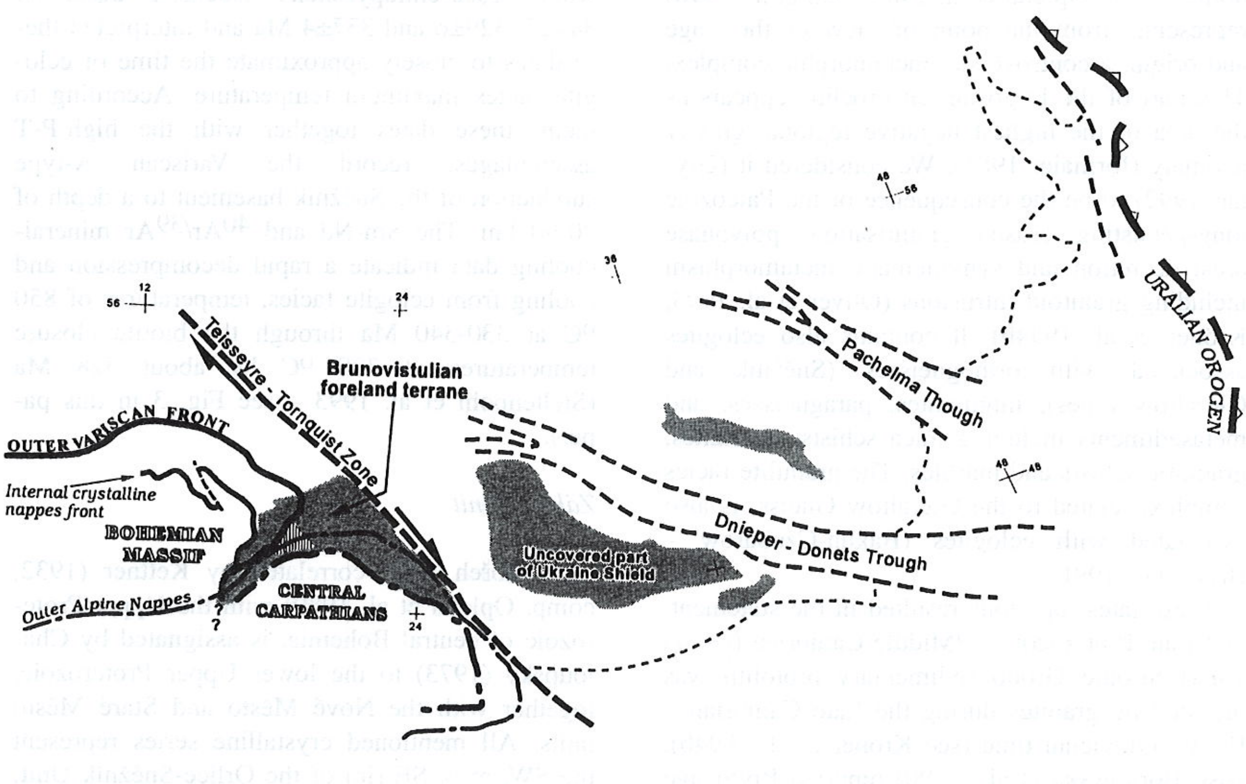

Fig. 2. Sketch map of the mutual relations between the Variscan orogenic belt, the Brunovistulian foreland terrane and the Baltica

Stínava village, the Silurian sequence is well documented paleontologically (Kettner – Remeš 1935, Bouček 1935). The occurrence of the allochthoneous tectonic slice (Llandowery to Wenlock black graptolithic shales passing into Ludlow – Přídolí limestone facies) is compared by Chlupáč et al. (1992) with Silurian of the Barrandian area.

The characteristic bend of the Lugosilesian orocline is pronounced likewise by a range of late Variscan granitoid intrusions and corresponding negative gravimetric anomalies. Granitoids represent the final products of polyphase Caledonian-Variscan migmatization and granitization of inner, more deeper levels of accretion wedge.

Two connected intramountain basins, the Krkonoše-piedmont and Intra Sudetic basins (uppermost Carboniferous up to Permian intracontinental molasse) of the latest stage of Variscan orogeny are located in the inner core zone of the orocline.

In the next part we briefly describe the units studied especially from the viewpoint of their age and lithostratigraphic mutual relations.

Orlice-Sněžník Unit

The Orlice-Sněžník Unit (distinguished also as the „Orlické Hory-Kłodzko or Orlica-Śnieznik dome“ – e.g. Opletal et al. 1980, Don et al. 1990) represents, from the point of view of their age and origin, a controversial metamorphic complex. This part of the Lugosilesian orocline appears as the area of the highest negative regional gravity anomaly (Ibrmajer 1981). We considered it (Grygar 1992) to be the consequence of the Paleozoic long-persisting crustal granitisation, polyphase crust accretion and synkinematic metamorphism including granitoid intrusions (Oliver et al. 1993, Kröner et al. 1994b). It contains also eclogites associated with orthogneisses (Sněžník and Gieraltow types), migmatites, paragneisses, and metasediments including mica schists, quartzites, graphitic schists and marbles. The granulite-facies complex, related to the Gieraltow Gneiss, is also associated with eclogites (Bakun-Czubarow – Brueckner 1991).

These latest opinions resulted in the statement, that Late Proterozoic – ?Middle Cambrian (Gunia 1984) Stronie Group sedimentary protolith was intruded by granites during the Late Cambrian – Early Ordovician time (see Kröner et al. 1994b). Also Borkowska et al. (1990) reported Rb/Sr age of 464±18 Ma interpreted by them as an emplacement of Gieraltow „granite“. According to Borkowska et al. (1990), the early retrograde tectonometamorphism, synchronous with the emplacement of the younger Sněžník Granite (Rb/Sr 395±35 Ma), started during the Early Devonian.

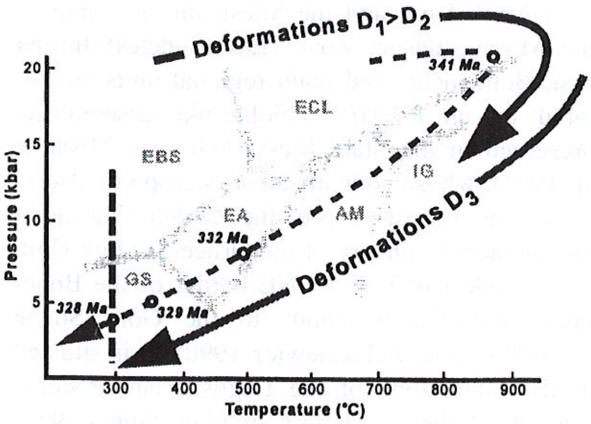

Fig. 3. Diagram showing mutual relations between the deformation stages $D_1 > D_3$ and the p-T-t path of the Sněžník Unit (p-T-t path according to data of Steltenpohl et al. 1993)

The subsequent Variscan (sensu stricto) synkinematic metamorphism is more precisely determined, between 341 and 329 Ma (Brueckner et al. 1991, Cymerman 1992, Steltenpohl et al. 1993). Brueckner et al. (1991) reported Sm-Nd garnet-whole rock-clinopyroxene isochron dates of 341±7, 329±6 and 337±4 Ma and interpreted these dates to closely approximate the time of eclogite facies maximum temperature. According to them, these dates together with the high-P-T assemblages, record the Variscan A-type subduction of the Sněžník basement to a depth of 70-90 km. The Sm-Nd and $^{40}Ar/^{39}Ar$ mineral-cooling data indicate a rapid decompression and cooling from eclogite facies, temperatures of 850 °C at 330-340 Ma through the biotite closure temperatures of 300 °C by about 328 Ma (Steltenpohl et al. 1993 – see Fig. 3 in this paper).

Zábřeh Unit

The Zábřeh Unit, correlated by Kettner (1932, comp. Opletal et al. 1980) with the Upper Proterozoic of central Bohemia, is assignated by Chaloupský (1973) to the lower Upper Proterozoic, together with the Nové Město and Staré Město units. All mentioned crystalline series represent the SW, resp. SE rim of the Orlice-Sněžník Unit. The characteristic feature of the Upper Proterozoic complex of Zábřeh, as the Nové Město and Staré Město units, is a relatively uniform development of the pelite-psammitic and psammitic protolith accompanied by the intense, predominantly basic volcanism. On the basis of lithological similarity, the Zábřeh Unit was also correlated with the Polička and Letovice crystalline units cropping out on the opposite flank of the post-Variscan Bohemian Cretaceous Basin in the northern periphery of the Moldanubian (e.g. Chaloupský 1973). New geological mapping of the Zábřeh Unit done by B. Koverdynský, simultaneously with the paleontological investigation (Koverdynský – Konzalová 1986), documented that metasediments of the central and SE parts of the Zábřeh Unit belong to the Paleozoic, most probably to the Devonian. They are lithostratigraphically correlated (Koverdynský 1993) with the Devonian metasedimentary suite of the Branná Group (see later) in the footwall of the Ramzová overthrust, as well as partly with other Devonian localities – outcrops in the vicinity of Městečko Trnávka (Chlupáč 1961) and boreholes in vicinity of Hradec Králové (Chlupáč – Zikmundová 1976, Čech et al. 1989) to the W from the S-ward prolongation of the Ramzová thrust.

The contact relations with the Stronie Group of the Orlice-Sněžník Unit is obscured by the younger Sněžník type orthogneiss, and additionally tectonized. The Zábřeh Unit s.s. (i.e. the part of the Zábřeh Unit without the incorporated formations of proposed Paleozoic age according to Koverdynský – Konzalová 1986) is distinguished by the paragneiss, or migmatite-gneiss especially in the neighbourhood of syntectonic „tonalite" bodies, which are most frequent in the northern domain, along the contact with the Orlice-Sněžník Unit. „Tonalites" comprise mainly granodiorites predominating over quartz diorites. The age of „tonalites", sampled from equivalent bodies of the Nové Město and Staré Město Units determined by K/Ar method, displays a wide range of values, from 360 to 295 Ma (Opletal et al. 1980). But the age of about 360 Ma (early Variscan) prevails.

The Zábřeh Unit shows the metamorphic grade of the lower part of the garnet zone and an increase of metamorphism in the proximity of „tonalite" bodies; sillimanite and cordierite have been identified sporadically. Zones of mica schists with staurolite are most probably linked to the pelitic protolith.

Staré Město Unit

The Staré Město Unit (also distinguished as the Staré Město belt or metaophiolite zone – Mísař et al. 1983, Skácel 1989 etc.) represents a complex, metamorphic, deep crustal zone with polyphase evolution ranging from a HP event recorded by tectonic pod-like bodies of eclogites and pyroxene-bearing granulites, and of a LP/HT stage (production of K-feldspar and sillimanite in metapelites). The Staré Město belt corresponds to tectonically positioned melange – suture zone, located on the boundary between the Lugicum (the Orlice-Sněžník Unit) and the Moravosilesian area, i.e. its crystalline subarea – Silesicum. It was thrusted along the Nýznerov shear zone over the Velké Vrbno Group (Květoň 1951, Skácel 1989) and the Devonian Branná Group – the part of Silesicum. Skácel (1989) considered the Staré Město belt to represent, together with the Zábřeh Group, an envelope of the Orlice-Sněžník Unit.

The association of paragneiss, retrograde two-mica schists with frequent metabasites (less acid metavolcanites), was intruded in Variscan time by frequent granodiorite – „tonalite" bodies (compare with the Zábřeh Unit). The older K/Ar data displayed a wide range of ages between 289 and 255 Ma (Borucki 1966, Šponglová et al. 1975 – all in Mísař et al. 1983). The Hraničná Group comprising marbles, calc-silicate gneisses, graphitic schists and quartzites represents a variegated sequence in the north-western part of the Staré Město Unit (Skácel 1989).

Silesicum

The Silesicum was distinguished as the northern metamorphosed crystalline part of the Moravosilesian Zone of the Bohemian Massif cropping out east (in the footwall) of Ramzová thrust (Suess 1912). The Silesicum is traditionally subdivided (see e.g. Suk et al. 1984) into both Keprník and Desná dome-like structures (pre-Devonian), and their Devonian (upper part of the Branná and Vrbno Groups) and/or ?Early-Paleozoic – Silurian (part of the Velké Vrbno Group and lower part of Branná Group) envelope (e.g. Květoň 1951, Skácel 1984, Koverdynský 1993).

Desná Group

The paraautochthoneous Desná Group consists of a medium-grade to migmatitic, biotite-rich, mostly banded gneiss, containing numerous amphibolite bodies. The Sobotín amphibolite massif represents their main concentration. The Desná Gneiss corresponds to the Proterozoic greywacke-pelitic protolith, usually compared with the gneiss of the Zábřeh Unit (Mísař 1963). The weakly metamorphosed Vidly brook Group (metaarkoses and metasiltstones) was interpreted by Cháb et al. (1984) as a relic of a pre-Variscan synorogenic basin. Both mentioned groups crop out in the core of the Desná dome-like structure and are rimmed by Devonian (paleontologically indicated Pragian, Givetian, Famenian – e.g. Chlupáč 1989) sedimentary cover of the Vrbno Group.

The allochthoneous lower crystalline thrust sheet of the Silesian crystalline and the Desná „Dome", as its sub-structure, corresponds to the Vysoká Hole nappe (Cháb et al. 1984). It is formed by quartzo-feldspathic mylonites derived from granodioritic intrusions and migmatites. The protolith ages, both of paraautochthoneous and allochthoneous pre-Devonian crystalline units, are most probably Precambrian. By a majority of authors, they are compared with the Brunovistulian foreland basement of the Moravosilesian branch of the Variscan orogen. A new estimation of absolute age was done by Kröner et al. (1994b). Zircon from orthogneiss from the Desná Group yielded an array of $^{207}Pb/^{206}Pb$ ages between 507±11 and 1019±16 Ma, the youngest of which was interpreted to reflect the time of granitoid emplacement.

Keprník Group

The Keprník Group represents a more western Silesicum unit. It corresponds to the Keprník nappe (Kölbl 1929) in the hangingwall of the Vysoká Hole nappe. The large body of the Keprník Orthogneiss in the core of the Keprník dome-like structure is enveloped by staurolite-bearing metapelites, biotite- and calc-silicate gneisses at the top. The last mentioned lithotypes represent a variegated sequence (Variegated Group according to Mísař 1963), which is at least partly substituting, especially in the southern part of the Keprník „Dome", the lower part of the Branná Group, which is the uppermost unit of the Silesicum.

The age of the main metamorphic crystallisation of the Keprník Group is estimated by van Breemen et al. (1982) to be between 480-570 Ma (Rb/Sr whole rock), with relics of zircon, dated at 1400 Ma. The synmetamorphic structures of the Keprník Gneiss are characterised by a medium- to high-grade mylonitic fabric. The orthogneiss bodies were together with the upper mica-schists and the variegated group affected by extensional deformation with a very uniform ENE-WSW distribution of stretching lineations (Fig. 4) contemporaneous with perpendicular quartz-andalusite filled tension gashes.

Branná Group

The low-grade metamorphosed rocks of the Branná Group occur in the footwall of the Ramzová thrust, and its lower part (Upper Proterozoic up to ?Lower Paleozoic – Silurian according to e.g. Koverdynský 1993) most probably links eastward to a variegated sequence of the Keprník Unit. The upper part (Devonian age – e.g. Hladil 1988) of the Branná Group is represented by quartzites (also quartz conglomerates), graphitic phyllites, marbles etc. Its lithological development is partially similar to the Devonian Vrbno Group, cropping out along the eastern limit of the Silesian crystalline. Metavolcanic rocks, that are typical for the Vrbno Group, are absent in the Branná Group, and the limestone facies of the Branná Group are different in relation to the limestones of the Vrbno Group (Hladil 1988). Also the stratigraphic position of the Branná Group limestones is lower (Givetian – Koverdynský and Hladil 1985, Koverdynský 1993) in relation to limestones of the Vrbno Group (Famennian – Hladil 1988). Facies of the Branná Group, together with its equivalent along the southern boundary of the Silesian crystalline, belong (according to Koverdynský – Hladil 1985, Hladil 1988 etc.) to the Tišnov Development defined in the Moravicum. This carbonates are different from both the Basinal Development, and also Broad Platform Development. The Broad Platform carbonates, including the Moravian Karst Development of the Moravosilesian Zone (Hladil 1988), are resting predominantly on the crystalline complex of the Brunovistulicum.

Vrbno Group

The Pragian age of basal quartzites of the Vrbno Group, cropping out on the eastern limit of the Silesicum, is paleontologically well documented (e.g. Chlupáč 1982, 1989). Scattered finds of microfossils indicate a Pragian, Givetian to Famennian ages for the group (also Hladil 1987).

The basal quartzites and quartz-metaconglomerates interfinger with various peraluminious rocks (mostly chloritic- and dark graphitic schists). The

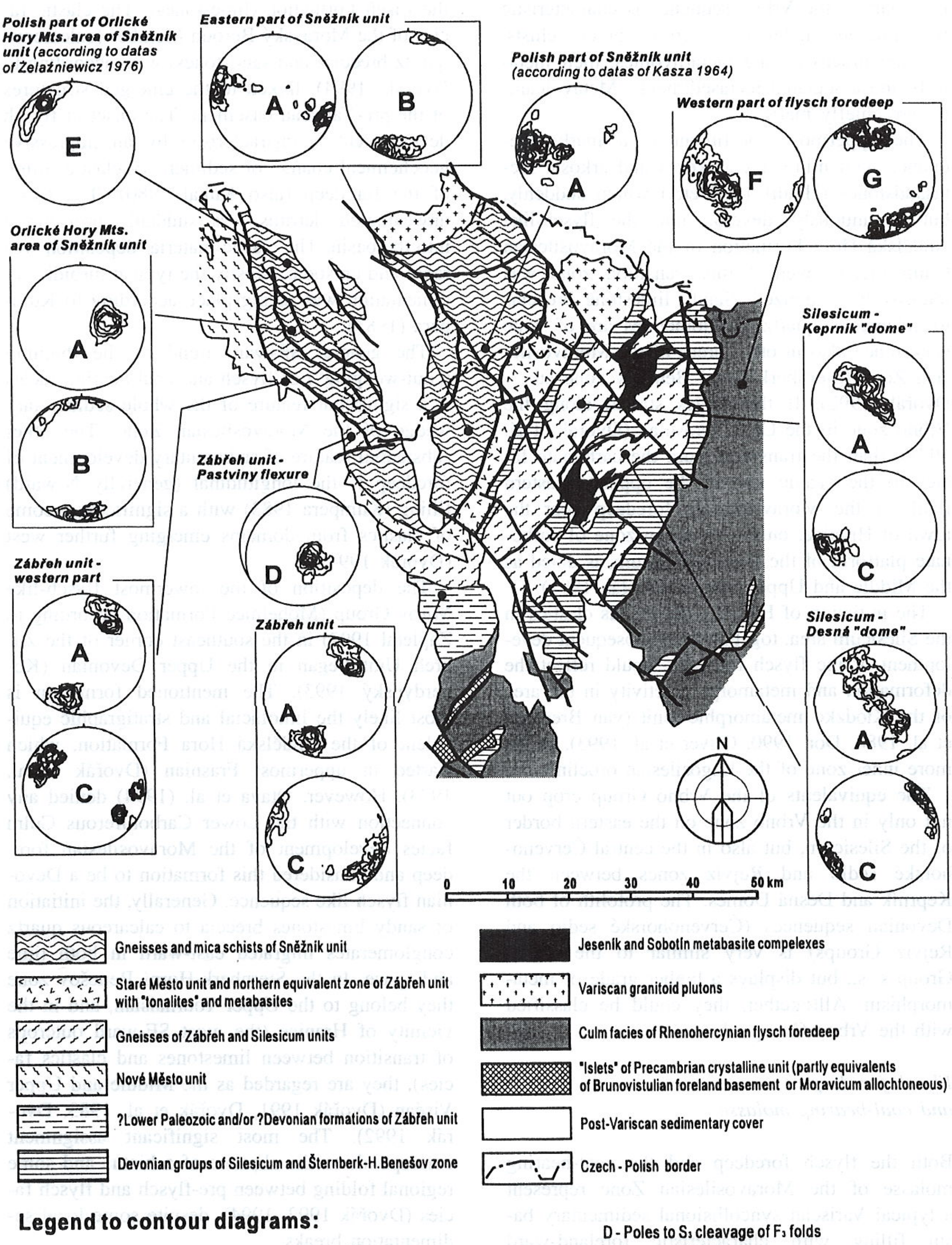

Fig. 4. Schematic map of representative contour diagrams (lower hemisphere projection) of main lineation and poles of foliation systems from studied area (geological sketch map represents pre-Mesozoic units)

next part of the Vrbno sequence is characteristic by numerous metavolcanic rocks, green schists, less metatrachytes and metarhyolites, their metatuffs and associated metasediments. Metavolcanites are chiefly mafic.

The uppermost constituent is a marble sequence with minor metaarkoses and arkosic metasandstones (Hladil 1988 etc.) which suddenly, but continuously, develop into the flysch-like Andělská Hora Formation of the Moravosilesian Culm facies, even if this transition zone was intensively tectonized. Sandy limestone breccias to calcareous quartz conglomerates are of wide occurrence also in other areas of the Moravosilesian Zone (Šternberk-Horní Benešov zone etc. – Dvořák 1992). If this facies started along the Vrbno zone in the Upper Frasnian (Dvořák et al. 1973), than the transition from the carbonate facies to the clastic one in the opposite eastern flank of the Moravosilesian foredeep near the town of Hranice, on the elevation zone of carbonate platform of the Brunovistulicum, is dated as the Middle and Upper Viséan (Dvořák 1991).

The initiation of Frasnian calcareous clastics in the Silesicum area, together with subsequent development of the flysch foredeep, could reflect the deformation and metamorphic activity in the area of the Kłodzko metamorphic Unit (van Breemen et al. 1988, Don 1990, Oliver et al. 1993), in the more inner zone of the Lugosilesian orocline.

The equivalents of the Vrbno Group crop out not only in the Vrbno zone on the eastern border of the Silesicum, but also in the central Červenohorské sedlo and Rejvíz zones between the Keprník and Desná Domes. The protolith of both Devonian sequences (Červenohorské sedlo and Rejvíz Groups) is very similar to the Vrbno Group s. s., but displays a higher grade of metamorphism. Alltogether, they could be classified with the Vrbno Group s.l.

Flysch foredeep and coal-bearing molasse

Both the flysch foredeep and the coal-bearing molasse of the Moravosilesian Zone represent a typical Variscan syncollisional sedimentary basin filling with characteristic foreland-ward migration of the subsidence axis (Dvořák 1975, 1994, Havlena 1982, Kumpera 1983 etc.). The beginning of the flysch sedimentation (Andělská Hora Formation) alternated laterally (e.g. Dvořák 1992, 1994 etc.) with other non-flysch facies like the Poniklá Formation (shales with silicites) or the Líšeň Formation (limestones). The clastic facies of the Moravský Beroun Member (calcareous quartz breccias and sandstones) was, according to Dvořák (1994), linked to the emerged structures of the pre-Variscan basement. The onset of flysch development is characterised by an impressive geochemical change of sedimentary clastic filling of the foredeep (also Kukal 1980). The fresh, unweathered detritus was suddenly transported into the basin. The clastic material deposition was rapid and episodic. Mostly the typical turbidic sedimentation was taking place according to Kumpera (1983).

The general SE-ward trend of the thinning („out-wedging“) of flysch and coal-bearing facies is a significant feature of the whole sedimentary wedge of the Moravosilesian Zone. The other substantial feature of sedimentary development of foredeep is the longitudinal (generally N-ward) filling (Kumpera 1983) with a significant income of clastics from domains emerging further west (Dvořák 1994).

The deposition of the lowermost flysch-like Mírov Group (Mohelnice Formation according to Zapletal 1992) in the southeast corner of the Zábřeh Unit began in the Upper Devonian (Koverdynský 1993). The mentioned formation is most likely the lithofacial and stratigraphic equivalent of the Andělská Hora Formation, which started in uppermost Frasnian (Dvořák et al. 1973). However, Otava et al. (1994) denied any connection with the Lower Carboniferous Culm facies development of the Moravosilesian foredeep and considered this formation to be a Devonian flysch-like sequence. Generally, the initiation of sandy limestones breccia to calcareous quartz conglomerates migrated east-ward in both time and space. In the Šternberk-Horní Benešov zone they belong to the Upper Tournaisian, and in the vicinity of Hranice (the most SE-ward outcrops of transition between limestones and clastics facies), they are regarded as the Middle and Upper Viséan (Dvořák 1991, Dvořák et al. 1983, Dvořák 1992). The most significant assignment corresponds to the absence of a hiatus and some regional folding between pre-flysch and flysch facies (Dvořák 1992, 1994), despite some local sedimentation breaks.

The flysch sedimentation culminated in the lowermost Namurian A (zone E1) when it is changed to a paralic molasse facies of the Ostrava Formation (Štur'group of marine bands) of the Upper Silesian Coal Basin (see e.g. Havlena 1982, Dopita – Kumpera 1993). The Karviná Formation (Namurian B-Westphalian) represents the latest stage of the continental coal-bearing molasse.

Brunovistulian foreland terrane

The Brunovistulian foreland influenced essentially the structural, kinematic and complete geological development of the Moravosilesian branch of the Lugosilesian orocline. The origin of a „suspect-like" Brunovistulian terrane is puzzling (see e.g. Mísař et al. 1983), but a majority of authors support the idea of its original relationships to the Baltica Old Red Continent (see also Orlowski 1975, Milanowska 1983 in Ziegler 1986 etc.). However, Matte et al. (1990) expressed an opinion, according to which the Brunovistulian, as a basement of their „Moravian zone", is correlated with the Aquitaine Montagne Noire terrane. They believed it to be both a part of the pre-Variscan Pan-African Gondwana plate and to correspond to the southern foreland of the Variscan orogenic belt. However, Matte et al. (1990) do not mention the well known continental „Old Red Sandstone" facies on the Brunovistulian basement, which is different from the marine littoral clastic facies of the opposite (accretion) flank (Silesicum) of the Moravosilesian foredeep. Moreover, they omit some other well verified biostratigraphic and lithofacial facts (e.g. Orlowski 1975, Ziegler 1982, 1986, Hladil 1987, 1988 etc.) concerning the reconstruction of the original position of the Brunovistulian terrane.

The Cadomian Brunovistulian foreland (Dudek 1980, Kotas 1983 etc.) is not as a whole a compact „massif". Its Vistulian part (as defined by Stille 1948) is partly comprised of the Malopolska Massif. Dudek (1980) considered the „Bruno-Vistulicum" to be composed of two sub-massifs: Brunia and Upper Silesian Massif (part of Vistulian basement, see e.g. Kotas 1983). From the Malopolska Massif (at the NE), this Upper Silesian Massif is tectonically sutured by the Cracow Fold Belt (Bukowy 1978). All the above mentioned sub-massifs are limited by WNW-ESE major shear zones which originally represented mobile basin structures (e.g. the above mentioned Cracow Fold Belt, Holy Cross Mts. Belt etc.). The late Variscan wrench movement on these zones displays a dextral strike-slip component (Bogacz – Krokowski 1981, Kotas 1983 etc.). A similar kinematics can be deduced from the structural pattern and complex long-time geological development of the Caledonian-Variscan orogeny of the Holy Cross Mts. (e.g. Pożaryski et al. 1977, Mizerski 1979) and of the Lublin-Volynian Carboniferous coal-bearing Basin (along the NE boundary of the Malopolska massif), in the domain of the Teisseyre-Tornquist shear zone.

Structural and kinematic evolution

One of the key areas of the Lugosilesian orocline from the view point of kinematic analysis is the Orlice-Sněžník Unit. It was, as the most inner domain of an accretion wedge, gradually thrust during the prolonged Variscan s.l. collision along the Ramzová and Nýznerov shear zones over the easterly outcropping Staré Město Unit and both together over the Silesicum crystalline with its envelope Devonian sequence (Branná Group). These shear zones were till now interpreted as pure orthogonal thrusts with the tectonic transport from W to E (e.g. Skácel 1979, Źelaźniewicz 1988 etc.). However, their polyphase kinematic history is more complex (Grygar 1988, 1991, Cymerman 1992). Before we will discuss it, let`s describe deformation history of each essential unit separately.

Orlice-Sněžník Unit

The first deformation phase D_1 of the Orlice-Sněžník Unit corresponds to rootless synschistose folds F_1 in the tectonic pods as the final products of a layer-parallel shearing. The main metamorphic foliation S_1 is generally copying the protolith sedimentary foliation S_0. A transition to the mylonitic S-C foliation is obvious in the deeper crust formations (Sněžník and Gieraltow gneiss). Anyhow, only scarce relics of first F_1 folds (in the final state nearly coaxial in relation to next F_2 asymmetric sheath-like folds – Pl. I-1) and other corresponding structures are preserved in the Stronie Group (see also Źelaźniewicz 1976, 1988, Cymerman 1992 etc.). The b-axes and the corresponding intersection L_i lineations of F_1 folds display a wide range of directions, although they have a general NW-SE (NNW-SSE) trend and a north-eastern asymmetry (see Źelaźniewicz 1976 on the Polish territory and Fig. 4 in this paper).

Źelaźniewicz (1988) presented the opinion that the irrotational strain was the main mechanism during the incremental shortening, which suffered an extension parallel to the hinge lines of the folds. Grygar et al. (1991) prefer the concept of a rotational (noncoaxial) strain in long-lived,

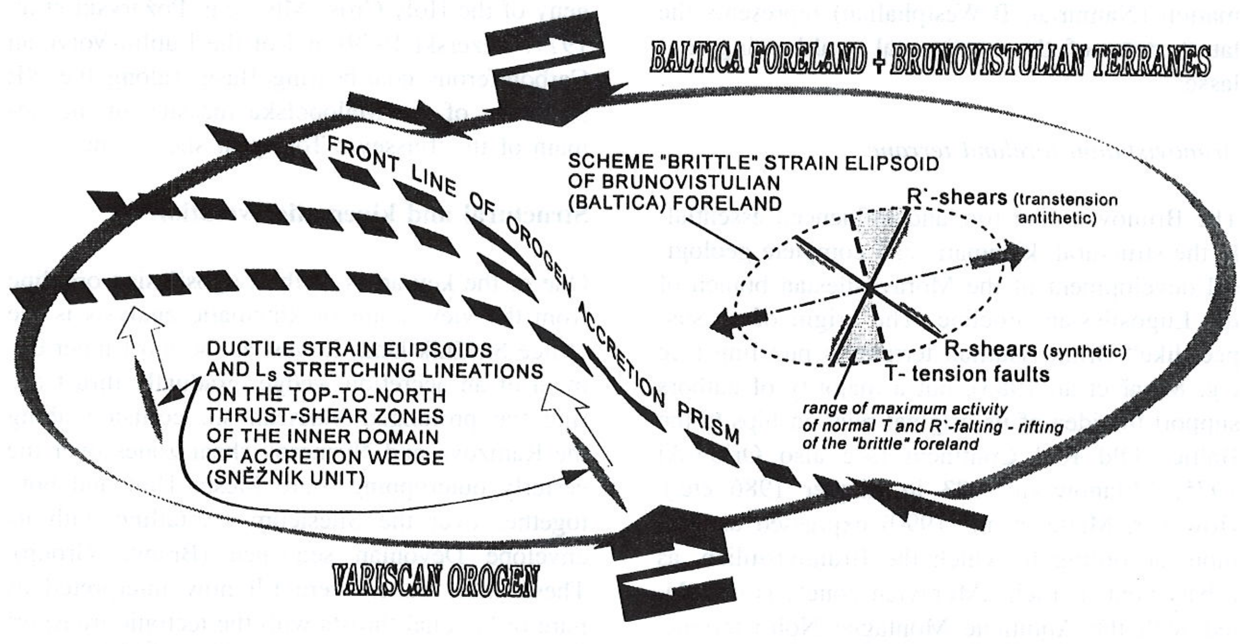

Fig. 5. Schematic regional deformation ellipsoid of mutual strain relations between the active Variscan accretion wedge and the Brunovistulian foreland

nearly constant, global stress fields (Fig. 5). According to them, the deformation could be evoked by the progressive oblique collision of the Variscan accretion wedge with the oblique ramp of the foreland terrane which occured NE-ward (Figs. 9 and 10). Due to an incremental strain on the oblique thrust shear zones, hinge lines of the first generation of folds rotated to a position subparallel with the kinematic stretching „a-type" lineation L_S. The top-to-NNW asymmetry of shearing linked to the above mentioned mechanism was presented also by Cymerman (1992) from the Polish part of the Orlice-Sněžník Unit. Due to the high constrictional strain of L>S mylonites in the amphibolite facies conditions and due to the next superposed coaxial F_2 deformation, it is not so easy to recognise the sense of shearing. The structures observed in the thin sections and the field mesoscopic observations display frequently symmetric or variable senses of displacement, but the general sense is evident especially in the northern Polish part of the Orlice-Sněžník Unit (Cymerman 1992). Also, a general E-ward asymmetry in the YZ-section of strain ellipsoid is evident. Moreover, in the most southern part of the Orlice-Sněžník Unit the top-to-S sense of the shearing D_{2-3} was recognised (Pl. I-2). According to Grygar et al. (1991), it represents the higher stage of a nappe imbrication stacking associated with a back-thrusting (top-to-S), opposite to the top-to-NNW main frontal thrusting.

In the coarse-grained (augen) type of the Sněžník orthogneiss, the F_1 folds are missing due to reological reasons, but this stage of transpressional deformation is substituted by extensive S-C mylonite structures of higher rank of amphibolite facies conditions, shear bands etc., with a general top-to-N sense of shearing observable in the XZ section of finite strain ellipsoids (see also Cymerman 1992). However, the very significant result of meso-, or scarcely microstructural studies shows again the eastward asymmetry in the YZ plane (see Pl. I-1). Otherwise, rare noncylindrical folds in the fine laminated gneiss mylonites of progressive continuous phases $F_1 \rightarrow F_2$ do not display typical features of a-type sheath folds (e.g. Malavielle 1987), but rather asymmetric transpressional fabric, typical for transition zones (e.g. Wilkerson et al. 1992, Calassou et al. 1993 etc.) developing in the hangingwall over oblique ramps.

Significant differences exist in the geometrical distribution of foliation and cleavage systems in between the western (Orlické Hory Mts.) and eastern (Kralický Sněžník Mts.) limbs of the Orlice-Sněžník Unit (Fig. 4). All the foliation systems of the eastern Sněžník limb were overprinted by F_3 folds and systems of a new crenulation cleavage S_3. The B_3 axes are coaxial with previous

$F_1 \rightarrow F_2$ folds and also geometrically correspond to the first generation of L_S stretching lineations (mineral elongation, rodding lineations etc.). Although, in comparison to the flat lying planar structures of the western Orlické Hory Mts. subarea, the foliation systems of the Sněžník limb are subvertical (display typical flower-like structure pattern – see corresponding diagram in Fig. 4).

The distribution of all B-axes and lineation systems is very uniform, which is in contrast to a wide dispersion of these systems in the more northern areas of the Orlice-Sněžník Unit in the Polish territory (Żelaźniewicz 1976, 1988 and Cymerman 1992). We explain it as the consequence of a more intense constrictional strain in shear zones at the deeper level of the accretion wedge, now exposed in the Czech region of our study, compared to the less deformed upper levels in the northern Polish part (see diagrams on the Fig. 4).

All ductile deformation structures correspond to a progressive synkinematic metamorphism. However, due to reactivation of planar structures during the later incremental strain stages, it is difficult to distinguish the exact age of the superposed transtensional deformations. Based on the isotopic data of Bakun-Czubarow – Brueckner (1991) and Steltenpohl et al. (1991), the deformation preceded the ~ 335 Ma (hornblende $^{40}Ar/^{39}Ar$), whose value reflects the beginning

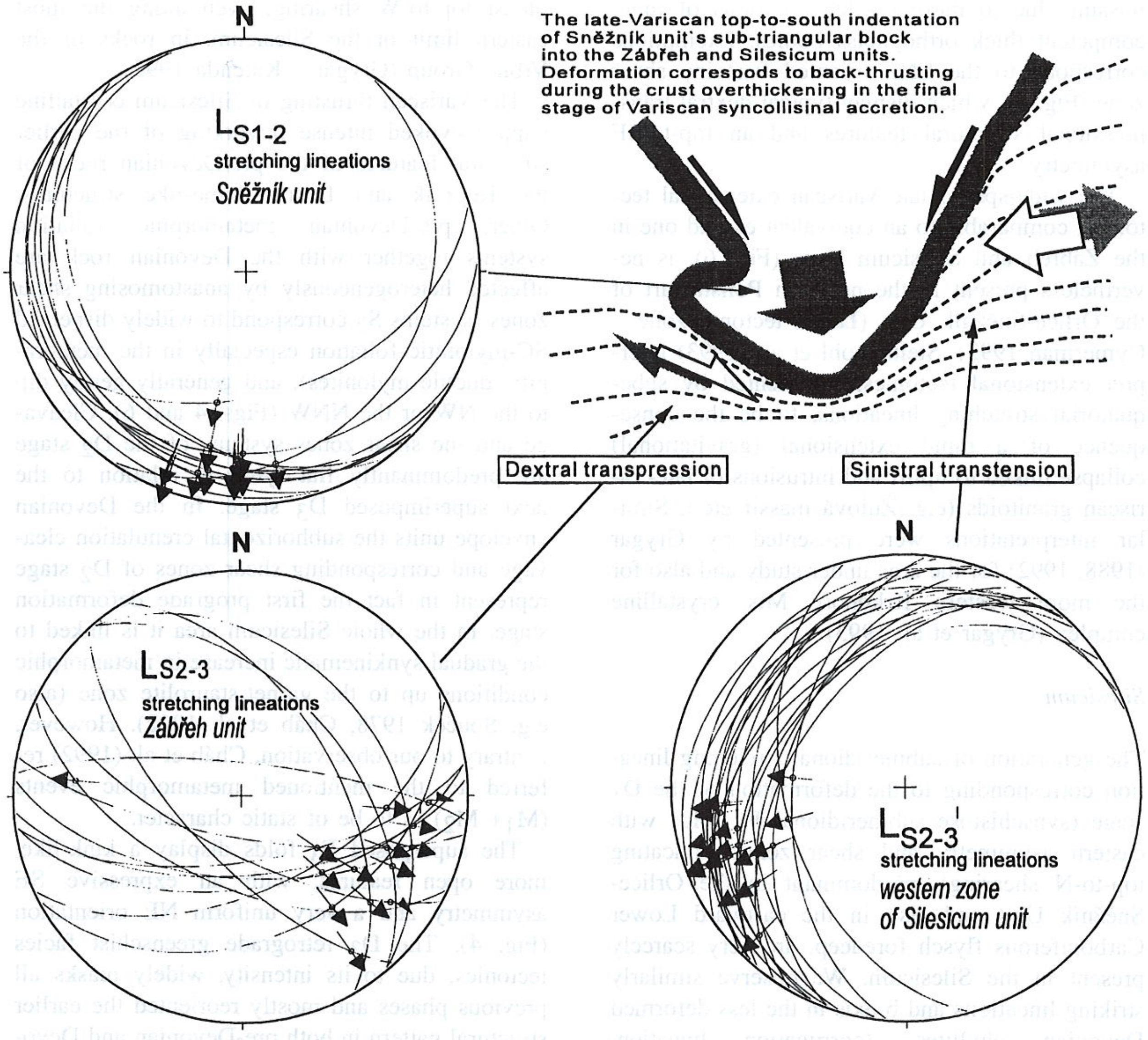

Fig. 6. Explanation scheme of the late-Variscan top-to-S indentation of the Sněžník unit`s subtriangular „block" into the Zábřeh and Silesicum envelope unit during the $D_2 > D_3$ stages of dextral transpressional wrenching along the NNW striking shear zones and post-collisional transtension

of cooling through the ~ 500 ^{o}C isotherm during the uplift of the Sněžník gneiss (Fig. 3) and the beginning of the transtensional phases. The earliest ductile displacement run according to Borkowska et al. (1990) in Lower Devonian. However, the deformations $D_1 \rightarrow D_2$ have to be undoubtedly younger than intrusions of the Early Paleozoic Sněžník granite (507-499 Ma according to Kröner et al. 1994b).

The later deformation D_3 resulted in the ENE-WSW to WNW-ESE oriented younger generations of stretching lineations. They are recorded foremost in the rim and footwall units of the Orlice-Sněžník Unit (Silesicum, Staré Město and Zábřeh units etc.). In the core of the Orlice-Sněžník Unit, southerly on the Czech territory, the ENE-WSW stretching lineations L_{S2} are practically missing due to more brittle conditions of more competent thick orthogneiss bodies. Exemptions correspond to the ENE oriented Pastviny shear zone (Fig. 4), which display typical dextral transpressional structural features and an top-to-SE asymmetry.

The wide-spread late-Variscan extensional tectonics, comparable to an equivalent extend one in the Zábřeh and Silesicum units (Fig. 6), is nevertheless present in the northern Polish part of the Orlice-Sněžník Unit (Ładek tectonic zone – Cymerman 1992). Steltenpohl et al. (1993) interpret extensional tectonics, represented by subequatorial stretching lineations, to be the consequence of a rapid extensional (gravitational) collapse linked to uplift and intrusions of late-Variscan granitoids (e.g. Žulová massif etc.). Similar interpretations were presented by Grygar (1988, 1992) for the area under study and also for the more western Krkonoše Mts. crystalline complex (Grygar et al. 1993).

Silesicum

The generation of submeridional stretching lineation corresponding to the deformation of the D_1 stage (synschistose submeridional F_1 folds with eastern asymmetry and shear zones indicating top-to-N shearing), predominant in the Orlice-Sněžník Unit and also in the eastward Lower Carboniferous flysch foredeep, are very scarcely present in the Silesicum. We observe similarly striking lineations and b-axis in the less deformed Devonian phyllites, (corrugation lineation, alignment of mica flakes etc.) especially in the southern part of Desná and Keprník dome-like structures. It's presence in some relics of banding in the mylonitic gneiss tectonic pods of the pre-Devonian paraautochtoneous components of the Desná Group is a subject of discussion. Additionally, the geometrically subparallel stretching and common X-axes lineations in the Devonian rocks of the Silesicum and the Lower Carboniferous flysch molasse could not be most probably completely identical with the responded L_{S1} ones of the Orlice-Sněžník Unit due to different age.

Cháb et al. (1992) considered the first Variscan deformation event D_1 in the Silesicum to correspond to the large scale W-vergent thrusting and folding. This deformation was referred to also earlier by e.g. Orel (1973) and Rajlich (1974). However, we did not find in the both pre-Devonian and Devonian rocks any structures and kinematic markers, providing evidence for the oldest top-to-W shearing, even along the most eastern limit of the Silesicum, in rocks of the Vrbno Group (Grygar – Kalenda 1992).

The Variscan thrusting of Silesicum crystalline nappes evoked intense reworking of the earlier structural features of the pre-Devonian rocks of the Keprník and Desná dome-like structures. Older, pre-Devonian metamorphic foliation systems together with the Devonian rock are affected heterogeneously by anastomosing shear zones (systems S_2 correspond to widely dispersed SC-mylonitic foliation especially in the metagranitic ductile mylonites), and generally gently dip to the NW or the NNW (Figs. 4 and 6). Cleavage and the shear zones systems of the D_2 stage are predominantly flat lying in relation to the next superimposed D_3 stage. In the Devonian envelope units the subhorizontal crenulation cleavage and corresponding shear zones of D_2 stage represent in fact the first prograde deformation stage. In the whole Silesicum area it is linked to the gradual synkinematic increase in metamorphic conditions up to the garnet-staurolite zone (also e.g. Souček 1978, Cháb et al. 1992). However, contrary to our observation, Cháb et al. (1992) referred to the mentioned metamorphic events (M_1+ M_2) as to be of static character.

The superposed F_3 folds display a kink-like, more open features, with an expressive SE asymmetry and a very uniform NE orientation (Fig. 4). The D_3 retrograde greenschist facies tectonics, due to its intensity, widely masks all previous phases and mostly reoriented the earlier structural pattern in both pre-Devonian and Devonian rocks. The D_2 to D_3 deformation stages, according to our observation, correspond to a continuous transition. The steepening of axial planes of F_3 folds, in relation to subhorizontal axial cleavage of the previous F_2 folds, most probably reflects synchronous uplift and resulted decrease of vertical gravitation stresses in the relation to generally NNW-SSE oriented maximum of regional shortening.

For both deformation stages $D_2 \rightarrow D_3$ the NE-SW extension is typical, accrued progressively, to be expressed by widely present stretching and mineral lineations (Fig. 6), X-axis of pebbles (see also Rajlich 1993), as well as corresponding perpendicular tension gashes, bone-structures, boudins and joint systems. On the basis of a mutual relationship between tension structures and the HT-LP metamorphism, there is evidence for a certain genetic connection to the late- and post-orogenic magmatism, e.g. intrusion of Žulová pluton in the northern part of Keprník Unit. Excellent examples of an HT/LP synkinematic periplutonic metamorphism are exhibited in the mantle rocks of the Žulová pluton, where tension gashes are filled with sillimanite (Cháb – Žáček 1994) and in the more outer mantle rocks of the Keprník „Dome" also with andalusite. Also the 344 Ma ages of cross muscovites of the Desná units, and $^{40}Ar/^{39}Ar$ of 305 Ma (Maluski unpubl. data in Rajlich 1993) for amphibolite (corresponding L_m mineral lineation are parallel with L_S stretching lineations) of the Jeseník metabasite complex, indicate an extensive time range for the described tectonometamorphic activity and inversion from the transpressional to transtensional tectonic setting. The above mentioned dating seems to be in agreement with the data from the Orlice-Sněžník Unit, published by Steltenpohl et al. (1993), where the rapid cooling from the eclogite-facies conditions at 340 Ma passed through a biotite closure temperatures at about 328 Ma (Fig. 3).

The normal top-to-WSW (see Pl. II-1 and Fig. 6) shearing is uniform in the whole western flank of the Keprník „Dome", the envelope Branná Group and with some exceptions also in the Staré Město Unit (Grygar et al. 1991, Cymerman 1993, Cháb et al. 1994). It corresponds to the transtensional sinistral shearing in the wide shear zone in the footwall of the Nýznerov and Ramzová thrusts in the general conditions of a post-collisional orogenic collapse (Fig. 6). The comparable extensional stage of the eastern flank of Orlice-Sněžník Unit in the Polish northern part was also referred to by Cymerman (1992, 1993). This oblique shearing is conjugated with dextral wrenching along the WNW-ESE Sudetic transcurent shear zones, e.g. the Zábřeh shear zone and the Ładek tectonic zone (Grygar et al. 1991, Cymerman 1992).

The kinematic study of the above mentioned transtensional structures indicates a different sense of shearing in the western and eastern part of the Silesicum area. Generally, the top-to-E movement is recorded along the more eastern edge of the Silesicum crystalline (represented mainly by the Devonian Vrbno Group and also by the Lower Carboniferous flysch-like Andělská Hora Formation), corresponding to the tectonic extrusion of internal ductile domains of an accretion wedge outward, into contemporaneously subsided flysch and coal-bearing molasse foredeep. However, this kinematic stage had already started earlier in the period of the D_2 stage, because the F_2 synschistose flat axial planes of the recumbent folds and synchronous shear zones in the Vrbno Group exhibit outward (E-ward) asymmetry. The expressive top-to-NE shearing in the XZ-plane of the strain ellipsoid together with the SE-ward asymmetry in the YZ-section is a very significant feature of the D_2-D_3 deformation stages, referenced to the transpressional top-to-SE oblique thrusting of nappe sheets of Silesicum over Brunovistulian foreland (Grygar 1992).

Zábřeh Unit

The oldest apparent deformation D_1 in the Zábřeh Unit corresponds to synschistose shearing parallel to the sedimentary foliation analogous to the D_1 stage of the Stronie Group of the Orlice-Sněžník Unit. The scarce, predominantly rootless F_1 folds (striking N-S upto NNE-SSW), which are parallel with L_S stretching lineations (mineral elongation of quartz-feldspar and micaceous aggregates), are present in both north and south flanks of the synformal Zábřeh structure with axes striking WNW-ESE (Figs. 4 and 6). The metamorphic S_1 foliation and the SC-mylonitic schistosity in the northern part neighbouring with the Orlice-Sněžník Unit display a uniform flat distribution, gently dipping to SW. It is fully equivalent to the metamorphic foliation trends of the Sněžník Gneiss. In the central Zábřeh (Hoštejn) shear zone area (Grygar 1992) with incorporated lower grade metamorphic rocks, partly of Paleozoic age (?Devonian – Koverdynský and Konzalová 1986), this structural feature was absent or was totally overprinted by later intense $D_2 \rightarrow D_3$ deformations (Pl. II-2).

In the northern flank of the Zábřeh Unit, near the contact with the Sněžník Gneiss, we find kinematic criteria exhibiting top-to-S shearing with SW asymmetry in the YZ section of the strain ellipsoid. Corresponding stretching lineations are parallel with F_2 fold noses with ESE trend (see Fig. 4). The pencil-like structures (L-tectonites) parallel with the B_2 axis are developed in some domains. This deformation is also associated with perpendicular tension gashes, boudins etc. The kinematic analysis of the mentioned deformation phase verify a dextral strike-slip regime – transpressional deformation (compare Pl. II-2). The representative case crops out in the axial belt of the Zábřeh structure – the Hoštejn shear zone (Grygar 1988) in the Moravská Sázava river valley.

The new generation of transpressional F_3 folds, with axial planes dipping steeply NNW with ENE up to E strike, was constituted. This stage corresponds mostly to open kink-folds, with an irregularly developed crenulation cleavage, frequently substituted by kink-bands only, especially in phyllites and greenschist facies rocks. The more brittle domains with C`-shear bands (in position of synthetic Riedl R-shears) developed. This D_3 deformation corresponds to an intense dextral wrenching along Sudetic transcurent shear zones (Fig. 6).

The southern part of the Zábřeh crystalline area, corresponding to the Maletín Formation, most probably of the Devonian age (Koverdynský – Konzalová 1986), is characterised by a tectonic style very similar to the one in the southern part of Silesicum, especially its envelope Devonian Vrbno Group. The dominant deformations correspond to the D_3 stage represented by F_3 folds with subequatorial up to ENE hinge lines and uniform SSE-ward asymmetry. The parallel L_{S3} stretching lineations exhibit similar orientation trend to that of the Silesicum and a top-to-ESE shearing.

The comparable tectonic pattern is likewise representative of the flysch-like facies of the Mohelnice Formation, which fill the Mírov synclinorium in the roof of the Maletín Formation. There is a significant fact linked to the deformation`s age point of view – namely, no structural pattern disconformity exists between the Zábřeh Unit (including ?Devonian Maletín Formation) and the flysch-like Mohelnice Formation itself. It means, that the mentioned units were deformed together in the same tectonic setting. This event is recorded mainly by the onset of immature clastics supply in the growing synorogenic foredeep. The first records of this influx in the western flank of the foredeep is of Frasnian age, but more rapid income of pebbly mudstones etc. facies is of the Tournasian age (Dvořák et al. 1983 in Dvořák 1992, Dvořák 1994 etc.). The same is true for the mutual relationships between the Devonian Vrbno Group and the Culmian Andělská Hora Formation, along the more northern rim of the Silesicum.

The brittle-ductile conditions of D_3 deformations changed to an intensive, brittle fault tectonics which was related to late- and post-Variscan dextral strike-slip movements along the NW-SE Sudetic faults (in position and with kinematics of R-shears) coupled with NNE striking faults (antithetic R`-shears).

Flysch foredeep
and coal-bearing molasse

The Moravosilesian flysch foredeep and the coal-bearing molasse represent a typical asymmetric sedimentary prism structure, developed during the stages of long-lived syncollisional stacking inside internal zones of the Variscan orogen (Moldanubian and Saxothuringian). The well known E- to SE-ward synsedimentary thinning of the foredeep flysch-like sedimentary facies with a maximum thickness to the west (e.g. Havlena 1982, Kumpera 1983, Kotas 1983, Dvořák 1994 etc.) indicate a typical synsedimentary flexure of the foreland continental crust dipping WNW-ward.

The main deformation fold-thrust F_1 system has a ESE-ward vergency (e.g. Kumpera 1983). However, the western synclinorial structure (west from the Šternberk-Horní Benešov „klippen zone") has a dominant western asymmetry (see Fig. 7). The W-ward assymetry is valid for the eastern margin of the Šternberk-Horní Benešov zone. Some authors (Rajlich 1974, Dvořák 1994), who considered W-wergent folding to be the first one, explain this bivergent tectonic style as a superposition of the E-vergent folding over the older W-vergent one. On the basis of detailed strain and kinematic analysis of mutual relations of both systems, Grygar (1985, 1988) proposed, that a bivergent structural pattern corresponds to a typical flower-like, let`s say „pop-up", structural tectonic style. It developed due to activity of complementary (conjugated) systems of shear cleavage, which corresponds to published experimental and field works (e.g. Davis et al. 1983, Lallemand et al. 1992, Brown et al. 1993, Jamisson 1993, Willet et al. 1993 etc.). According to this concept the W-ward thrusting and folding represents, in relation to a dominant E-ward one, practically contemporaneous back-thrusting structures. Additionally in the most western flank of post-erosional relics of the foredeep prism, along the tectonic contact with the Vrbno zone of Silesicum, there is the transpressional back-thrusting preceded by a synschistose intrafolial folding and east-ward shearing (Grygar 1988). Also same rootless noncylindrical and recumbent folds $F_0 \rightarrow F_1$ display features of syndiagenetic gravitational slumping (F_0 folding) that preceded the above mentioned later synschistose folds F_1.

The paleostress analysis, based on the striation measurements of the bedding-parallel faults, resulted in our conclusion about the WNW-ESE orientation of maximum of compression for the local imbrication thrust-fold structures development E-ward from the Šternberk-Horní Benešov „klippen zone“ (Fig. 8).

Typical out-of-sequence thrust structures (Morley 1988) were observed not only in the eastern area of flysch zone, but also in the Upper Silesian Coal Basin, also conditioned by a widespread sedimentary bedding parallel shearing (for „progressive easy-slip thrusting“ see Gayer et al. 1991). Čížek – Tomek (1991), on the basis of drilling and seismic profiling of the eastern part of flysch foredeep, reported tens of kilometres long internal detachment and thrusting in between Culm facies and Devonian limestone facies in the cover of the Brunovistulian foreland. A similar kilometres scale thrusts were distinguished and interpreted from the Czech part of the Karviná subbasin of the Upper Silesian Coal Basin (Grygar et al. 1989). Due to previously mentioned facts, we do not believe that Paleozoic sedimentary filling of the flysch foredeep (including Variscan molasse) is completely autochthoneous. Accordingly, also in the outermost zone of the sedimentary accretion prism the thrust intraformational detachment have to be considered in the regional synthesis.

In the western part of the Moravosilesian flysch basin it is possible to observe the similar mutual relations between the strain ellipsoids, as was mentioned earlier in the Orlice-Sněžník Unit. The shear criteria and strain ellipsoids reflect unimodal flattening, rather than asymmetry in the XZ-section. Also, in the Ostrava Formation of the Upper Silesian Coal Basin, the measurement of X-axis from the remnants of standing trees and stump in the coal seams (Dopita – Havlena 1960) displays the same relationship between the fold`s b-axes and the X-axis of measured final strain ellipsoids (Fig. 8). However, our new paleostress analysis from the western limit of the Upper Silesian Coal Basin, resulted in the statement of WNW-ESE, almost pure shortening without significant strike component. This assignment points to necessary care in interpretations assuming that all L_S lineations and X-axis of the measured finite strain ellipsoids correspond to kinematic a-axis of fold-thrust structures and therefore indicate the top-to-NNE to NE nappe thrusts movement in the Moravosilesian zone of the Variscan orogen (e.g. Matte et al. 1990, Schulmann et al. 1994 etc.) and/or dextral transpression along the inherited NNE trending subvertical shear zones (Rajlich 1990, 1993). Our observations are, from this point of view, more similar to those, which were presented by Fritz and Neubauer (1993). For the D_2 deformation phase (from the

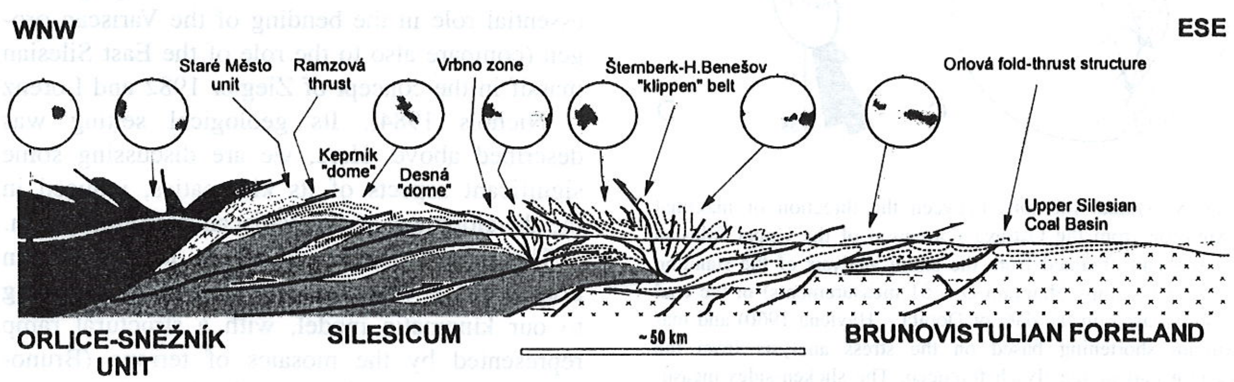

Fig. 7. Sketch structure profile across the Variscan accretion wedge of the Moravosilesian Zone of the Bohemian Massif. Simplified representative contour diagrams correspond to pole of the main foliation systems S_0, resp. S_1

age point of view it is equivalent to the main folding phase in the flysch foredeep and coal-bearing molasse), they reported also top-to-E shearing in the Moldanubian nappe complex of the southern (Moravicum) part of the Moravosilesian Zone.

The inherited pre-Variscan and Variscan structural framework of the Brunovistulian basement had an essential role in the tectonic development of the sedimentary wedge. Its main feature corresponds to expressive NNW-SSE structural depth polarity, deduced first from the geophysical measurement and interpreted from the thickness of sedimentary filling. The presence of the WSW-ENE trending mobile depression zone, running from the Main Jeseník Mts. Depression (Grygar 1988, partly also Čížek in Suk et al. 1991) on the west, to the Main Depression in the Polish part of the Upper Silesian Coal Basin E-ward (e.g. Kotas 1983), caused during the out-of-orocline core polyphase thrusting, more intensive lateral tectonic extrusion (for the discussion of lateral extrusion concept,

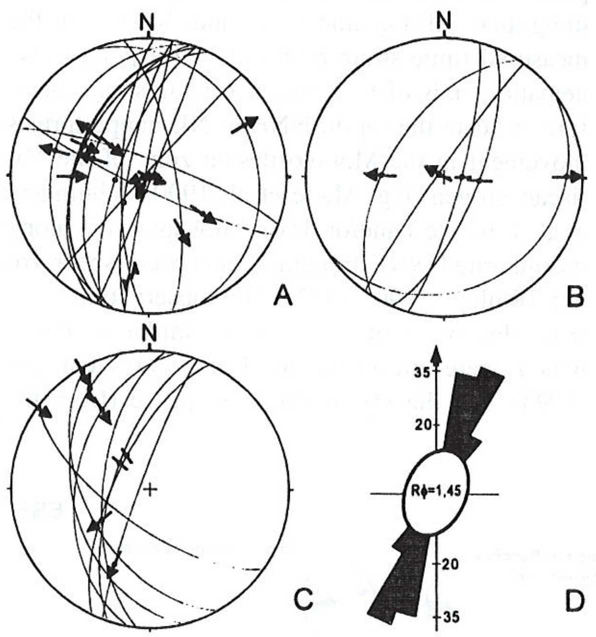

Fig. 8. Mutual relations between the direction of maximal extension from the Ostrava Formation of the Upper Silesian Coal Basin obtained from the strain analysis of the standing trees and stumps (diagram D – 61 measurements) in the coal seams (based on the data of Dopita – Havlena 1960) and maximum shortening based on the stress analysis from the eastern part of the flysch foredeep. The slicken-sides measurements (diagrams A, B and C from three representative different localities) indicate W-E to NW-SE orientation of Z-axes, which are subperpendicular to the X-axis preferred orientation (diagram D) of strained trees and stumps

see Ratschbacher et al 1991). On the other hand, the parallel Brunovistulian elevated domain had been blocking the thrust wedge progression. It resulted in dextral transpressional oblique shearing along the northern slope of the mentioned elevation, linked to dextral transcurent fault activity (see Figs. 8 and 9). Excellent examples were presented by Grygar et al. (1989) and Grygar (1993), from the coal-bearing molasse of the Ostrava-Karviná Coal Basin.

This deformation continued up-to the post-Westphalian time. This statement is based on the fact, that it also folded the Karviná Formation (Namurian B – Westphalian A). Moreover, tectonic development of the main longitudinal Orlová fold-thrust structure of the Upper Silesian Coal Basin culminated in the same time, because it also deformed the above mentioned Karviná Formation (also Havlena 1982). Therefore, the statement by Dvořák (1994), that thrust-fold deformations in the whole Variscan „tectogene" were finished before the sedimentation of the lowermost Prokop seam of the Karviná Formation (Namurian B), can not be exactly valid.

Facts presented here lead us to the conclusion that the transpressional deformation in the apical domain of the Variscan accretion sedimentary prism (in the coal-bearing molasse) was contemporaneous with intensive uplift, above all with strong transtensional stretching in the inner domains of the accretion wedge corresponding to the Orlice-Sněžník Unit and the Silesicum (see data published by Steltenpohl et al. 1993 and other presented earlier).

Tectonic setting and kinematic role of the Brunovistulian foreland terrane

The Brunovistulian foreland terrane played an essential role in the bending of the Variscan orogen (compare also to the role of the East Silesian massif in the concept of Ziegler 1982 and Lorenz – Nichols 1984). Its geological setting was described above. Here, we are discussing some significant aspects of its kinematics, induced in the development of the Variscan accretion prism.

The more inner zones of the Moravosilesian branch of the Variscan orogen collided, according to our kinematic model, with a structural ramp represented by the mosaics of terrane (Brunovistulicum s.l.), perhaps partly derived, or more probably during the early Paleozoic (Caledonian events) docked to the Ukrainian shield, as the southern promontory of Baltica continent. The

Ukrainian shield was acting as a S-ward projected part of its Sarmatia-Volga anteclise, stretched in the NE-SW direction. It represents a stationary area of the Baltica, from the Upper Vendian to Silurian (see e.g. Khain 1985). The earlier Upper Silurian – Lower Devonian transpressional collision (recorded well among other in the Lugicum area – see above) – caused consequent transtension and gradual polyphase detachment of the early described system of Malopolska, Upper Silesian and Brunia Massifs from the southern edge of the Baltica promontory. The eastward opening of the hinge-like Dnieper-Donets graben (Figs. 2 and 11), followed by the Middle Devonian basic magmatism (Khain 1985), can be considered as the beginning of the transtensional dynamic regime (oblique rifting) evoked by an oblique collision with the Caledonian (let`s say Early Variscan) orogenic front. The age and character of the Devonian magmatic activity is relevant to Devonian-Early Carboniferous basic volcanism of the Moravosilesian Zone. Přichystal (1990, 1993) considered the Devonian volcanites, located in the more E and Sward part of the Moravosilesian Zone, as a product of continental rifting of the Brunovistulian basement. The same author (Přichystal 1990, 1993) also referred to the geochemical differences between the mentioned volcanites from the south-eastern area and magmatites from the western and north-western part (Silesicum area).

The transtensional WNW-ESE striking mobile grabens (in position of synthetic R-shears – see Figs. 5 and 10) and inserted R`-shears and T-normal faults, with consequent complex geological history, developed in the brittle deformation conditions of the formerly consolidated Brunovistulicum s.l. This oblique rifting stage (indicated by continental conglomerates and „Old Red"-like sandstones facies and Devonian volcanism) in the Brunovistulian basement of the Moravosilesian area indicates a transtensional tectonic setting, which reflects collisional events in the more inner zones of the accretion prism in the Lugicum area, recorded in the Kłodzko metamorphic unit and the Orlice-Sněžník Unit (van Breemen et al. 1988, Borkowska et al. 1990, Oliver et al. 1993).

In the late-Variscan time of out-ward fold-thrust propagation of accretion wedge (mirrored by the subsidence axis translation), the Brunovistulian basement flexure with its fault ramps (created in the earlier oblique rifting stage) influenced (induced) essentially the geometry and character of mentioned transpressional structures of the active orogen (Fig. 9). The progradation into the Brunovistulian subequatorial depression zone – both the Jeseník and Main structural depressions (Grygar

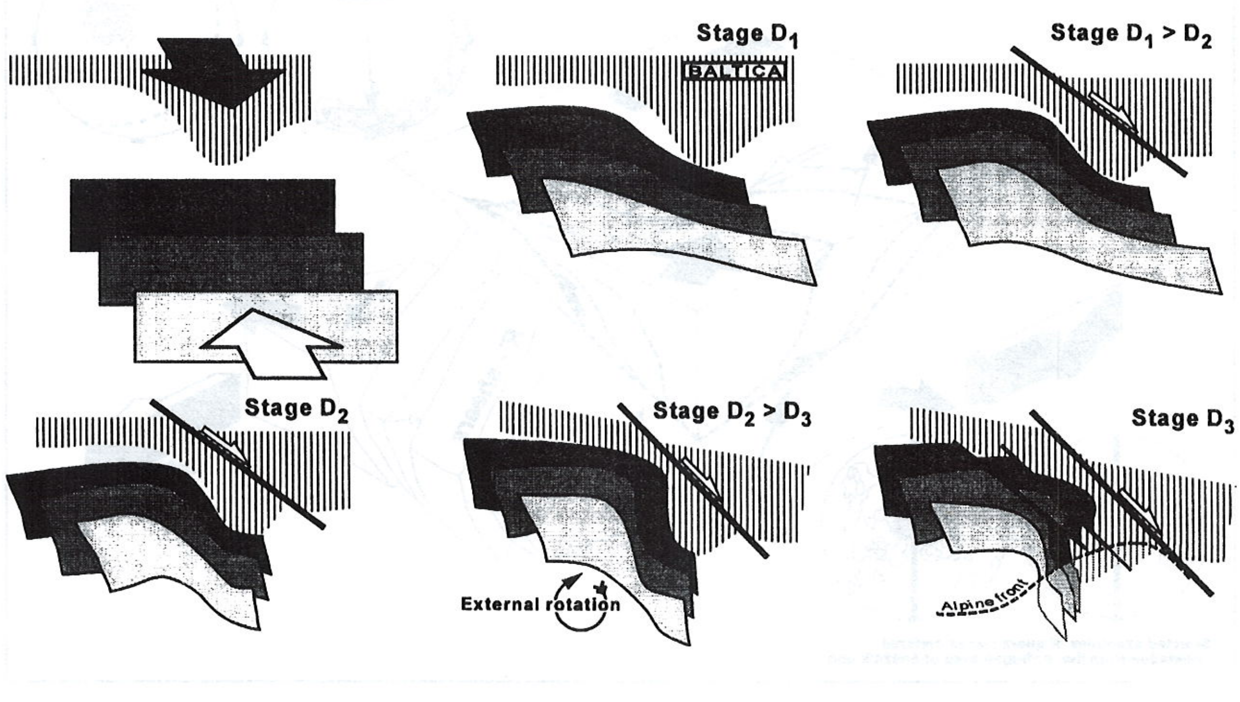

Fig. 9. The set of schematic diagrams illustrates kinematic development of the Variscan orogenic bend in the Moravosilesian area – genesis of the Lugosilesian orocline

1988) was more intense, due to the fact that it preceded the thrusting on the southern elevated zone of Brunovistulian (Fig. 10). This development resulted into the out-of-foreland convexity of practically all fold-thrust structures (Šternberk-Horní Benešov „klippen zone", Orlová thrust-fold structure etc. – see Fig. 1). The described structural framework and kinematic history is reminiscent of the model of lateral tectonic extrusion reworked by Ratschbacher et al. (1991).

The later dextral wrenching activity along the strike-slip domains of the WNW and also NW trend means the „retardation of southern blocks" (see e.g. Grygar et al. 1989). This kinematic setting also emphasises the recent typical bend shape of the Lugosilesian orocline (see Fig. 9).

Conclusion – kinematic history of Lugosilesian orocline

The first stage of Early Variscan oblique collision of a rising accretion wedge is indicated by several tectonothermal events in the Saxothuringian zone of the Lugicum area (~ 380-370 Ma in Sowie Góry Mts. – van Breemen et al. 1988). Also lithofacial changes and pre-Upper Devonian hiatus in the Kłodzko unit (Wojciechowska 1990), and in other areas of Sudetes, indicate local uplift and magmatic activities (Borkowska et al. 1990) in this period.

In the core of the Orlice-Sněžník Unit, the first generation of a-type L_{S1} stretching lineations reflect a top-to-N ductile shearing in the lower crust in the amphibolite up to eclogite-granulite facies conditions (see also Steltenpohl et al. 1993). Syncollisional thickening, according to data of Borkowska et al. (1990), began at about 420 Ma. However, a corresponding generation of N-S to NNE-SSW striking stretching lineations confirming the same top-to-N shearing, to be widely recorded in the south-eastern part of the Moldanubian zone of the Bohemian Massif, is dated between 360 and 325 Ma (e.g. Kröner et al. 1988, Carwell – Jamtveit 1990 in Fritz and Neubauer 1993, Dallmeyer et al. 1992, Schulmann et al. 1994). There is a good concordance with data presented for the Orlice-Sněžník Unit by Steltenpohl et al. (1993).

Together with Chlupáč (1993), we prefer the

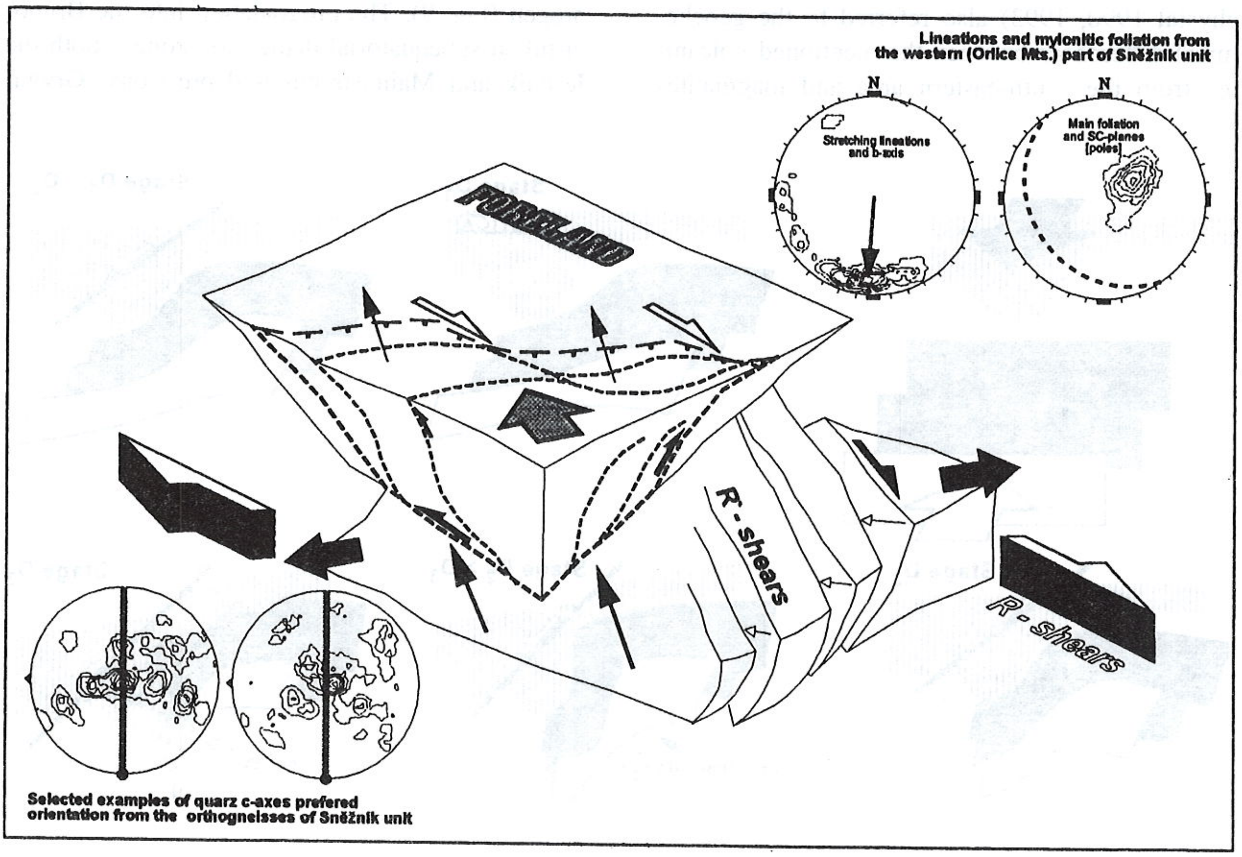

Fig. 10. Schematic blockdiagram of interaction between the active „ductile" accretion wedge of the Variscan orogen and „brittle" oblique rifting tectonic setting of the Brunovistulian foreland

opinion, that the above mentioned Late Silurian-Early Devonian events correspond to early phases of long-lived Variscan s.l. orogeny, rather than to the late Caledonian final orogenic stage.

In the Moravosilesian Zone the late Silurian (Ludlow-Přídolí) limestone facies developed from Lower Silurian (Llandovery-Wenlock) graptolite shales occurring in the vicinity of Stínava (Kettner – Remeš 1935, Bouček 1935). Chlupáč et al. (1992) compared this Silurian allochthoneous occurrence with the Silurian of the Barrandien area. Very similar changes are reflected in the Kłodzko unit (Wojciechowska 1990). The Silurian age of the lower part of the Branná Group of Silesicum in the footwall of the Ramzová overthrust in the western area of Silesicum is still unproved but on the base of lithology very likely (Květoň 1951, Koverdynský 1993).

The evident zonation of Devonian limestones facies in the Moravosilesian branch of the orocline (Hladil 1992) indicates a distinct polarisation between the both northern stable foreland and the prograded accretion wedge of Variscan orogen, already from the Lower Devonian. Also, Lower Devonian siliciclastic facies on the Brunovistulian foreland (continental „Old Red" type sandstones and conglomerates) differ from those in the Silesicum (littoral and sub-littoral mature sandstones interfinger with mostly graphitic shales and acid or intermediate volcanites). Together with the presence of Silurian strata from Stínava village in the axial zone of Moravosilesian flysch foredeep, they indicate different „basinal" deep sea Drahany Devonian facies and the presence of the Rhenohercynian suture zone closed gradually later, i.e. during the Lower Carboniferous.

An early Variscan collision of the moving orogenic front with Brunovistulian terrane most probably docked early to the southern promontory of the Baltica caused forelands oblique rifting – the transtensional faulting of the brittle pre-Variscan continental crust (see Figs. 5 and 10). It is also documented by a divergent type of syn-rifting volcanism (Přichystal 1990, 1993). Also in the Kłodzko metamorphic unit, Narębski et al. (1988) referred to pre-Late Devonian metabasite rocks indicating submarine rifting tectonic setting.

The origin of the Brunovistulian terrane (including both Upper Silesian and Malopolska Massifs) is still an open question, which need a separate synthesis from a wider point of view. Most probably there is not only one complex terrane. The position and significance of the Cracow Fold Belt and the Holy Cross Mts. mobile domains represent suture-like belts with complex Caledonian – Variscan history. Also the problem of a possible original linking between the Malopolska sub-massif of the Brunovistulian terrane and the Ukraine shield promontory of Baltica (Grygar 1988, 1993) remain open questions.

Nevertheless the most significant point for the next kinematic history of the Moravosilesian Zone was the presence of the stable terrane (microcontinent) in front of the top-to-N moving early Variscan orogenic accretion prism (Fig. 7, 11). This configuration caused the initial oblique collision and transposition of the orogenic front. The bud of Lugosilesian orocline raised and an early

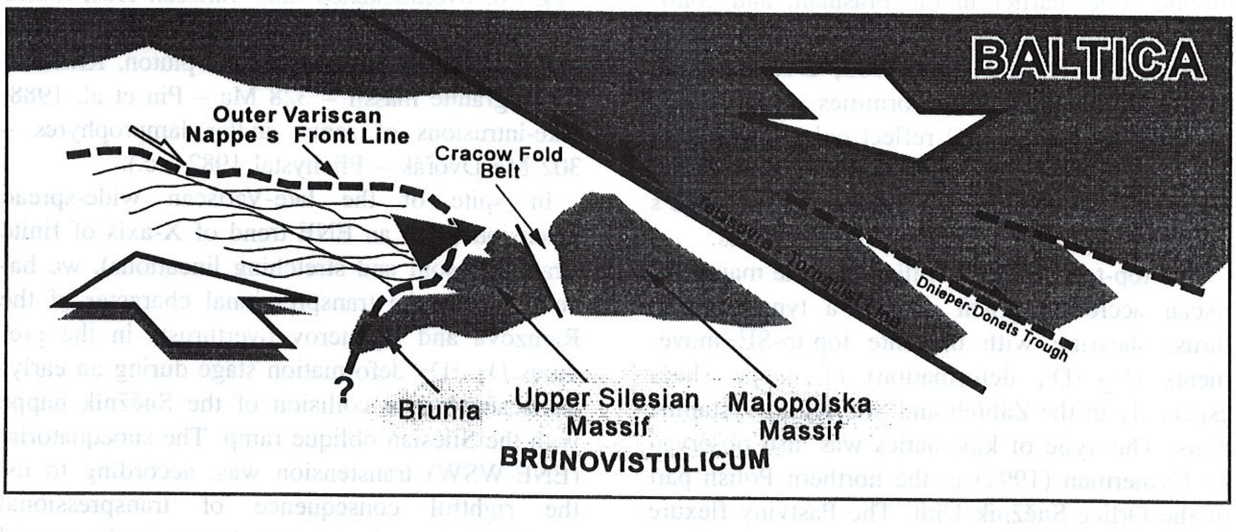

Fig. 11. Explanatory sketch map of mutual relation of the NE-ward lateral extrusion of the Lugosilesian orocline bend and position of individual parts of the Brunovistulian terrane

oblique collision with the southern promontory of foreland initiated its early Devonian transtension followed by the corresponding magmatic activity (Přichystal 1990, 1993). From the point of view of the role of irregularity of the northern foreland, our explanation is similar to that published by Lorenz and Nicholls (1984).

The final orocline bend framework visible in the geological map (Fig. 1) resulted above all from two factors: a) a dextral transpressional shearing on the originally more NNW-SSE striking (in relation to their present, post-rotational NNE-SSW position) shear zones along the western flexural ramp of the tectonically loaded Brunovistulian foreland (see Fig. 5, 9 and 10); b) a dextral wrenching on the WNW-ESE Sudetic transcurent shear zones (Fig. 9). We believe that only gentle external rotation of both the Moravosilesian segment of the Variscan accretion wedge and the Brunovistulian foreland basement took place. This model is also supported by recent palaeomagnetic data from the Moravosilesian Carboniferous presented by Krs et al. (1993).

Later a rapid uplift of internal Saxothuringian and Moldanubian zones of the orocline is indicated by isotopic dating, e.g. Steltenpohl et al. (1993). The generally early Viséan ages (~ 340 Ma) reflect a rapid exhumation in the core (backstop) of the accretion prism, which is in harmony with the beginning of the dramatic influx of immature clastic material into the Moravosilesian foredeep of the Rhenohercynian type (Kukal 1980, Kumpera 1983, Dvořák 1994 etc.). However, the first synorogenic clastic filling of Moravosilesian basin began, especially in the western mobile zone, earlier in the Frasnian, and continued in the time E-ward without any regional discordance (Koverdynský 1993, Dvořák 1993, 1994). Some local unconformities reported e.g. by Dvořák (1991, 1994) reflect only the paleorelief complexity and above all local tectonic structures of tilted block type and/or snake`s head-like („pop-up") synorogenic structures.

The top-to-N oblique collision of the major Variscan accretion prism evoked a typical backthrust shearing with opposite top-to-SE movements ($D_2 \rightarrow D_3$ deformation) of nappe slices especially in the Zábřeh and Silesicum crystalline units. This type of kinematics was also observed by Cymerman (1992) in the northern Polish part of the Orlice-Sněžník Unit. The Pastviny flexure in the western Orlické Hory Mts. flank of the Orlice-Sněžník Unit also belongs to this stage of D_3 transpressional tectonics in the whole orocline. However, inside of the more reologically competent orthogneiss rocks of the Orlice-Sněžník Unit these deformations are rare. They are more frequent in the envelope units and especially in the Silesicum crystalline.

The D_3 stage culminates in the transtensional crust stretching with ENE-WSW to NE-SW trend of stretching lineations and the X-axis of final strain ellipsoids (Grygar 1988). Top-to-NE shearing of this phase in the eastern edge of the Silesicum (Vrbno zone etc.) corresponds, according to our study, to an out-ward (out-of-core of orocline) „ductile crust flow" – a tectonic lateral extrusion of the overthickened crust (for model of lateral extrusion and its application see Ratschbacher et al. 1991) over subducted, tectonically and gravitationally loaded, foreland in the footwall (for the rapid subsidence ratio see e.g. Dvořák 1994). However, this out-ward lateral extrusion started already during D_2 stage and was passing continuously to D_3 stage. The E-ward extrusion of the accretion prism thrusts caused, together with the dextral wrenching on the Sudetic (WNW and/or NW trend) transcurent shear zones, a recent E-ward shape convexity of the Lugosilesian orocline (Figs. 1 and 11).

The top-to-W normal shearing, with the WSW trend of stretching lineations L_{S3} at the western edge of Silesicum in the footwall of the Ramzová and Nýznerov thrusts, followed the period of their sinistral transtensional activity linked to the top-to-SE indentation of the subtriangular Orlice-Sněžník Unit over the Brunovistulian foreland (see Fig. 6). The second main reason is connected with the general gravitational collapse (see Stehltenpohl et al. 1993) of overthickened Late Variscan crust linked also to the intrusions of the late Variscan S-type granitoid bodies (like the Žulová pluton, Krkonše-Jizera granite massif – 328 Ma – Pin et al. 1988, dike-intrusions of semi- and/or lamprophyres – 302 Ma Dvořák – Přichystal 1982 etc.).

In spite of the late-Variscan wide-spread extension (with an ENE trend of X-axis of finite strain ellipsoid and stretching lineations), we have to verify the transpressional character of the Ramzová and Nýznerov overthrusts in the previous $D_1 \rightarrow D_2$ deformation stage during an early-Variscan oblique collision of the Sněžník nappe with the Silesian oblique ramp. The subequatorial (ENE-WSW) transtension was, according to us, the rightful consequence of transpressional overthickening of an accreted crust in the special tectonic setting of wide dextral wrench zone of Lugicum area (Grygar 1988, 1992).

The sub-perpendicular interrelation between the stretching lineations in the hangingwall Orlice-Sněžník Unit and the footwall Silesicum and Zábřeh units (Fig. 6) display a typical pattern discussed by Ellis and Watkinson (1987) for the other orogens with an oblique tectonics regime. A subequatorial trend of stretching lineations in the Zábřeh and Silesicum units reflects the NNW-SSE oriented plate motion and global stress fields during the gradual Variscan s.l. orogeny oblique convergence.

Also, the transtensional asymmetric halfgraben of the Boskovice and Orlice furrows of the submeridional trend, filled by the uppermost Carboniferous up to lower Permian continental molasse sediments, represent typical intramountain basins of the latest brittle stage of the upper crust of the Variscan orogen, oriented subperpendiculary to the maximum of tension stresses indicated by the stretching lineations. Also, Havlena (1982) referred the superposition of the trough with a NNW trend (perpendicular to the axis of regional transtension – Grygar et al. 1989), filled with Westphalian continental coal-bearing sediments over the NNE striking paralic molasse of the Upper Silesian Coal Basin.

Finally, we may conclude that one of the main open questions of proposed synthesis is the accurate dating. The detailed correlation of succession of deformation phases in the Moravosilesian Zone of the orocline is still problematic, because of the lack of isotopic data especially from the Silesicum crystalline (except some new data presented by an unpublished contribution of Maluski – Rajlich 1993) and especially from the Zábřeh Unit for which till now data are completely missing. The pre-Devonian deformation dating in the Zábřeh and Silesicum units and their correlation with the equivalent phases in the Orlice-Sněžník Unit, for which important data have been published recently, is impossible without progress in this research field.

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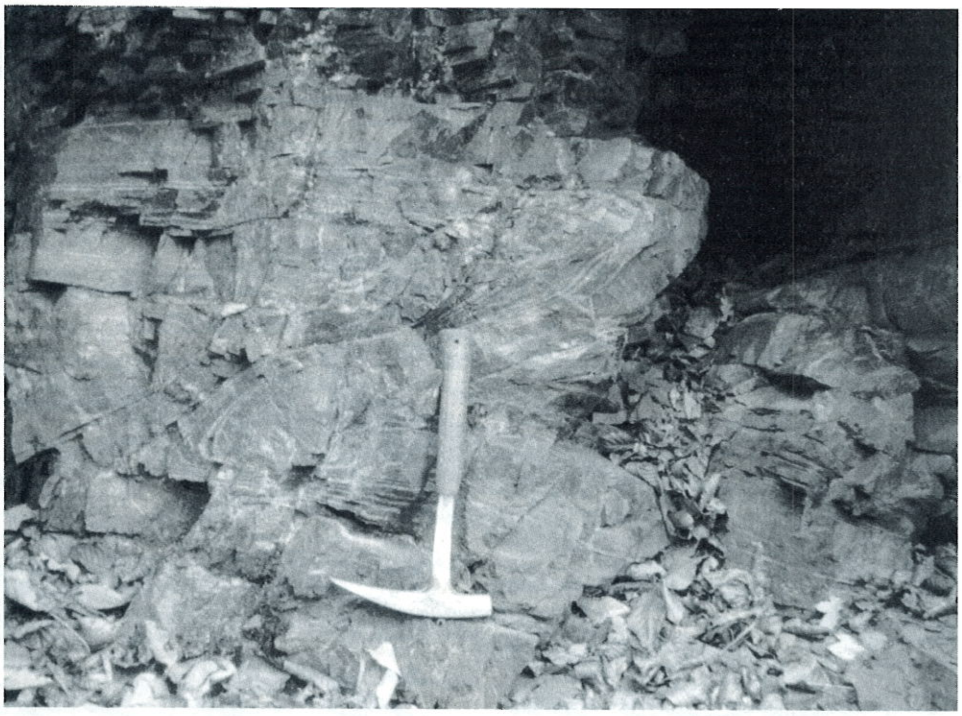
Vývoj lužicko-slezské oroklíny (severovýchodní okraj Českého masívu): Kinematika variské deformace

Severovýchodní okraj Českého masívu byl konsolidován během dlouhotrvající polyfázové variské s.l. orogeneze, mající charakter subekvatoriální kosé kolize vnitřních zón variského akrečního klínu s „mikrokontinentem" (terranem) brunovistulika. Toto k J vybíhající předpolí postupujícího akrečního klínu reprezentuje mozaika dílčích jednotek („masívů"), které byly velmi pravděpodobně původně odděleny a pak společně akretovány k Baltice v průběhu kaledonské orogeneze.

Regionální kinematická analýza poměrně rozsáhlé oblasti vnitřních zón variského akrečního klínu – tj. orlicko-kladského (sněžnického) krystalinika a jeho obalových jednotek – dokládá synmetamorfní raně variský tektonický transport (příkrovové sunutí) k SSZ ve spodních korových etážích. Raně devonská kolize s j. okrajem předpolí – Brunií – následně vyvolala vsv.-zjz. transtenzi tohoto předpolí – tj. kosý rifting kadomského patra brunovistulika. Severozápadní postup variské akreční fronty je dokumentován zejména a-lineacemi roztažení v duktilně deformovaných rulách sněžnického krystalinika. Díky původnímu sz.-jv. směru omezení z. okraje předpolí brunovistulika měla kolize v moravskoslezské zóně Českého masívu zřetelně kosý dextrální charakter. Pozdně variské transpresní zkrácení způsobilo nárůst mocnosti kůry doprovázený zpětnými násuny k JV, a to zejména v zábřežském krystaliniku a silesiku. Pozdně variská transtenze (dokumentovaná ve zmíněných jednotkách L_{S2} lineacemi roztažení mladší generace vsv.-zjz. směru) zákonitě následovala zmíněný nárůst mocnosti kůry vnitřních akretovaných domén. Gravitační kolaps orogenu a rozsáhlá laterální extruze vnitřních zón ve směru maximální vsv.-zjz. extenze byly doprovázeny intruzemi S-granitoidů a vznikem tenzních příkopů (brázdy boskovická a poorlická).

Pozdně variské až post-variské dextrální směrné posuny na zsz.-vjv. zlomech sudetského směru následně dotvářely podobu typického ohybu variského orogenu do „příčného" moravskoslezského směru. Je tak dokončen dnešní strukturní obraz lužicko-slezské oroklíny.

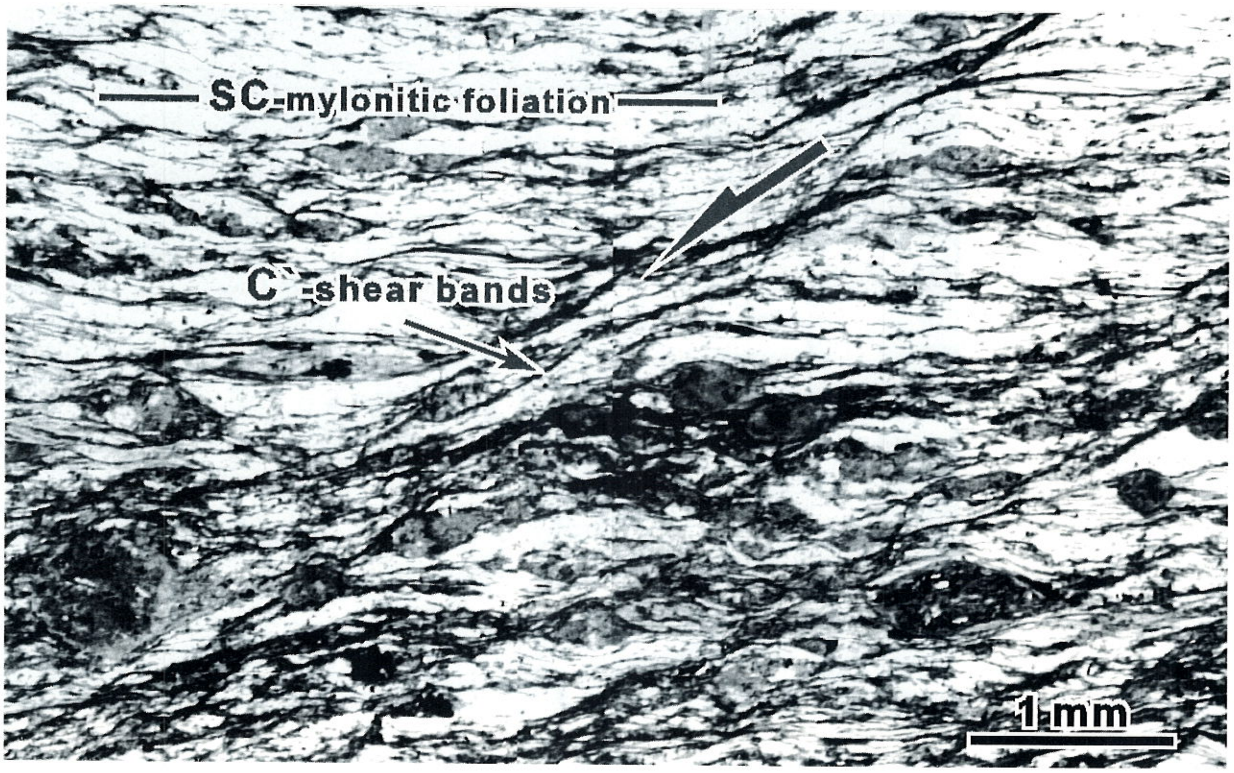
R. Grygar – M. Vavro: Evolution of Lugosilesian Orocline (Northeasthern periphery of Bohemian Massif): Kinematics of Variscan deformation (Pl. I)



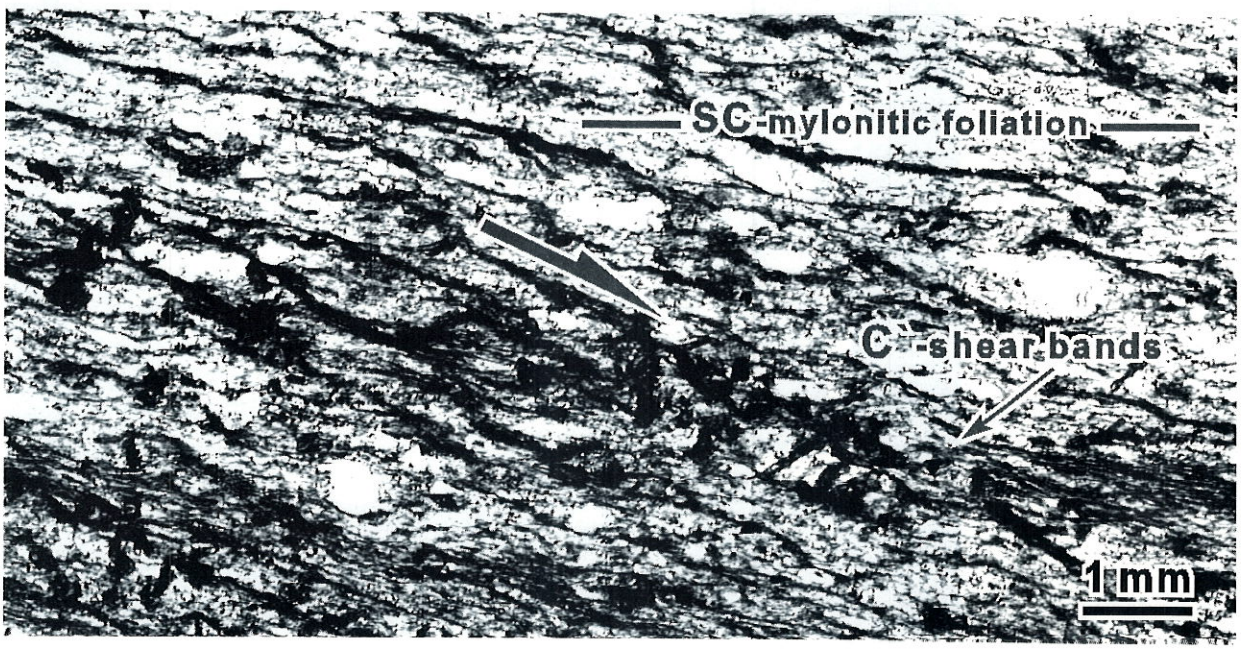
1. Noncylindrical F_{1-2} sheath-like fold (b-axis = 350/10) with eastern assymetry in banded gneisses near Nýznerov (Staré Město Group). The fold axes and corresponding intersection lineations are due to strong internal rotation during polyphase incremental dextral shearing nearly subparallel with X-axis of final regional strain ellipsoid (stretching lineations in the Sněžník Unit). View is to N

2. The C`-shear bands (extensional crenulation cleavage) which display top-to-south shearing (stretching lineations $L_{S2}$ = 170/46 on the planes of C`-bands 194/48). Coarse grained, banded „reddish" orthogneisses of Sněžník type. Locality Zemská brána – about 3 km NE of Klášterec n/Orlicí) in the Pastviny flexure zone. View is to E

R. Grygar – M. Vavro: Evolution of Lugosilesian Orocline (Northeasthern periphery of Bohemian Massif): Kinematics of Variscan deformation (Pl. II)



1. The SC-mylonites (micaceous schists from the road-cut outcrop between Branná and Hanušovice – Staré Město Group in the zone of Ramzová thrust) with C`-shear bands corresponding to the top-to-WSW shearing in the latest transtensional deformation stage linked to the post-collisional collapse of orogen. Parallel polarizers



2. Quartz metaconglomerate – SC-mylonites with C`-shear bands from the Hoštejn shear zone (central part of Zábřeh Group, outcrop in the Hoštejn village), indicate dextral strike-slip kinematics on the WNW shear zones (compare with Fig. 6). Parallel polarizers