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Towards an evolutionary tectonic model of the Krížna cover nappe (Western Carpathians, Slovakia)

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Abstract. The Krížna nappe, belonging to the Fatric system, is an areally extensive, but relatively thin allochthonous sheet composed of Mesozoic sediments detached from a disappeared substratum and overthrusting the Tatric basement and cover units. The principal Zliechov unit was formed at the expense of a wide basinal area floored by continental crust strongly stretched and thinned during Early Jurassic rifting. In Mid-Cretaceous times, the Zliechov basin was progressively shortened through underthrusting of its basement and tegument complexes below the Veporic thrust wedge. The sedimentary filling was detached along the horizon of Upper Scythian shales and evaporites and formed an initial fold-and-thrust stack prograding outwards. After the complete elimination of the Zliechov basin substratum, its southern Tatric and northern Veporic margins came into collision and the Krížna stack was pushed over the frontal southern Tatric ramp, from which the frontal Fatric elements with slope and ridge-related sedimentary successions were torn off. Finally, in the Late Turonian, the Fatric nappe elements gravitationally glided northwards in a diverticulation manner from the southern Tatric elevation over the unconstrained basinal northern Tatric areas.

Key words: Central Western Carpathians, Krížna cover nappe, paleotectonic evolution, emplacement mechanisms

Introduction

The Krížna nappe group, or "stem nappe" (MAHEĽ, 1983), redefined as Fatricum consisting of the Vysoká and Krížna principal nappes by ANDRUSOV et al. (1973), is a tectonic unit representative of the Central Western Carpathians (CWC). It overlies various Tatric cover units and it is overlain by another important group of cover nappes - the Choč and higher nappes (the Hronic and Silicic systems). The Krížna nappe is a relatively thin (1-3 km), but widespread (more than 12,000 km^2 - JACKO & SASVÁRI, 1990) overthrust sheet composed of Lower Triassic to mid-Cretaceous sediments of diverse, although mostly carbonatic lithologies. They were sheared off their mostly disappeared original basement and tegument along décollement horizons of Werfenian and Keuper shales and evaporites to form a far-reaching allochthonous body. The nappe consists of numerous dismembered slices, recumbent folds and imbricates, but sections with relatively undisturbed stratigraphic successions are present as well. The CWC nappe system is assumed to be a lateral continuation of the Austroalpine system of the Eastern Alps. Both were primarily shortened during the Cretaceous paleo-Alpine (eo-Alpine) orogenic contraction.

As it appears today, the Krížna unit is a complex overthrust sheet exposed from its "roots" in the rear part (Veľký Bok unit related to the north Veporic basement wedge), positioned between the Tatric and Veporic basement thick-skinned sheets, through a wide central allochthonous body resting on the Tatric substratum, up to frontal subunits with a complicated structure in the Periklippen zone. The Krížna nappe is a uniquely preserved early Alpidic, thin-skinned overthrust body for which hardly any analogue can be found in the European Alpides (MAHEĽ, 1983). Therefore, a relevant tectonic reconstruction of the generation and final emplacement of the Krížna nappe might provide a world-wide applicable model for the development of extensive superficial nappe sheets.

From the lithostratigraphical point of view, the Krížna nappe is generally subdivided into the Vysoká and Zliechov-type units. The Vysoká units contain shallow-water Jurassic successions similar to the Tatric (High Tatra-type successions), while the Zliechov is an antagonistic, deep-water Jurassic-Cretaceous succession. In central Slovakia, both units form independent nappe bodies, the Vysoká-type forming slices or duplexes (Belá, Ďurčiná, Havran) at the sole of the huge Zliechov nappe. At the western (Malé Karpaty Mts.) and eastern (Branisko and Humenské vrchy Mts.) termination of the CWC the Vysoká type becomes to be the main constituent of the Fatricum and the Zliechov type gradually wedges out.

There are several crucial problems in the interpretation of the frontal parts of the Krížna nappe. Some authors (e.g. MAHEĽ, 1978, 1983, 1986 etc; MICHALÍK et al., 1987) consider the important Manín unit of the Periklippen belt (the zone between the northern edge of the Tatricum and the Pieniny Klippen belt itself) as a partial, Vysoká-related unit of the Krížna nappe group because of the resemblance or even correspodence of its Jurassic-Lower Cretaceous sequence to the Vysoká type, while the majority of other authors (e.g. ANDRUSOV, 1968; RAKÚS, 1977; MARSCHALKO, 1986; SALAJ, 1994a, b, 1995) stress the continuation of the Middle to Upper Cretaceous succession and they place the Manín unit paleogeographically north of the Tatricum. If the Manín unit is really a constituent of the Krížna nappe group, one cannot exclude that also some other Periklippen units, such as the Drietoma, Bošáca, Kostelec and even the Klape unit, presumably their pre-Upper Turonian formations, also belong to the Krížna system (PLAŠIENKA, 1995a).

The southern extension of the Krížna nappe is limited by the northern edge of Veporicum, an important crustal-scale sheet of the Central Western Carpathians. No wonder that the boundary fault of the Tatricum and Veporicum - the Čertovica line - has been considered for decades the suture, the "root zone" of the Krížna nappe (e.g. BIELY & FUSÁN, 1967). The sedimentary cover of the northern Veporic basement, the Veľký Bok unit, displays some similarity to the Krížna (Zliechov) type of successions, although its southernmost zones show clear shallowing of their Jurassic formations (PLAŠIENKA, 1983, 1995b; SOTÁK and PLAŠIENKA, 1996).

Lithostratigraphy, structural position and tectonic prominence of the Krížna unit were treated by numerous authors, e.g. ANDRUSOV (1968), JAROŠ (1965,1969, 1971, 1980), VOZÁR (1965) MAHEĽ (1983, 1986), or BIELY (1978, 1989). The emplacement mechanism of the Krížna nappe was discussed by BIELY and FUSÁN (1967), MAHEĽ (1983), JACKO & SASVÁRI (1990) and JAROSZEWSKI (1982). A more detailed paleotectonic scenario of the generation of the Krížna unit was reconstructed by JAROŠ (1971), PLAŠIENKA (1983, 1987, 1991, 1995a), PLAŠIENKA et al. (1989), and HÄUSLER et al. (1993), based on the interpretation of sedimentary-lithostratigraphic, metamorphic and structural rock records especially in the rear part of the nappe (Veľký Bok unit). However, the central and frontal nappe parts have only scarcely been subjects of thorough structural studies, with the exception of important papers by BAC (1971), BUJNOVSKÝ (1979), BAC-MOSZASZWILI et al. (1981), JAROSZEWSKI (1982), BUJNOVSKÝ & LUKÁČIK (1985), HÓK et al. (1994) and PROKEŠOVÁ (1994).

This contribution deals with the most important geometrical, mechanical and temporal signatures of the Krížna nappe formation and outlines the main aspects of its evolutionary tectonic model. Interpretative assumptions presented here outline a strictly tentative working hypothesis which will be tested by several independent analytical procedures during further research.

Main points of the tectonic model

For the elaboration of an updated tectonic model of the Krížna nappe, all the available and relevant information which can be read from the rock record has to be taken into account. This includes analyses of the material (lithostratigraphic, sedimentologic, volcanic, metamorphic) and structural records, as well as paleogeographic assumptions. As the extent of the present paper is limited, all the extensive dataset sources will not be quoted here and readers are recommended to the review articles by ANDRUSOV (1968), ANDRUSOV et al. (1973), BIELY & FUSÁN (1967), BIELY (1978, 1989), JAROŠ (1971, 1980), MAHEĽ (1982, 1983, 1986), PLAŠIENKA (1983, 1991, 1995a, b, c), PLAŠIENKA et al. (1989), HÄUSLER et al. (1983) and to the references cited therein. In the next paragraphs, only the most important (from the authors' viewpoint) aspects of the structure and evolution of the Krížna nappe system will be stressed.

Paleogeographic setting

The original homeland of the Fatric (Krížna s.l.) units was a basinal area (Zliechov basin) some 100 km wide, flanked by elevated domains from its subaequatorial sides (in the present coordinates): the Tatra swell, or South Tatric ridge in the north with the adjacent, dissected shelf margin originally occupied by the Vysoká and Manín-type units, and the North Veporic (Veľký Bok - Lučatín) continental margin in the south. The basin was floored by a thinned, strongly stretched continental crust. Westward lateral wedging out of the Zliechov unit points to a lozenge-shaped basin formed by transtensional movements during Jurassic rifting. The along-strike length of the basin was at least 250 km.

Pre-contractional paleotectonic evolution

The Zliechov basin was formed by Early Jurassic rifting and distension of the European crust composed of the deeply denuded crystalline basement of inner Variscan zones and its Permotriassic continental and shelf carbonate platform sedimentary cover generally approaching developments of the Germanic basin. After the Upper Jurassic period of thermal subsidence, renewed rifting events are recorded, especially in the Barremian and Aptian. Lithospheric-scale extension is revealed by extrusions of basanitic lavas, followed by mid-Cretaceous shortening period heralded by Aptian olistostromes and then by coarsening-upward Albocenomanian siliciclastic flysch.

Mechanical stratigraphy

Most of the sedimentary infill of the Zliechov basin has been detached from its substratum along the horizon of Upper Scythian shales and evaporites. The underlying Permoscythian clastic sequence, the tegument, remained attached to the pre-Alpine crystalline basement and both were largely underthrust during shortening of the Fatric area. The complete detached Zliechov succession, originally some 3 to 4 km thick, is composed of:

– slices of Upper Scythian (Werfenian) shales at the nappe sole;

– huge competent complex of Middle to lower Upper Triassic carbonates (mostly Gutenstein and Ramsau formations), up to 1,000 m thick, intercalated by thin Lunz beds in the upper part;

– weak Upper Triassic (Norian) Carpathian Keuper formation of variegated shales, sandstones and evaporitic dolomites and gypsum, with variable thickness up to 300 m;

– Rhaetian fossiliferous Kössen (Fatra) formation;

– Lower Liassic shales and sandy limestones of the Kopienec fm.;

– variable complex of Middle and Upper Liassic biodetritic and sandy limestones, sandstones, spotted (Allgäu) and nodular (Adnet) limestones, marlstones etc. of rapidly changing thicknesses (syn-rift strata), relatively competent;

– thick-bedded Allgäu limestone-marlstone formation (basinal syn-rift) with the thickness reaching several hundreds of metres in some sections;

– well-bedded Upper Jurassic radiolarites, siliceous, nodular and biancône-type limestones form a comparatively weak, easily foldable (but not décollement) complex some 50-200 m thick;7

– Lower Cretaceous marlstones and marly limestones attain thicknesses in excess of 1,000 m (probably not primary), it is an incompetent sequence often partly detached from its underlier;

– the uppermost Albocenomanian flysch sequence (Poruba fm.) is usually detached, even not present in large areas of the dorsal and inner nappe parts; since it was deposited immediately before and during thrusting, sediments were probably still not lithified, but water-saturated, hence mechanically very weak.

This generalized mechanostratigraphy includes three most important potential decoupling layers. The lower one occurs within the Werfenian formation, the middle in the Carpathian Keuper formation, and the upper at the base of unconsolidated mid-Cretaceous flysch sequence. Corresponding décollement horizons are present also in the Manín and Vysoká-type successions, though these are generally stronger due to prevalence of massive or thick-bedded limestone bodies. In the direction of the translation path, the importance of higher detachments increases. From the rheological point of view, the Fatric successions may be regarded as a multilayer, with downward increasing competence and upward increasing ability of folding and decoupling.

Crustal shortening processes

The contraction of the Fatric realm prograded in mid-Cretaceous times from the south to the north (in present coordinates). The southern flanks of the Zliechov basin were inverted to form an orogenic wedge with a set of superimposed large-scale recumbent folds and partial nappe units at its toe. The cover (Veľký Bok and Lučatín units) was only partly stripped off the northern Veporic basement and each partial subunit contains a lithostratigraphic succession differing to some extent from the neighbouring subunit (Fig. 1, see also Soták & Plašienka, 1996). This feature can be attributed to the pre-existing depositional diversities in individual fault-bounded marginal halfgrabens. Special geometrical characteristics of recumbent folds (intact overturned limbs, but sheared-off normal upper limbs) would imply development of folds by horizontal-axis rotation, tightening and distributed non-coaxial shearing of halfgraben blocks at the tip of compressional wedge (Fig. 2).

Most of the Zliechov basin substratum (basement and its tegument) disappeared by underthrusting beneath the northern Veporic thrust wedge. However, a part of this substratum was detached to form a thin-skinned imbricated duplex thrust over the southern Tatric basement and cover (Staré hory Mts. - Jaroš, 1971; Rázdiel block of the Tríbeč Mts. - Hók et al., 1994; Vozárová & Vozár 1988). The roof thrust transported the whole Zliechov succession further towards the foreland. It might be speculated that this basement duplex represents upper crustal slivers torn off the southern Zliechov basin floor in front of the developing northern Veporic basement wedge (Fig. 2).

Detachment of sedimentary successions

The above-described décollement horizons represent rheologically predisposed layers of high strain rates enabling differential movements of inserted stronger rock units. At the incipient stage of the cover detachment, the lower "Werfenian" décollement was operating. In the course of underthrusting of the Zliechov basin substratum, the detached sedimentary complexes created an imbricated fold-and-thrust belt and the upper two detachments became active during ramp-flat thrusting.

The Vysoká and Manín-type units, located originally at the Tatric-Fatric transitional basinal slope dissected by basinward dipping normal faults (Fig. 2), were detached in two ways: (1) more commonly along the middle "Keuper" décollement; (2) some partial nappes (e.g. Belá) involve also basal slices of substratum (basement and tegument), these are probably torn off edges of tilted extensional blocks truncated by footwall-shortcuts during inversion and ramping in front of the Zliechov stack.

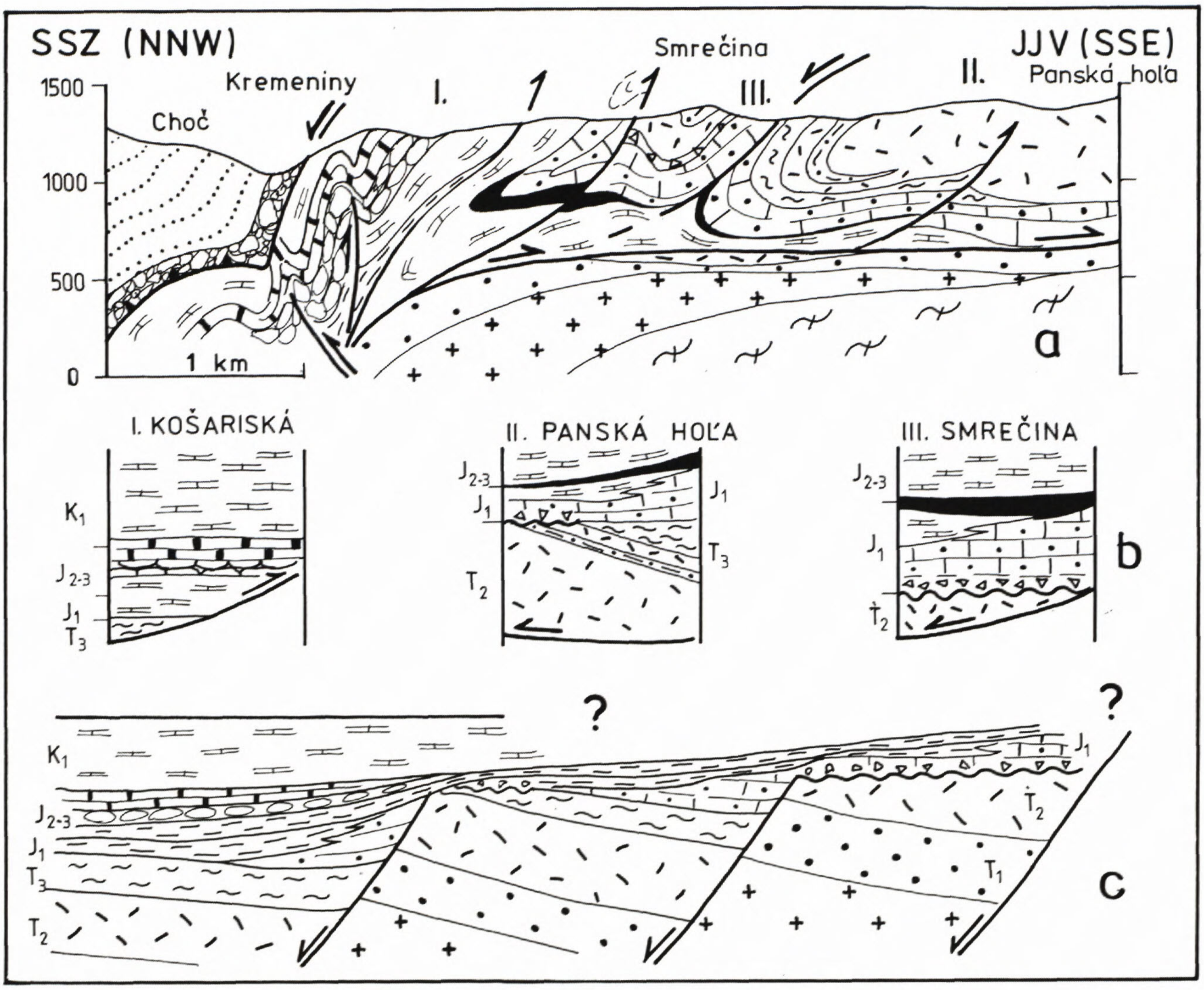

Fig. 1 Structure and lithology of the Veľký Bok unit on northern slopes of the Nízke Tatry Mts. (cf. Plašienka 1995b)
a- tectonic profile with three principal subunits; b - Košariská subunit (I.) approaches basinal Zliechov succession, the Panská hoľa (II.) and Smrečina (III.) subunits represent faulted basin flanks with thick Lower Jurassic syn-rift deposits and deep erosion of the original position of the Triassic substratum; c - tentative reconstruction of the original position of the Veľký Bok subunits based on structural and lithostratigraphic signatures. J_{2-3}-K_1 post-rift deposits.

Structural evolution

The conspicuous structural record, especially in the rear part of the Krížna system (Veľký Bok and related units), has been studied by few authors (cf. Plašienka, 1983, 1995b and references therein). Numerous small-scale structures have been grouped into several deformation stages (Plašienka, l.c.), the first two being intimately related to the generation and emplacement of the Krížna unit. The AD1 stage records thrust stacking, the AD2 additional collisional shortening of a weak suture zone between the Tatric and Veporic crustal sheets, after the principal body of the Krížna nappe was expulsed and translated northwards.

At the passage from the rear to the central parts of the Krížna nappe body, the AD1-2 structural associations are overprinted by flat-lying extensional structures (Prokešová, 1994). The dorsal nappe elements exhibit mostly layer-parallel extensional structures superimposed on scarcely preserved older compressional ones, the whole nappe body is thinned and stripped off its uppermost mid-Cretaceous flysch complexes.

The frontal nappe parts show complicated structure with often pervasive mesoscale fold structures especially in the higher, well-bedded formations. The lower structural complex (Middle Triassic carbonates) is often doubled, forming at least two superimposed recumbent or northward-plunging "digitations" (Maheľ, 1983). However,

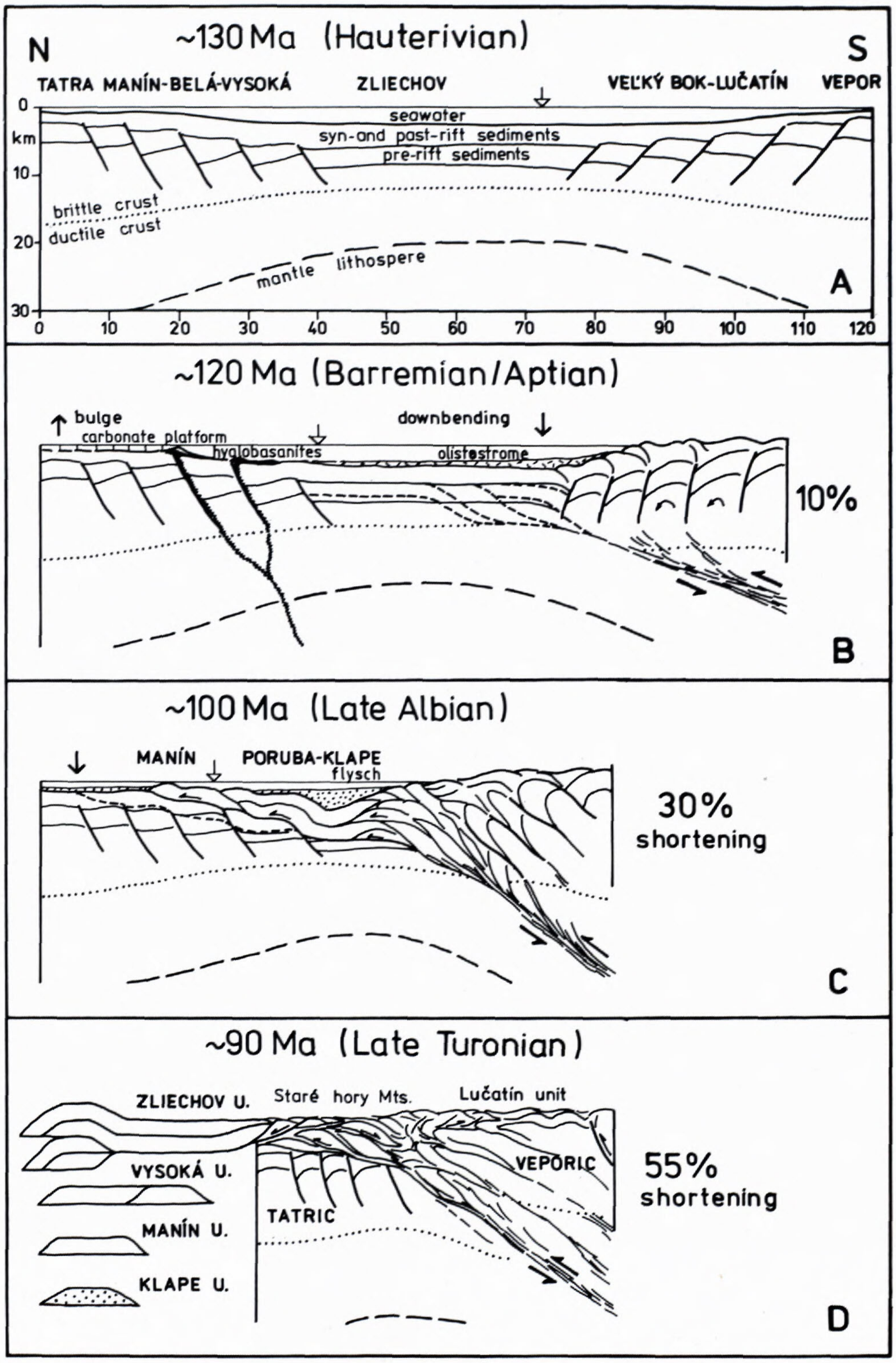

Fig. 2. Paleotectonic scenario of the Krížna nappe origin. A - general pre-compression architecture of the Fatric realm with principal isopic zones. B - incipient shortening of the Fatric-Veporic margin. C - stacking of detached units of the Zliechov basin, piggy-back flysch sedimentation. D - elimination of the Zliechov trough, collision of the Tatric and Veporic crustal superunits, foreland-ward diverticulation gliding of individual Fatric units (Krížna nappe s.l.).

according to preliminary structural observations, these digitations are in fact original thrust imbrications formed during the initial shortening of the Zliechov basin. They were passively transported towards the nappe fronts, suffering only flattening and some additional foreland-ward gliding of the upper subunit with respect to the lower one to form false synclines.

The emplacement-related structures in the frontal Fatric units are strongly overprinted by younger transpressional deformation and are hardly recognizable without a careful analysis. Nevertheless, the AD1 thrusting-related structural record is still preserved, e.g. in the Manín unit.

Final emplacement mechanisms

Where the Krížna nappe is in a clear allochthonous position above the Tatric units, structures at the nappe base provide an insight into the ways of its final emplacement. There is one aspect of the mechanical paradox often mentioned in connection with large-scale superficial décollement cover nappes that their overthrusts apparently have not considerably affected the structures of the substratum (e.g. Bac-Moszaszwili et al., 1981; Jaroszewski, 1982). Unlike other famous thrust and nappe systems (e.g. Helvetic), there are no signs of ductile straining within the Krížna nappe or its substratum which might be ascribed to the overthrust event. On the contrary, only brittle crushing and cataclastic flow within a narrow layer at the nappe sole can be observed. This horizon is formed by carbonate tectonic breccias, often rauhwackized. Brecciation should have been triggered by high pore-fluid pressure during thrusting (Jaroszewski, 1982; Plašienka & Soták, 1996) to reduce friction within the brittle shear zone loaded by the whole nappe. Overpressured sole permitted more-or-less free, most probably gravity-driven nappe gliding towards the foreland. The necessary topographic downslope (however moderate required) was produced by the compressional uplift of the rear nappe parts, thereby accompanied by pushing up the Krížna stack over the south Tatric margin as a frontal ramp. Afterwards, individual Fatric units glided gravitationally in a "diverticulation" manner to spread over the unconstrained, basinal Tatric foreland (Plašienka, 1995c). The frontal and uppermost units (Klape, Manín, Vysoká) had the potential for the farthest translation.

There is a remarkable relationship between the character of the discrete nappe sole and lithology of the underlying Tatric cover. If the substratum is composed of mid-Cretaceous flysch sediments, the layer of rauhwackized carbonate breccia often occurs at the nappe sole. This signature has been tentatively explained by Plašienka & Soták (1996) as an indication of a subaqueous overthrusting, when the nappe overrode in large areas unconsolidated, water-saturated flysch sediments. Tectonic load and aquathermal pressuring caused devolatization of substratum sediments and produced continuously excess fluid pressures in a contact horizon, possibly up to lithostatic values, thereby enabling almost free nappe movement. However, where the overpressured layer superposed the lithified substratum, the water influx ceased and fluids were released from the nappe sole. The brecciated layer was sometimes entirely dissolved together with some wall rocks (mostly underlying) to form a "macrostytolitic" discrete Tatric-Krížna contact (Jaroszewski, 1982) of apparently non-tectonic origin. This inevitably led to the inhibition of any further movement along this rugged contact, consequently a new thrust plane had to be formed, or the movement relocated to some of the higher décollement horizons. These features are typical for the inner central nappe parts, above the South Tatric ridge, which at least partly emerged in the course of thrusting due to internal shortening (relief nappe - Bujnovský, 1979).

Summing up, the Krížna nappe should have been finally translated gravitationally along an extremely weak overpressured cataclastic breccia horizon supporting the nappe weight and allowing frictionless gliding. The weak sole accomodated most of or all thrusting-related shear stresses, therefore mostly extensional structures accompanied the final emplacement event: brittle fracturing and veining, meso- to macroscale boudinage of competent units, or reactivation of décollement horizons.

Post-emplacement deformation

Immediately after its emplacement onto the Tatric substratum (for the temporal considerations about the nappe thrusing events see Plašienka, 1996), the Krížna unit had to be overridden by the higher Hronic superficial cover nappe system (the Choč and related nappes). Similarly as the Fatric vs. Tatric, also the Hronic vs. Fatric is of apparently non-tectonic nature, being formed by (often even missing) rauhwackized tectonic breccias again (cf. Plašienka & Soták, 1996). Obviously, the final emplacement of the Hronic nappes had comparable characteristics to that of the Fatric nappes.

A variety of deformation features postdating the final nappe emplacement event is frequent especially in the frontal parts of the Fatric system, which is incorpoarted into a broad wrench corridor in the Periklippen zone active in the Tertiary. Superimposed structures are not always unambiguously distinguishable from the thrusting-related, therefore a thorough structural analysis has to be applied in this area.

Aspects of the geodynamic model

After a relevant tectonic model of the Krížna nappe origin is elaborated, a comprehensive lithospheric-scale geodynamic model should be the next step. It has to include physical evaluation of extensional and contractional processes, first of all isostatic and thermal modelling, rheological considerations and reconstruction of driving forces of operative processes. The whole-Carpathian context should be taken into consideration.

Conclusions

The above outlined aspects impose significant constraints to any viable tectonic model of the Krížna nappe origin. Though our data base is not complete and straightforward, a lot of indications points to:

* the Krížna nappe was formed at the expense of a wide basinal domain floored by attenuated continental crust, which was mostly underthrust below the hinterland orogenic wedge (Veporicum);
* the sedimentary filling of this basin was detached along the Upper Scythian décollement horizon to form an initial fold-and-thrust complex;
* after the elimination of the basin substratum, the detached imbricated sedimentary complex was pushed over the frontal ramp (Fatric-Tatric basin flanks) and the basal marginal Vysoká and Manín-type imbrications were sheared off this ramp;
* the Krížna nappe was finally emplaced by the gravity gliding mechanism from the topographic elevation towards unconstrained foreland basinal domains, where it spread out to create a thin blanket covering the Tatric units.

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