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Cleavages and Folds in Changing Tectonic Regimes: The Veľký Bok Mesozoic Cover Unit of the Veporicum (Nízke Tatry Mts., Central Western Carpathians)

DUŠAN PLAŠIENKA

Geological Institute of the Slovak Academy of Sciences, Dúbravská cesta 9, 842 26 Bratislava, Slovakia

(6 figs., 2 pls.)

Abstract: The Mesozoic Veľký Bok cover unit on northern slopes of the eastern part of the Nízke Tatry Mts. forms the rear, paraautochthonous part of the Krížna nappe system. It is built of several recumbent fold subunits partly differing in their lithostratigraphical signatures. Fold subunits were generated by northward thrusting of the Veporic basement in the rear of the Krížna accretionary wedge, which was later destroyed by gravitational collapse and northward gliding. The Veľký Bok unit suffered additional collisional shortening and backthrusting before being overridden by the higher Choč cover nappe during the Late Cretaceous. The structural associations of several successive deformation stages are described and some aspects of tectonic evolution of the area are discussed.

Key words: Krížna Nappe, Veľký Bok unit, Mesozoic lithostratigraphy, Cretaceous thrusting, tectonic regimes, structural analysis

Introduction

Sedimentary rock sequences with alternating strata of different compositions and competencies, deformed under very low to low grade metamorphic conditions, usually provide a reliable structural record of changing tectonic regimes in a certain orogenic domain. In the Alpine-Tethyan regions, the complicated Mesozoic paleotectonic evolution generated sedimentary successions with variable, although mostly carbonatic lithologies. In the inner zones of orogenic belts, marked by stacking of basement/cover nappes, metamorphism and often penetrative ductile deformation, the primary lithological differences are reflected in rheological layering of sedimentary rock units and occasional recording of changing deformation processes acting within a certain time span. Beautiful examples of lithological and rheological control over the structural recording of deformation processes have been given e.g. by RAMSAY (1967, 1982), BORRADAILE et al. (1982), TALBOT and SOKOUTIS (1992), or PFIFFNER (1993) in large-scale nappe tectonics.

The common tectonic evolution of internal orogenic zones, as can be inferred from structural associations in sedimentary cover units, includes:

(a) shortening through nappe piling and crustal thickening, very low to medium grade metamorphism (depending on the burial depth) and ductile straining usually along flat-lying overthrust shear zones. The index mesoscopic structures are: penetrative bedding-parallel metamorphic foliation, stretching lineation normal to the orogenic front and several generations of intrafolial or recumbent, tight to isoclinal folds;

(b) ductile unroofing of uplifting metamorphic core complexes, extension and transtension, recorded by orogen-parallel stretching lineation within low-angle normal shear zones, possible gravitational gliding of cover units;

(c) out-of-sequence thrusting along steep reverse faults under decreasing ductility, backthrusting and transpression, with mesoscale structures such as high-angle secondary cleavages (usually crenulation), related to late open to tight orogen-parallel trending folds;

(d) "cross folding" along zones with high angles to the orogenic fronts, reflecting oroclinal bending and transpression of internal zones, possibly connected with lateral escape of crustal blocks. Mesoscale structures are typically brittle:kink bands, parallel flexural-slip folds, several sets of joints and slickensides.

Depending on the degree of shortening and crustal thickening achieved during (a) and crustal and lithospheric thermomechanical parameters, the tectonic development proceeds from (a) to (b) and to (d), or from (a) to (c) and (d).There have been described numerous case histories, based on detailed structural and metamorphic studies, for in-

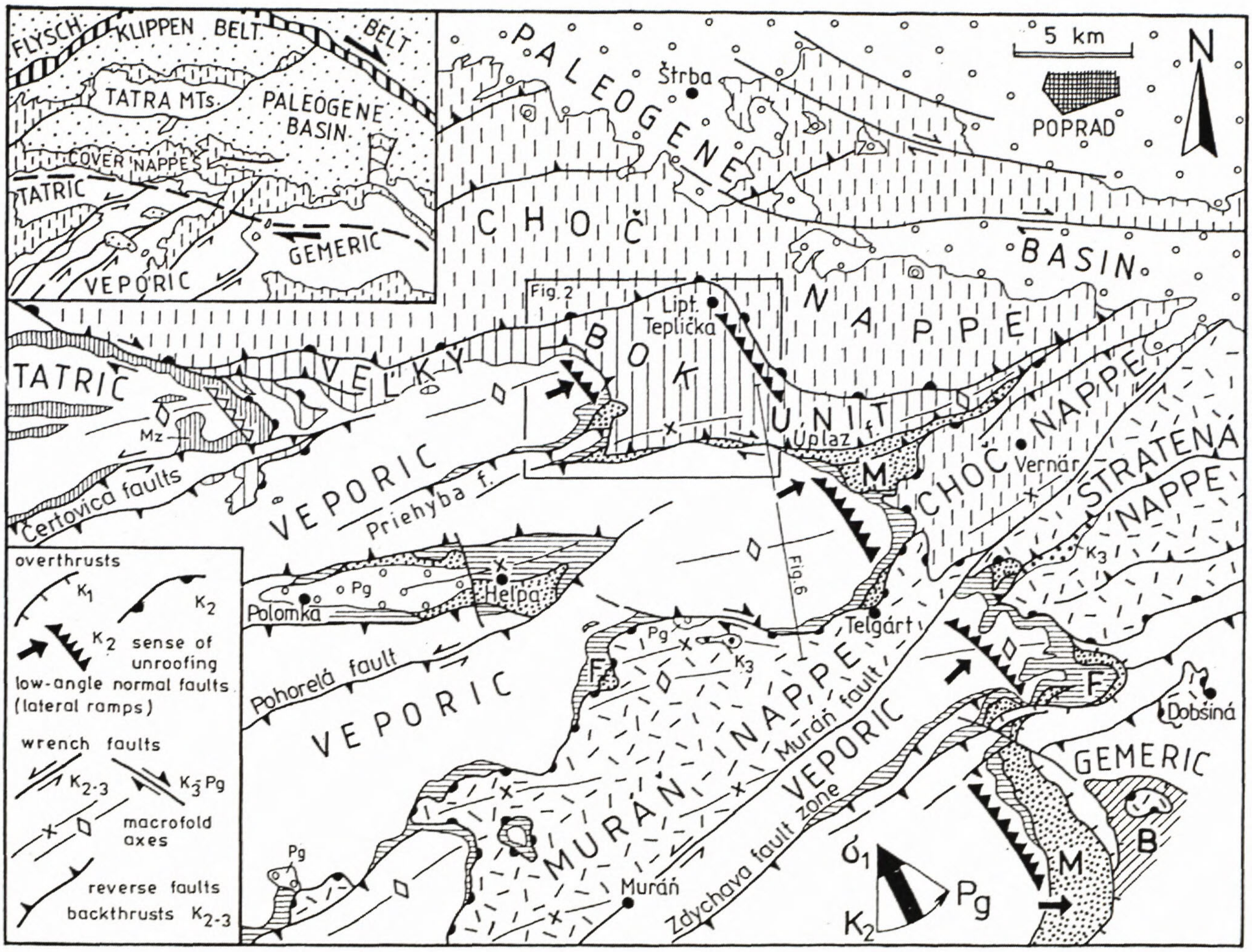


Fig. 1 Tectonic sketch and kinematic framework of principal large-scale structures of eastern part of the central Slovakian Veporic domain. Inset - spatial separation of areas with prevailing sinistral and dextral wrenching in northern Slovakia during the Late Cretaceous and Early Tertiary. The rectangle frames the area examined in this paper (Fig. 2). Abbreviations: F - South Veporic Foederata cover unit (Permian - Triassic), M - South Veporic Markuška Nappe (Devonian - Triassic), B - Meliatic Bôrka Nappe (Permian - Triassic).

stance in the Alps (AYRTON and RAMSAY, 1974; WILSON, 1978; PASSCHIER et al., 1981; SIMPSON, 1982; PLATT and LISTER, 1985; RATSCHBACHER, 1986; PLATT et al., 1989; RATSCHBACHER et al.,1990; SCHULTZ, 1990; HOKE,1990; FRITZ et al.,1991; FROTZHEIM,1992; NEUBAUER ET AL.,1992; HANDY, 1993 etc.), in the Betic Cordilleras (PLATT, 1982; BAKKER et al., 1989; TUBÍA et al.,1992), in the Himalayas (LE FORT, 1975; BURG et al., 1983, 1984), or in the Circumpacific orogens of America (NELSON et al., 1980; NIELSEN, 1982; MATTAUER et al., 1983; MALAVIEILLE, 1987; GOTTSCHALK, 1990). Similar tectonic scenario is common also for the pre-Mesozoic orogenic belts, e.g. for the Caledonides of Northern America and Europe (TEARPOCK and BISCHKE, 1980; KARLSTROM et al., 1982; GOLDSTEIN, 1982; KRUHL,1984; TULL, 1984; GATES, 1987; STELTENPOHL and BARTLEY, 1988), or Variscan belt of Europe (CYMERMAN and STELTENPOHL, 1992; SCHULMANN et al., 1994).

Sometimes (b) and (c) are acting in a close relation or even simultaneously, when uplift and unroofing occur in an overall contractional tectonic setting (e.g. the mid-Cretaceous uplift of the Veporic dome in the Central Western Carpathians - PLAŠIENKA and PUTIŠ, 1993; PLAŠIENKA, 1993; for the general model see WALLIS et al., 1993, and references therein).

The aim and scope of the present paper is to describe the structural record in the Veľký Bok cover unit of the northern Veporic zone, illustrated by a case study in the Liptovská Teplička district, to present its kinematic interpretation and to discuss some aspects of large-scale tectonic structure of the eastern part of the Nízke Tatry Mts.

Regional geology

The Veľký Bok unit is the Permomesozoic sedimentary cover of the pre-Alpine, generally Variscan, crystalline basement of the northern part of the Veporic superunit of the Central Western Carpathians. Veporicum is a thick-skinned upper-crustal thrust sheet overriding the Tatric superunit and partly overthrust by the Gemeric sheet from the SE. Veporicum is subdivided into several partial basement imbrications, defined from surface geology already by ZOUBEK (1931, 1935) and from the Carpathian deep seismic transect 2T (TOMEK et al., 1989, TOMEK, 1993). Generally, Veporicum has been usually correlated with the (Middle) Austroalpine system of the Eastern Alps (cf. HÄUSLER et al., 1993 and references therein), derived from the northern passive Apulian margin (TOMEK, 1993).

The Veľký Bok unit, exposed on the northern slopes of the Nízke Tatry Mts. (Fig. 1), consists of Permoscythian arcosic and quartzose sandstones and variegated shales, Middle Triassic carbonate platform sediments, presumably dolomites, Upper Triassic marine siliciclastic flyschoid Lunz beds and terrestrial-lagoonal Carpathian Keuper formation of variegated shales, sandstones and evaporites. Permotriassic sediments create the pre-rift sequence, the Lower Jurassic syn-rift strata contain some carbonate breccias, sandy crinoidal limestones and calciturbiditic beds. The Middle Jurassic to Lower Cretaceous post-rift sequence is composed mostly of marly, siliceous, or nodular pelagic limestones. The Veľký Bok unit encompasses several more or less independent tectonic subunits (large-scale recumbent folds, partial nappes), in which the lithostratigraphic content slightly varies and indicates their paleogeographic position on a northward facing basinal slope. This slope has been interpreted as a southern passive margin of the broad Krížna (Zliechov) deep-water trough developed by Jurassic rifting and lithospheric extension between the Tatric and Veporic paleogeographic domains (PLAŠIENKA, 1983). The Zliechov basin was diminished by the mid-Cretaceous shortening and its attenuated continental crust was underthrust below the Veporic crustal wedge. The sedimentary filling of the basin was detached from its subducted substratun along a horizon of Upper Scythian (Werfenian) shales, piled up in an over-thickened accretionary complex, and gravitationally spread out towards the north during the Turonian, to form the extensive décollement Fatric (Krížna) nappe system overlying the Tatric Mesozoic cover. The origin of the Krížna nappe has been discussed e.g. by BIELY and FUSÁN (1967), ANDRUSOV (1968), JAROŠ (1971), BIELY (1978), MAHEĽ (1983), PLAŠIENKA (1983, 1991, 1995) and JACKO and SASVÁRI (1990).

Along the rear of the Krížna nappe, the Veľký Bok unit remained more or less confined to the Veporic basement, i.e. in intermediate position between the allochthonous nappe and paraautochthonous Veporic cover. In the studied area, however, it is completely detached from the Veporic substratum and its position is influenced by post-nappe oblique backthrusting.

The Veľký Bok unit, similarly as the whole Krížna Nappe, is overlain by another décollement cover nappe group - the Hronic (Choč) system. This was detached from the presently unknown basement and glided gravititionally with some delay after the emplacement of the Fatric nappes. Their overthrust base is marked by sometimes noteworthy thick rauhwackized carbonate tectonic breccias (see Fig. 3, 4, Pl. II-5), pointing to a hydrotectonically controlled thrusting mechanism.

The structure of the Veľký Bok unit in the area under consideration was studied especially by KETTNER (1937a, b) and ZELMAN (1963, 1967a, b).

Lithostratigraphy

Based on the structural position and lithostratigraphic content, the Veľký Bok unit is divided into three subunits in the area studied:

(1) The Košariská subunit contains only a Jurassic-Lower Cretaceous sequence detached from its Triassic substratum along the Keuper shales and evaporites. It is composed mostly of deep-water pelagic calcareous sediments correlable with a typical sequence of the Krížna (Zliechov) development of the Fatricum. However, due to very low to low grade metamorphism, the whole Veľký Bok unit is very poor in stratigraphically valuable fossils.Therefore, the stratigraphic correlation is

based mainly on lithological criteria.The lithostratigraphical succession is as follows:

(a) Liassic biodetritic crinoidal limestones and grey marly shales, maximum 100 m thick;

(b) greenish-grey siliceous and marly limestones (roughly Dogger - Oxfordian), 100-200 m thick;

(c) pale greenish and pinkish nodular limestones (Kimeridgian), up to 100 m thick;

(d) thick-bedded light grey limestones containing rare Calpionellids (Tithonian, Jánov 1978),100-200 m thick;

(e) thin-bedded to schistose grey, sometimes purple-red marly limestones and marlstones (Neocomian), more than 300 m thick.

The Košariská subunit continues westward as a W-E trending strip and forms the main structural unit in the Ipoltica, Veľký Bok and Malužiná area (Fig. 1).

(2) The Panská hoľa subunit is composed of:

(a) thick complex of Middle to Upper Triassic, thick-bedded to massive dolomites;

(b) the upper part of the dolomite complex is intercalated by a discontinuous, maximum 50 m thick layer of the Lunz beds - alternating dark grey shales and sandstones (Carnian);

(c) the Carpathian Keuper formation (Norian) contains red shales, evaporitic dolomites and sporadic quartzose sandstones, up to 300 m thick;

(d) Lower Jurassic thick-bedded pale grey or pinkish cherty crinoidal limestones, intercalated by grey marly limestones and shales. Sometimes marlstones prevail and biodetritic limestones form occassional graded calciturbiditic beds, resembling the Allgäu formation. The thickness may reach 100-200 m.

The Panská hoľa subunit builds up the southern part of the area studied and continues eastwards into the narrow strip NW of Vernár (Fig. 1), where it contains complete Jurassic to Lower Cretaceous sequence.

(3) The Smrečiny subunit occupies an intermediate structural position between the Košariská and Panská hoľa subunits. However, its restored paleogeographical position is in the southernmost, marginal shelf setting, confined to the Veporic basement. It consists of:

(a) Middle to Upper Triassic dolomites;

(b) sparsely preserved remnants of the Carpathian Keuper rocks;

(c) Lower Jurassic extraclastic breccia limestones directly overlying dolomites and filling the fissures and cavities in them. The Lunz beds and Carpathian Keuper formation are usually missing in this subunit;

(d) thick complex of Liassic cherty crinoidal limestones and marlstones (up to 200 m - Fig. 3, 4);

(e) grey-brown, Mn-bearing marly shales and crinoidal limestones (probably Toarcian, about 50 m);

(f) Middle to Upper Jurassic grey-green marly limestones and marlstones, more than 200 m thick.

This subunit is specific for the area and has no equivalents, as far as its lithofacial development is concerned, in other locations of the Veľký Bok unit exposures.

Structural geology

Sedimentary rock complexes of the Veľký Bok unit were deformed mostly under anchizonal metamorphic conditions (PLAŠIENKA et al., 1989) during the mid-Cretaceous orogenic contraction period of the Central Western Carpathians, followed by Late Cretaceous - Tertiary superimposed, mostly brittle deformations. The structural rock record involves several sets of cleavages, folds, lineations, veinlets and fractures, developed during two principal and several additional Alpine deformation stages (AD). The general trend of straining proceeded from ductile, thrusting-related deformation, through ductile-brittle oblique reverse faulting and backthrusting to brittle strike-slip faulting and transpression (Fig. 5).

AD_1 stage

The first recognizable structural paragenesis consists predominantly of bedding-parallel metamorphic foliation S_{01}, stretching lineation L_1 and cm- to dm- large flow folds F_1.

Spaced foliation S_{01} is well developed only in calcitic rocks, especially marlstones, where it is represented by solution cleavage surfaces enriched in insoluble quartz - fine grained white mica - opaques residuum. The penetrative planar ductile fabric of calcite-rich domains is less frequent, achieved by slight dynamic recrystallization and twinning of larger calcite grains, e.g. crinoid ossicles.

The flattening strain responsible for the formation of S_{01} foliation is documented also by flattening of limestone and chert nodules, buckling of calcite veinlets perpendicular or oblique to foliation (Pl. I-4) and boudinage and pinch-and-swell structures indicating foliation-parallel extension (Pl. I-3).

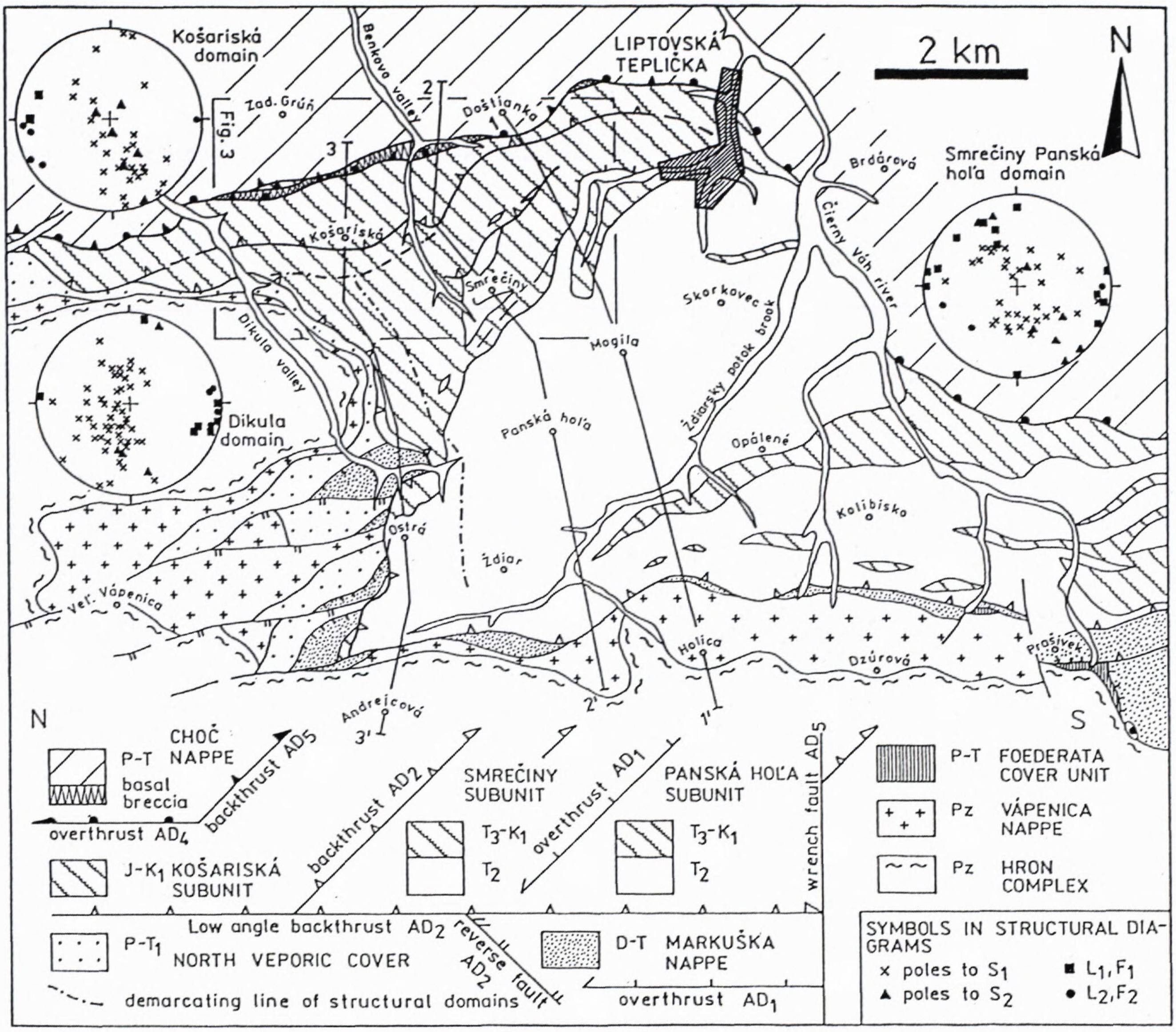


Fig. 2 Principal tectonic and structural domains of the investigated area. Rectangle indicates the area depicted in Fig. 3, lines the profile sections (Fig. 4). Structural diagrams are lower hemisphere, equal-area plots.

Fine-grained white micas from the insoluble material along S_{01} surfaces were dated by the K-Ar method, giving the formation model age of 101 Ma (NEMČOK and KANTOR, 1989).

The S_{01} foliation surfaces sometimes exhibit elongation and segmentation of quartz-mica aggregates or clusters of calcite grains defining the weak stretching lineation L_1. It trends generally NW-SE (Fig. 2). Foliation S_{01} represents the XY plane and lineation L_1 the X axis of the AD_1 strain ellipsoid.

The folds F_1 deforming the S_{01} foliation are very rare, restricted to high-strain ductile shear zones in limy and marly rocks.They are close to the similar type (Pl.I-1, 2), intrafolial flow folds generated by passive amplification of buckling instabilities within an inhomogeneously shear-flowing medium (PLATT, 1983).

Small-scale ductile/brittle, bedding-parallel shear zones indicating generally top-to-the north thrusting occur within the Lower Jurassic marly sequences of the Panská hoľa and Smrečiny subunits (Pl. I-5). North-directed sense of movement within bedding-parallel ductile shear zones was observed also by ZELMAN (1967b), based on deformation features of chert nodules.

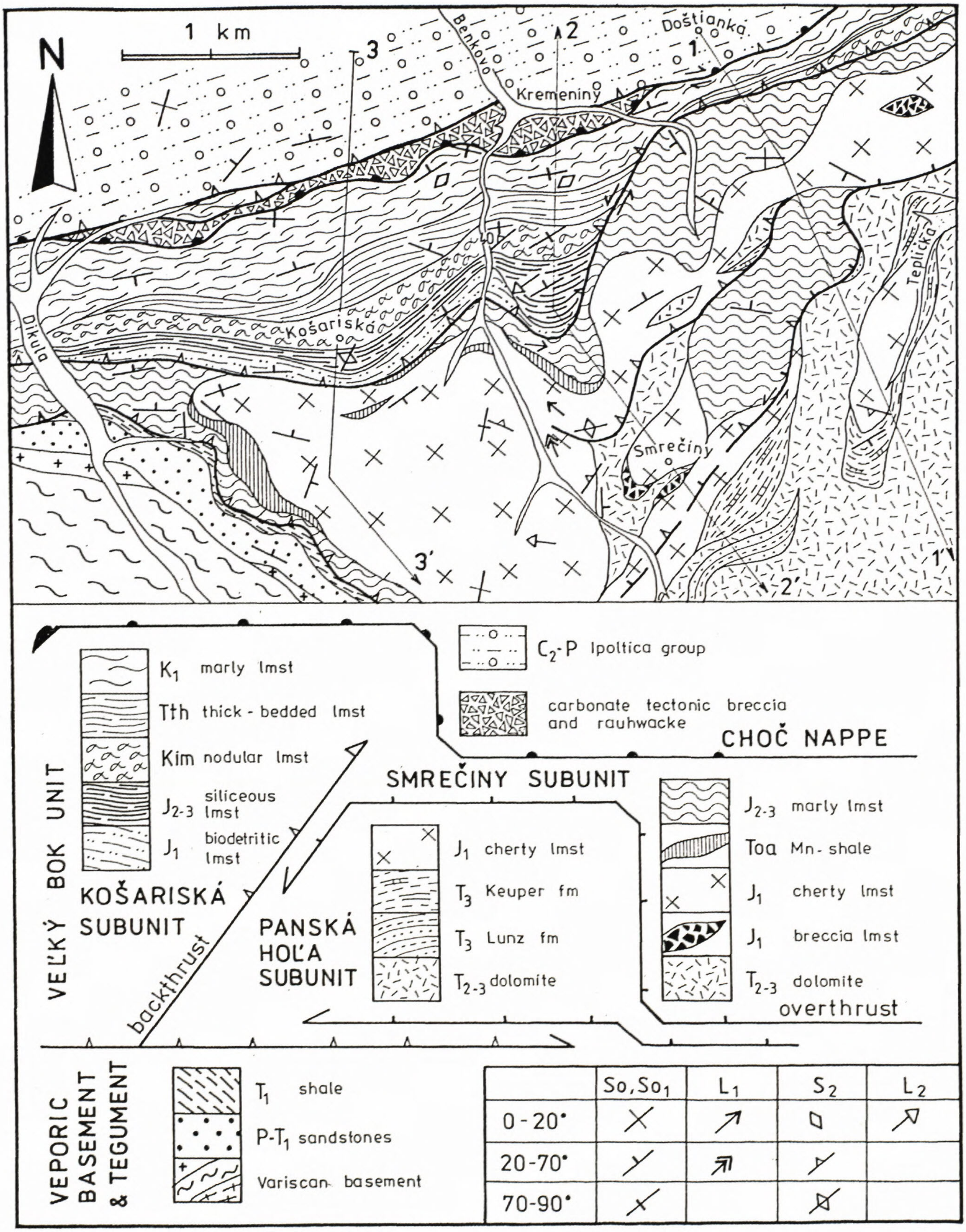


Fig. 3 Geologic-tectonic map of a part of the studied area. Profiles are presented in Fig. 4.

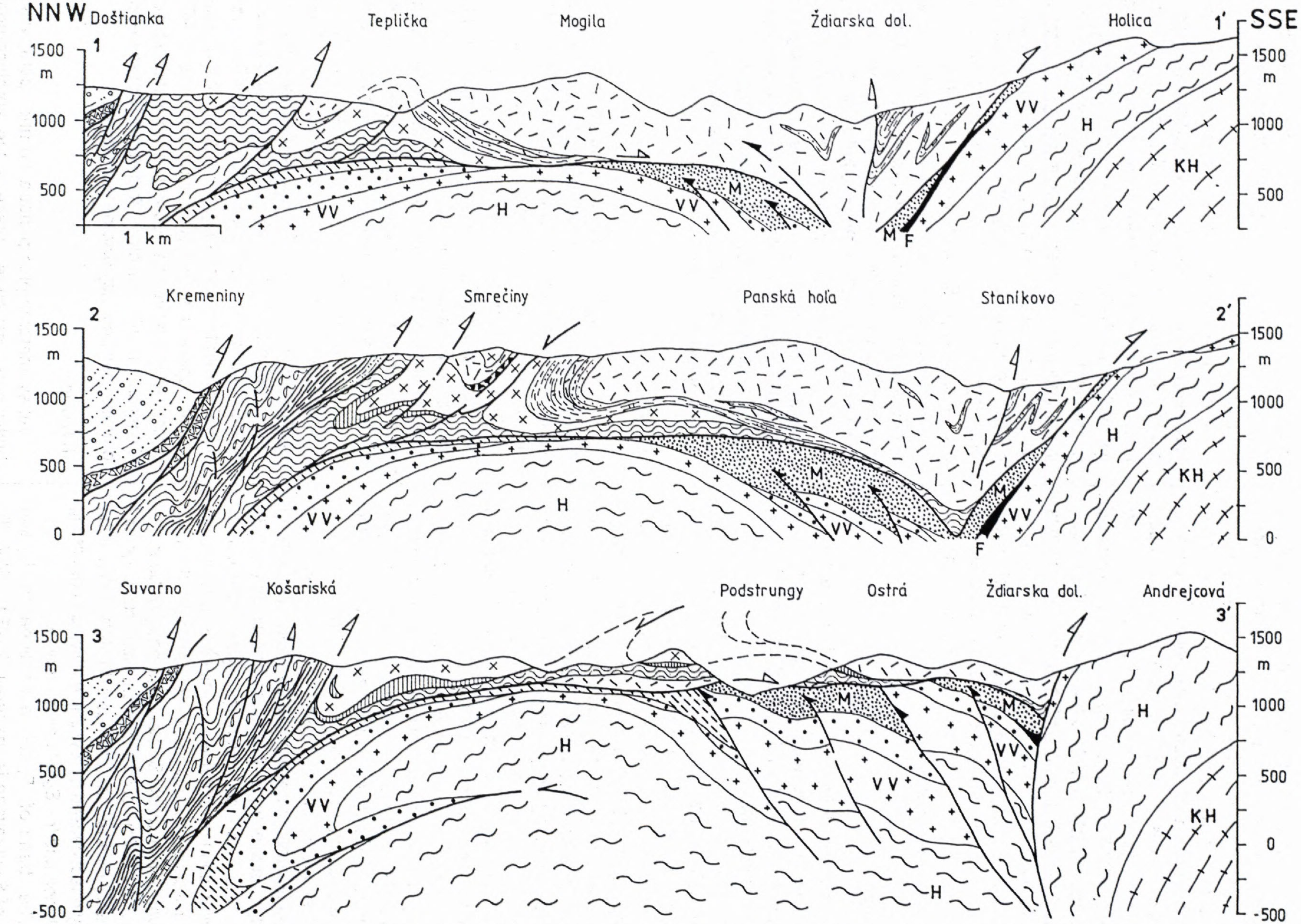


Fig. 4 Tectonic profiles of the area. For the legend see Fig. 3. Additional basement units: M - South Veporic Markuška Nappe (PLAŠIENKA, 1984), VV - Vápenica tonalite nappe (PUTIŠ, 1989), H - metamorphic rocks of the Hron complex (sensu KLINEC, 1966), KH - granitoids of the Kráľova hoľa complex (KLINEC, 1966).

This first structural paragenesis is interpreted to have been initiated by large-scale recumbent folding and overthrusting of partial fold nappes producing tectonic burial sufficient for very low grade metamorphism and ductile straining. Macroscopic recumbent folds to anticlinal synforms have been revealed by geological mapping (Fig. 3, 4; see also KETTNER, 1937a). Both meso- and macroscopic criteria indicate top-to-the N to NW sense of thrusting.

The Panská hoľa and Smrečiny partial subunits were individualized mainly during this stage as recumbent fold nappes. Both have probably overlain the outermost Košariská subunit, however, the present arrangement of the subunits is mainly the result of AD_2 backthrusting.

AD_2 stage

The second deformation stage is characterized particularly by crenulation cleavage S_2 parallel to axial planes of the F_2 folds which deform the AD_1 structural elements.

Solution cleavage S_2 is formed at high angles to primary bedding and bedding-parallel foliation S_{01}, best developed in calcite-rich rocks. Many types ranging from discrete to zonal crenulation cleavage (GRAY,1979) are present. The cleavage spacing and morphology reflect the rock medium. Mesopenetrative planparallel S_2 cleavage has been observed in marly schistose Jurassic and Lower Cretaceous limestones, discontinuous anastomosing surfaces occur in nodular and thick-bedded Upper Jurassic limestones (Pl. I-6).

Intersection of bedding S_0 and foliation S_{01} with cleavage S_2 produces lineation L_2 which is generally axial-parallel to the folds F_2. These are open to tight, upright to overturned, usually asymmetric buckle folds with southern vergency. Formation of crenulation cleavage S_2 slightly postdates the development of initial flexural curvature of the F_2 folds, because of cleavage parallelism in fold cores and limbs (Pl. II-3). Hence the final fold tightness was achieved by flattening along penetrative axial-plane S_2 cleavage. F_2 Folds resemble the so-called "shear folds" (Pl. II-4), however, shear along S_2 cleavage has not been observed. In the limb domains, crenulation cleavage has apparently extensional character (Pl. II-2), which is an illusory effect caused by low angle between preexisting S_{01} foliation and the S_2 flattening surfaces.

The trend of F_2 fold axes, lineation L_2 and strike of S_2 cleavage is generally W-E to SW-NE. Poles to S_{01} and S_2 planes lie on common girdles (Fig. 2) what points to roughly homogeneous AD_2 deformation.

In the macroscopic scale, the most prominent feature of the AD_2 stage is a structural discordance between the cover and basement structures. Asymmetric south-vergent macrofolds are typical for the Veľký Bok cover rocks, while mostly north-directed thrust faults have been observed in the basement and its tegument (Fig. 4 - profile 3). To explain this discordance, a backthrust superposition of the cover during the final phases of the AD_2 stage is assumed. Backthrusting attained some 5 km along the profile in the Dikula valley (Fig. 2, 4).

The Košariská subunit, as the most external and lower one during the AD_1 stage, was exhumed and thrust back in the rear of the backthrust sheet composed mainly of the Panská hoľa and Smrečiny subunits. During backthrusting, the Veľký Bok subunits in the studied area covered the basement units and structures of originally more southern zones and cannot be ultimately regarded as autochthonous or paraautochthonous with respect to the Veporic basement.

AD_3 stage

Structures of this stage can be generally characterized as "cross folding" with NW-SE to N-S trend. They are marked, on the contrary to the AD_1 and AD_2 structures, by typically brittle elements.

The most conspicuous AD_3 structures are the mesoscopic folds F_3 - open, mostly angular (kink) folds or kink bands (Fig. 5). The reason for the origin of these cross folds is not clear. They might have been generated partly by dextral transpression along lateral or oblique frontal ramps during AD_2 backthrusting (e.g. the Dikula ramp, Fig. 1, 2). However, the compressional cross structures have regional extent in the Central Slovakian Veporic block, being at least partly confined to transversal NW-SE fault zones with dextral kinematics (e.g. the Mýto-Tisovec fault zone - MARKO, 1993). This reveals partial spatial and temporal independency of AD_3 structures indicative of a separate deformation stage. Genetical relation of cross folding to processes of oroclinal bending may also be considered.

AD_4 stage

All synmetamorphic penetrative and partly also brittle cross structures precede the emplacement

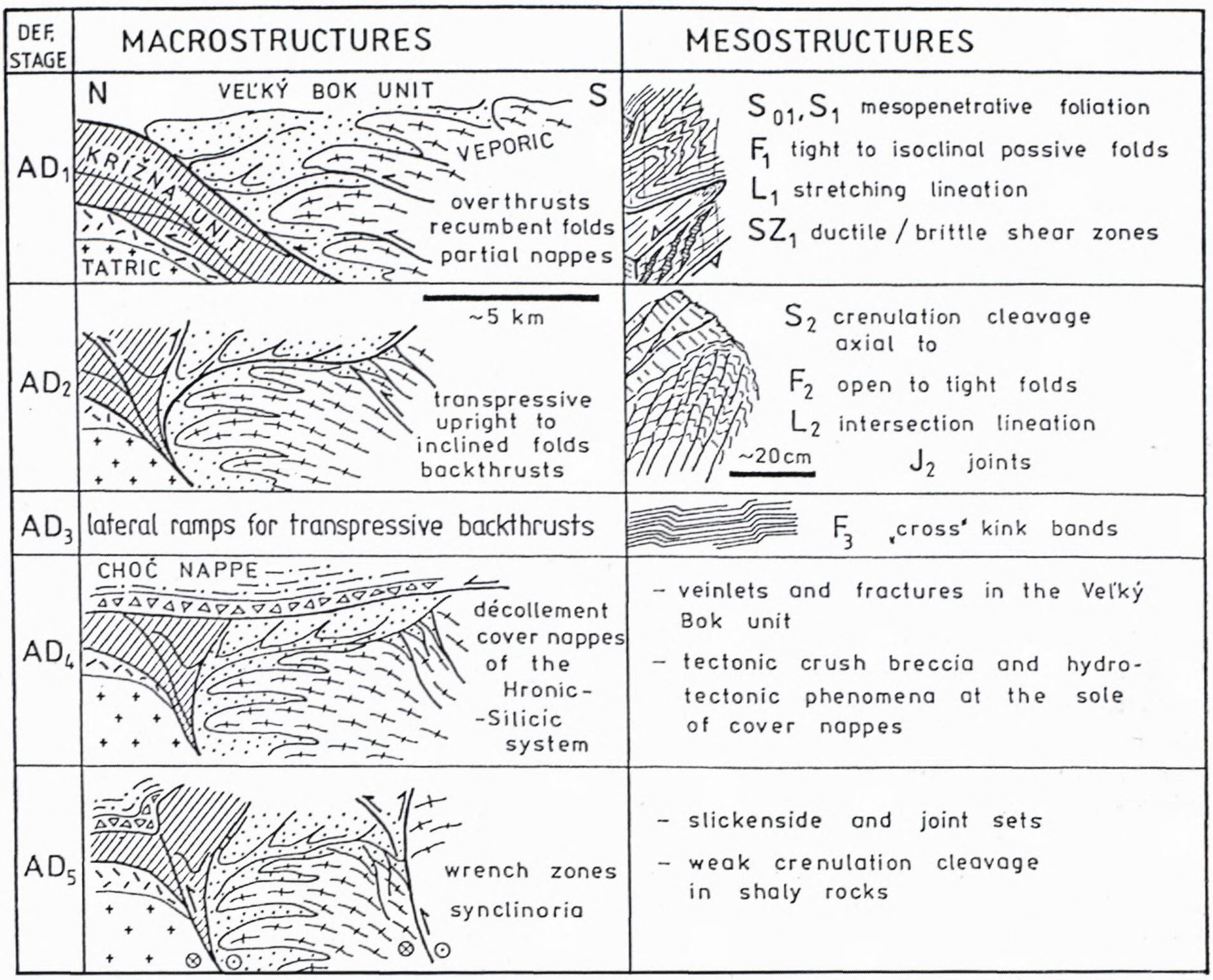


Fig. 5 Synoptic presentation of deformation stages and their main structural elements in the investigated area.

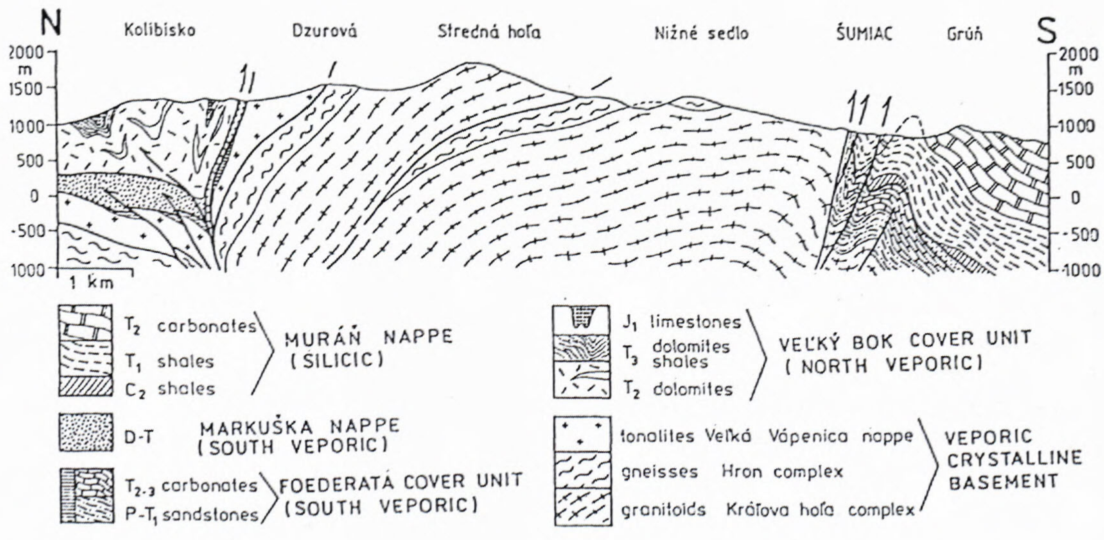


Fig. 6 Cross-section through the eastern part of the Nízke Tatry Mts. showing the transpressive character of boundary faults of the Veporic basement uplift.

event of superficial cover nappes of the Hronic-Silicic system. In the area of interest, thick volcanosedimentary complexes of the Upper Carboniferous - Scythian Ipoltica group belonging to the Hronic Choč nappe overrode the Veľký Bok subunit, mainly its Košariská subunit. The sole of the Choč nappe is formed by up to one hundred metres thick rauhwackized carbonatic tectonic breccia (the Kremeniny tectonic slice of ZELMAN, 1967a). The overthrust had no apparent influence on the structures of its Veľký Bok substratum, except some calcite-filled cracks as manifestations of hydrotectonic phenomena accompanying the thrusting. The breccia is composed of altered fragments of probably mostly Triassic carbonates, dominantly dolomites (Pl. II-5).

AD_5 stage

Post-nappe deformations are more obvious on macroscopic scale than on mesoscopic scale. Generally, AD_5 macrostructures copy the $AD_{2\text{-}3}$ ones, having developed in the kinematic framework of roughly N-S shortening with slight dextral transpression along NW-SE to WNW-ESE trending zones and sinistral transpression along SW-NE to WSW-ENE zones (Fig. 1). Some of these zones changed their kinematics in response to CCW rotation of the principal compression axis during the Early Tertiary.

Mesoscale AD_5 structures can be only rarely well defined. In the "Vernár strip" of the Choč nappe (Fig. 1), some traces of subvertical, NE-trending crenulation cleavage S_5 have been observed in the Upper Carboniferous shales. In the Veľký Bok unit of the same area, brittle chevron-type folds in marly slates are regarded as F_5 folds (Pl. II-6).

Several sets of joints and slickensides developed in the Veľký Bok unit were studied by NEMČOK and KANTOR (1989). They distinguished three principal phases of compression, the first with σ_1 directed to the SE (probably our AD_2 stage), the second with NE oriented compression (AD_3 in this work) and the third with N-S contraction (AD_5).

In the Veľký Bok unit, F_2 macrofolds were additionally tightened during AD_5 and sometimes rearranged into fan-wise forms in cross-sections due to slight transpression (Fig. 4, 6). In the investigated area, the originally flat basal plane of the Choč nappe was tilted northward into a steep, or even vertical position (Fig. 4). The adjacent $AD_{1\text{-}2}$ structures in the Veľký Bok rocks were occasionally also rotated to the north (Pl. I-6). This phenomenon can be tentatively explained by push-up of the crystalline core of the Nízke Tatry Mts. during the Late Cretaceous - Early Tertiary compression and transpression (Fig. 5, 6).

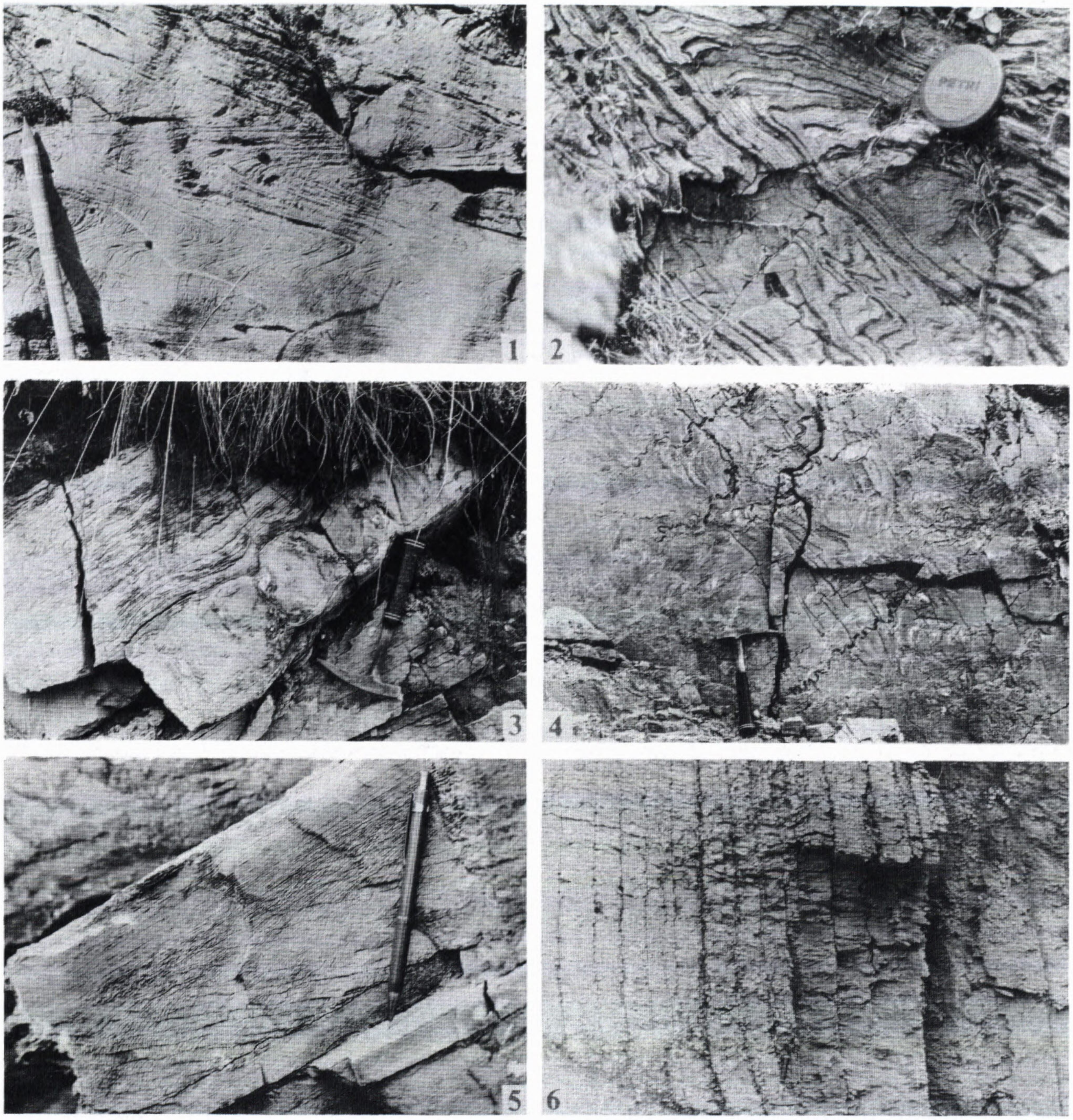
Discussion - Alpine tectonic regimes in the eastern part of the central Slovakian Veporic belt

Structural parageneses of the deformation stages described above record large-scale Alpine tectonic processes in the NE part of the central Slovakian Veporic domain. Tectonic structure and evolution of this part of the Central Western Carpathians is treated in numerous papers, the most outstanding being works of KETTNER (1937a, b, 1958), KUBÍNY (1959), BIELY (1961, 1964, 1978), BIELY and FUSÁN (1967), KLINEC (1966, 1971), BAJANÍK et al. (1979), PLAŠIENKA (1983, 1984, 1993), PUTIŠ (1987, 1989, 1991, 1994), VOZÁROVÁ and VOZÁR (1988), BEZÁK (1991), MARKO (1993), HÓK et al. (1993), MADARÁS et al. (1994) etc. Most of these authors have agreed that the Veľký Bok unit represents the rear part of the Krížna (Fatric) cover nappe system. Paleogeographically, the lithostratigraphical contents of its partial subunits reflect southward shallowing of the broad Krížna (Zliechov) basin developed on a thinned continental crust (JAROŠ, 1971; MAHEĽ, 1980; PLAŠIENKA, 1983). The subunits, usually large-scale recumbent folds, were generated by inversion of extensional north-facing normal faults (PLAŠIENKA, 1991). Some recumbent folds involve also the North Veporic basement, mainly in regions west of the studied area. From this point of view, the structural evolution of the Veľký Bok unit is regarded to reflect the tectonic regimes operative during the origin of the Krížna cover nappe (PLAŠIENKA, 1983), as well as during the subsequent deformation phases of its "root zone", which is an intracontinental suture.

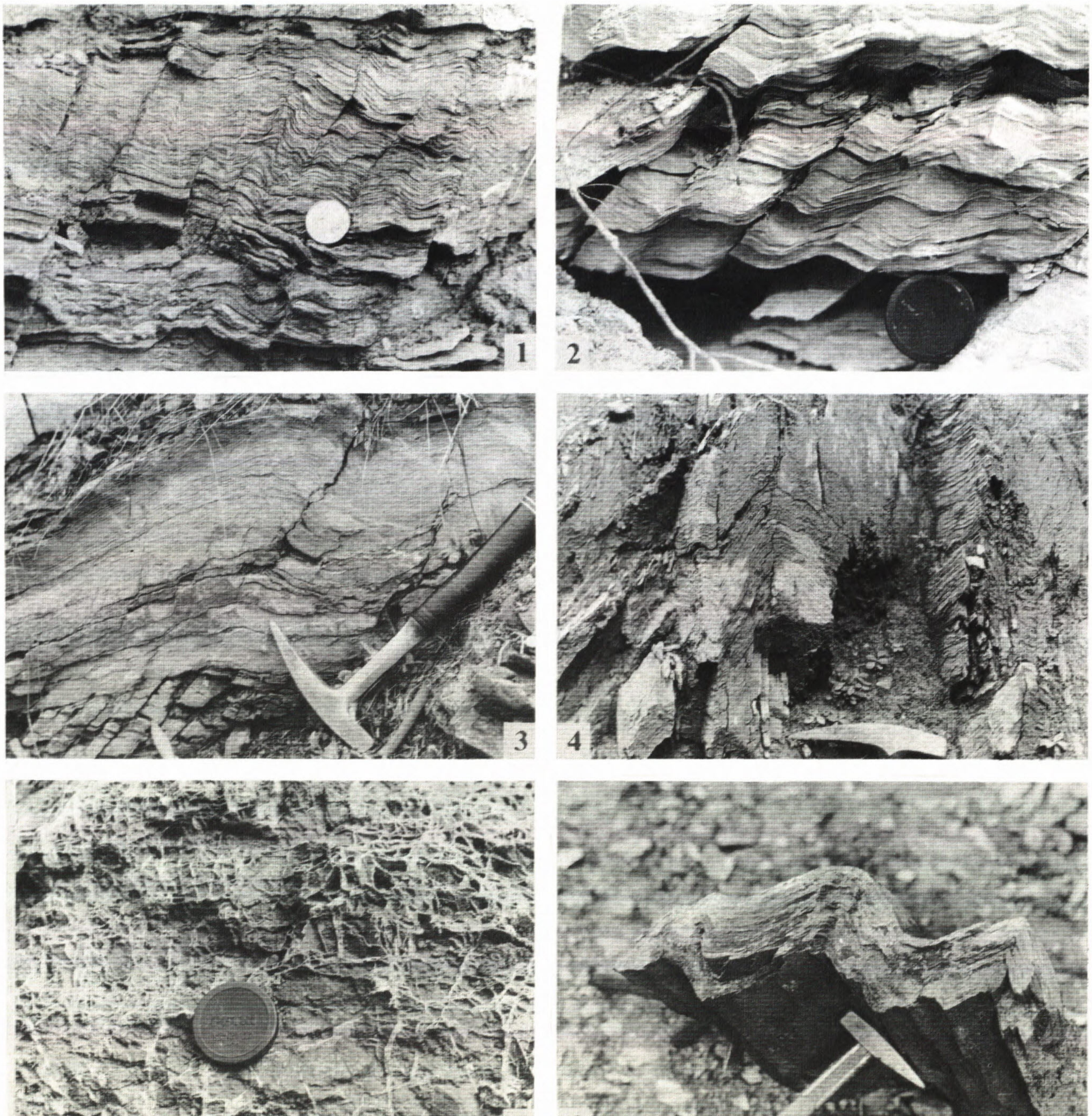
The Alpine history of the tectonic regimes acting in the area under consideration, and their assumed time controls, may be characterized as follows:

(1) The onset of shortening along the southern flanks of the Zliechov basin caused termination of mostly pelagic sedimentation in the Veľký Bok area probably during the Barremian-Aptian.

(2) Inversion of a passive margin into an active one during the intracontinental A-type subduction of



Pl. I. Small-scale structures of the deformation stage AD_1 (1-5). 1 - tight recumbent folds F_1 in the Lower Jurassic limestone of the Panská hoľa subunit, Teplička valley; 2 - subisoclinal fold F_1 in the Middle Jurassic marly limestone, Panská hoľa subunit, Ostrá hill; 3 - pinch-and-swell stretching of a competent allodapic sandy crinoidal limestone bed within the Lower Jurassic marlstones of the Smrečiny subunit, Benkovo valley; 4 - buckled calcite veins in a weakly nodular Upper Jurassic limestone of the Košariská subunit, Benkovo valley; 5 - ductile/brittle shear zone confined to a more competent bed in Lower Jurassic marly limestones of the Smrečiny subunit, Benkovo valley. Parallel lamination in the upper part of the bed is foliation S_{01}, penetrative crenulated surfaces in the centre are antitaxial fibrous calcite veinlets generated by extension normal to S_{01}, inclined spaced surfaces is solution clevage S_1. This geometry indicates top-to-the NW shearing (sinistral in the plane of the photo); 6 - Upper Jurassic nodular limestones of the Košariská subunit, Benkovo Valley. Bedding is vertical, S_2 solution clevage subhorizontal due to AD_5 tilting.



Pl. II. Mesostructures of the AD_2 and later stages. 1 - contractional crenulation cleavage in Lower Jurassic marly limestones, Smrečiny subunit, Benkovo Valley; 2 - apparently extensional crenulation cleavage, Middle Jurassic marly limestone, Smrečiny subunit, Benkovo Valley; 3 - open fold F_2 with contractional axial-plane cleavage S_2 in the core parallel to apparently extensional one in the limbs, Smrečiny subunit, Benkovo Valley; 4 - tight, penetratively parallelly cleaved "shear" folds F_2 in Lower Cretaceous marlstones of the Košariská subunit, Malužiná Valley; 5 - veined dolomite clast from rauhwackized carbonate tectonic breccia at the sole of the Choč nappe, Malužiná Valley (stage AD_4); 6 - symmetric angular folds F_5 in the Middle Jurassic marly limestones of the Panská hoľa subunit, Mlynná Valley near Vernár.

the Krížna basin substratum led to strong compression of marginal halfgrabens and their gradual transformation into large-scale fold thrusts along the trailing edge of the Krížna accretionary wedge. This was generated by décollement of the Zliechov basin sedimentary filling along the horizon of Upper Scythian shales and evaporites. Contemporaneously, in the backstop of the accretionary complex formed by thick-skinned Veporic basement sheet, processes of post-thickening uplift and orogen-parallel extensional unroofing of Alpine metamorphic core complexes occured during mid-Cretaceous times (Hók et al., 1993; Plašienka, 1993; Plašienka and Putiš, 1993; Kováč et al., 1994). Products of erosion of the uplifting domain might have supplied the Albian-Cenomanian flysches as the youngest Krížna basin deposits in front of the accretionary wedge (Plašienka, 1995).

(3) The final forming of the Veľký Bok recumbent folds in the rear of the Krížna accretionary wedge is recorded by mesostructures of the first Alpine deformation stage AD_1. These indicate northward thrusting, vertical flattening and very low to low grade metamorphic imprint of rock complexes buried at some 5-10 km.

(4) Superimposed deformation of the AD_2 stage was probably controlled by collision of the Tatric (northern) and Veporic (southern) margins of the Zliechov basin after its complete diminishing and after thrusting of the Krížna nappe over the Tatric units by northward gravity gliding during the Upper Turonian (Plašienka, 1995). Extreme compression of the intracontinental suture zone led to partial backthrusting in the rear of the destroyed accretionary complex, associated also with sinistral transpression widely recorded along the Veporic SW-NE to WSW-ENE trending basement fault zones (the Čertovica, Pohorelá, Zdychava and Luberník lines, cf. Putiš, 1991, 1993; Madarás et al., 1994). In higher structural levels and in more NE areas (Fig. 1), dextral transpression along NW-SE to WNW-ESE fault zones prevailed. Overall N-S AD_{2-3} shortening, accompanied by uplift and gravity-driven motion of the Krížna nappe, led to a rapid exhumation of deeper structural levels of the colliding zone built up by the Veľký Bok units and to their backthrusting into the superposition over the Veporic crystalline core complexes, which previously experienced a different structural development terminated by an older, mid-Cretaceous uplift and extension (especially units KH, VV, F and M in Fig. 4 and 6). Top-to-the E to NE extension produced a set of NW-SE trending low-angle normal faults which served as lateral or oblique ramps during AD_2 backthrusting (Fig. 1, 2).

(5) Already during the Upper Turonian or lowermost Senonian, the Veľký Bok unit carrying the structural record of stages AD_1 to AD_3 was exposed on the surface, being immediately overridden by the Choč superficial nappe.

(6) The post-nappe structural evolution is, probably uninterruptedly, characterized by overall N-S shortening in a kinematic framework of conjugate sinistral and dextral wrench zones partly inherited from previous stages (Fig.1). During the latest Cretaceous and earliest Tertiary, the main sinistral wrenching activity was concentrated to the Muráň fault zone (Fig. 1). The discrete fault is accompanied by an en-echelon system of large-scale flower synforms in sedimentary rocks of the Hronic-Silicic cover nappes (Choč, Muráň and Stratená nappes, Fig.1), incorporating also the post-nappe Gosau sediments. The main activity along the Muráň fault ended before deposition of the Paleogene (Eocene-Oligocene) cover sediments. A slight dextral inversion of the Muráň fault due to rotation of σ_1 into nearly W-E position has been interpreted by Marko (1993). In the studied area, the first post-nappe (Senonian) deformations indicate strong N-S compression, followed by slight dextral transpression along the generally W-E trending Priehyba-Úplaz faults bounding the northern edge of the crystalline core of the Kráľova hoľa (easternmost) part of the Nízke Tatry Mts. (Fig. 1, 6). The Priehyba fault zone is a reactivated AD_2 sinistral transpressional system, the Úplaz fault originally formed the southern front of the backthrust Veľký Bok unit (Fig. 1, 2, 4, 5, 6). W-E trending wrench faults restricted also the southern foot of the Nízke Tatry Mts. (Fig. 6) which indicates compressional push-up character of the Nízke Tatry Mts. uplift during the Paleogene (Kráľ, 1977; Kováč et al., 1994). The W-E dextral wrenching was probably induced by anticlockwise rotation of the main compressive stress to roughly NW-SE position during the Late Paleogene (Fig. 1).

(7) The younger tectonic history is poorly constrained because of scarcity of Neogene sediments in the whole area. The distribution of comparatively thick Pliocene and Quaternary fluvial and proluvial deposits in the Horehronské podolie (Upper Hron) valley indicates prolonged uplift of the Nízke Tatry

range controlled by a W-E trending, south dipping normal fault (Pohronie fault) along their southern foot.

Summary and conclusions

Conventional field structural analysis of the Veľký Bok units in the eastern part of the Nízke Tatry Mts. has revealed a complex structural evolution of the area with at least five deformation stages. The principal first two stages with complete structural parageneses developed in decreasing low-grade conditions during the early Late Cretaceous in connection with the generation and emplacement of the Krížna cover nappe (N to NW directed thrusting and recumbent folding, AD_1 stage), followed by backthrusting due to collision in the suture zone (S directed backthrusting and transpression, AD_{2-3} stage). The overthrust of the higher superficial cover nappes (e.g. the Choč nappe) appears to be only a short event driven by potential gravitational forces generated by an overall uplift due to crustal thickening. However, the homelands and transport directions of the Hronic-Silicic cover nappes is not exactly known. After the cover nappe emplacement, the compressional tectonic regime with N-S shortening continued up to the Early Paleogene, when the compression axis slightly shifted to the SE. The final large-scale fault pattern of the whole area (Fig. 1) includes mostly transpressive conjugate fault systems, partly with signs of reversals of their kinematic characters.

Some features of the tectonic scenario described pose several important, "orogen-scale" problems to be unravelled in the near future:

* mechanisms of formation of large-scale cover, or basement-involved recumbent folds at backstops of accretionary wedges - the Veľký Bok partial subunits were derived from domains with partly differing lithostratigraphic content, possibly halfgrabens;
* driving forces and emplacement mechanisms of large allochthonous cover sheets (orogenic contraction vs. gravity gliding) - the overthrust of the Choč nappe seems to be only a surficial episodic event occuring in an actively shortened and hence probably topographically differentiated area;
* crustal-scale compatibility of deformation processes, duration and temporal and spatial overlap of deformation stages and tectonic regimes, as well as their progradation or "polarity" in the evolution of an orogen. This strongly depends on the scale of observation - e.g. in the scale of Fig. 2 deformation stages and tectonic regimes clearly exhibit a time succession and superimposition, while in the scale of Fig.1 these are partly overlapping with generally forelandward (northward) migration.

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