GEOLOGICA CARPATHICA, FEBRUARY 2012, 63, 1, 13–32 doi: 10.2478/v10096-012-0001-y

Structural pattern and emplacement mechanisms of the Krížna cover nappe (Central Western Carpathians)

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(Manuscript received January 10, 2011; accepted in revised form June 9, 2011)

Abstract: The Central Western Carpathians are characterized by both the thick- and thin-skinned thrust tectonics that originated during the Cretaceous. The Krížna Unit (Fatric Superunit) with a thickness of only a few km is the most widespread cover nappe system that completely overthrusts the Tatric basement/cover superunit over an area of about 12 thousands square km. In searching for a reliable model of its origin and emplacement, we have collected structural data throughout the nappe body from its hinterland backstop (Veporic Superunit) to its frontal parts. Fluid inclusion (FI) data from carbonate cataclastic rocks occurring at the nappe sole provided useful information about the p-T conditions during the nappe transport. The crucial phenomena considered for formulation of our evolutionary model are: (1) the nappe was derived from a broad rifted basinal area bounded by elevated domains; (2) the nappe body is composed of alternating, rheologically very variable sedimentary rock complexes, hence creating a mechanically stratified multilayer; (3) presence of soft strata serving as décollement horizons; (4) stress and strain gradients increasing towards the backstop; (5) progressive internal deformation at very low-grade conditions partitioned into several deformation stages reflecting varying external constraints for the nappe movement; (6) a very weak nappe sole formed by cataclasites indicating fluid-assisted nappe transport during all stages; (7) injection of hot overpressured fluids from external sources (deformed basement units) facilitating frontal ramp overthrusting under supralithostatic conditions. It was found that no simple mechanical model can be applied, but that all known principal emplacement mechanisms and driving forces temporarily participated in progressive structural evolution of the nappe. The rear compression operated during the early stages, when the sedimentary succession was detached, shortened and transported over the frontal ramp. Subsequently, gravity spreading and gliding governed the final nappe emplacement over the unconstrained basinal foreland.

Key words: Slovakia, Central Western Carpathians, Krížna Nappe, structural evolution, fluid inclusions, driving forces, emplacement mechanisms.

Introduction

Thrust sheets or nappes (in Alpine terminology) are the elementary geological structures in compressional orogens everywhere in the world. The basic definition (see McClay & Price 1981 or Merle 1998) considers the nappe to be a large-scale, allochthonous tectonic sheet-like body, which was displaced along a basal, originally nearly horizontal fault (either contractional, or extensional, depending on the emplacement mechanism). The most commonly used division of thrust sheets is based on the presence or absence of crystalline basement rocks in a sheet. If the basement rocks are widely involved, the thrust is a so-called thick-skinned (or, alternatively, a basement nappe). The thin-skinned thrust sheets (superficial or cover nappes) consist of areally extensive, but relatively thin (a few kilometers) blocks of prevalently non-metamorphosed sedimentary rocks, which have been displaced on a thrust plane to the distance reaching several tens of kilometers. Most cover nappes completely lost connection with their homelands and their root areas are only tentatively identifiable.

Since their discovery in the nineteenth century, the mechanisms of nappe emplacement have been the main interest of geologists all around the world. As a result, a number of mechanical models were developed. Considering the driving forces, they can be categorized as gravitational and compressional ones (see Merle 1998 for review).

The first category invokes gravity as the force causing lateral rock movement. The motion results in loss of potential gravitational energy of the system in all gravity models. Gravity gliding (or sliding) requires sliding of the thrust sheet over a generally down-dipping basal slope. Frictional gliding (Hubert & Rubey 1959) and viscous gliding (Kehle 1970) are two end-members subcategories of the gravity gliding models. Gravity-driven internal distortion of rock mass accompanied by vertical flattening and lateral extension (Ramberg 1981) is the main principle of gravity spreading models.

Compressional stresses applied at the rear of the thrust sheet are the main driving forces of compressional models. Although the first to be proposed, compressional models were rejected due to so-called "mechanical paradox" (Smoluchowski 1909) until the plate-tectonics theory was formulated. Later on, the popular critical wedge model was introduced by Chapple (1978) and worked out in detail by Davis et al. (1983), Dahlen et al. (1984) and their followers. Instead of a single thrust sheet, this model rather considers orogen-scale thrust belts.

Overlooking the nature of driving forces, a weak base induced by mechanically weak rocks (cf. Kehle 1970), overpressured fluids (cf. Hubert & Rubey 1959) or other less known strain-softening mechanisms seem to play a key role in the motion of thrust sheets.

Unlike the various thrust and nappe units in the world, little attention has been paid to the Central Western Carpathian superficial nappe emplacement mechanisms that could be deduced from the strain analysis. Virtually, this is due to a non-simple relationship between strain and stress in such brittle-ductile deformed units for which cleavages and folds are the main structural features (Debacker et al. 2008). Likewise, the role of the overpressured base during emplacement of these cover nappes, although proposed from the hydrotectonic phenomena (Jaroszewski 1982; Plašienka & Soták 1996; Milovský et al. 1999), has not been confirmed by experimental data. The only exceptions are the work of Milovský et al. (2003) in which the role of supra-lithostatic fluid pressure at the sole of the Muráň Nappe (part of the Silica Nappe System) was discussed in detail; and research of Jurewicz & Slaby (2004) in the paraautochthonous Giewont thrust in the Tatricum unit.

This contribution presents the possible emplacement mechanisms of the Krížna Nappe System as they can be interpreted from deformation features and p-T data obtained from the Krížna Nappe sole. Furthermore, we discuss the extent to which this model fits (or disproves) formerly presented paleotectonic scenarios for the evolution of the Krížna Nappe (Plašienka & Prokešová 1996; Plašienka 1999).

Geological setting

The Western Carpathians, the northernmost part of the European Alpides, are a north-vergent stack of several crustal-scale (thick-skinned) and cover (thin-skinned) nappe superunits (e.g. Froitzheim et al. 2008). Thin-skinned thrust sheets — Krížna, Choč and Silica Nappe units (ordered uphill) in the central part of the Western Carpathians (Central Western Carpathians — CWC) were displaced from their original substratum during mid-Cretaceous times (Andrusov 1968; Maheľ 1986; Plašienka 1999).

The Krížna Nappe System (or the Fatricum, cf. Andrusov 1973) is the most representative thin-skinned thrust unit in the CWC. Most of geological and paleotectonic evidence confirm that this thin (1–3 km), but areally extensive (~12,000 km^2 cf. Jacko & Sasvári 1990; Fig. 1a,b) thrust sheet body has been transported over the underlying Tatric Superunit to a distance of several tens of kilometers (40–60 km) as a relatively coherent body (see Biely & Fusán 1967; Jaroš 1971; Plašienka 1983, 1995b,c, 1996, 1997, 1999 and references in these works). In contrast to the higher Central and Inner Western Carpathians nappe systems (Hronicum, Turnaicum, Silicicum), that are typical "rootles" thrust units, the Krížna Nappe is exposed from its root area up to the frontal zone (Maheľ 1983). This feature makes the Krížna Nappe the most suitable for structural studies, although its post-emplacement structural pattern has been affected by numerous younger tectonic events.

The Krížna Nappe System is composed mainly of Mesozoic sediments dominated by carbonate lithology sheared off their mostly disappeared original basement along a décollement horizon of Upper Scythian shales to form a far-reaching allochthonous body. Now it overlies various Tatric cover units and is overlain by the higher Hronic (Choč) cover nappe system (Fig. 1c).

Although its substratum mostly disappeared, the close spatial relations between the (southern) rear parts of the Krížna cover nappe and northern parts of the thick-skinned Veporic Superunit are clear. Here the sedimentary Krížna successions grade from their allochthonous position (Fig. 1c) to the sedimentary envelope of the North Veporic basement, which already forms the backstop of the Fatric thrust system (i.e. the Veľký Bok and Lučatín Units). Therefore, a widely accepted idea is, that the Krížna Nappe System as a part of the Fatric Superunit (cf. Plašienka (2003) originated from the area of stretched and thinned continental crust (Zliechov Basin) flanked by elevated domains of the South Tatric Ridge to the north and the North Veporic continental margin to the south (e.g. Plašienka 1999, 2003 and references therein).

Mechanical stratigraphy of the Krížna Nappe

Along with a stress field state, strain rates and p-T conditions, the lithology of deformed rock units is one of the main factors controlling the mode of deformation. It plays a significant role especially in deformation of upper crustal sedimentary rocks where the contrast in rheology between deformed strata is occasionally high and layers should accommodate strain in a different way. The numerous primary (e.g. bedding or compositional layering) and secondary (cleavage, joint systems) planar anisotropies represent the weakness zones that can be predisposed for slips in any phase of deformation.

From the lithostratigraphic point of view, the Krížna Nappe is generally composed of Middle Triassic to lower Upper Cretaceous strata. While the Triassic rocks are uniform throughout the nappe body, the Jurassic and Cretaceous sediments are subdivided into the restricted ridge or slope-type Vysoká Succession and prevailing basinal Zliechov Succession (e.g. Andrusov 1968; Maheľ 1983; Froitzheim et al. 2008). Most of the sedimentary infill of the Zliechov Basin has been detached from its original substratum along a Lower Triassic horizon of the Werfenian shales and evaporites. The underlying Permoscythian clastic sequence remained attached to the basin substratum that disappeared by underthrusting beneath the northern Veporic thrust wedge (Plašienka 1999, 2003). A small part of this substratum forms rare tectonic slices at the base of the Krížna Nappe in its rear parts (e.g. the Staré Hory Unit — Jaroš 1971, Plašienka 1999; and the Rázdiel Unit — Hók et al. 1994, 1997).

From the physical point of view, the detached Zliechov Succession (Fig. 2) is a typical sedimentary multilayer complex (cf. Ramsay & Huber 1987) with upward increasing anisotropy induced by variable thickness and rheology of deformed strata. In this sense, six main, rheologically different complexes were defined in the detached Zliechov Succession in order to fit the purpose of this work:

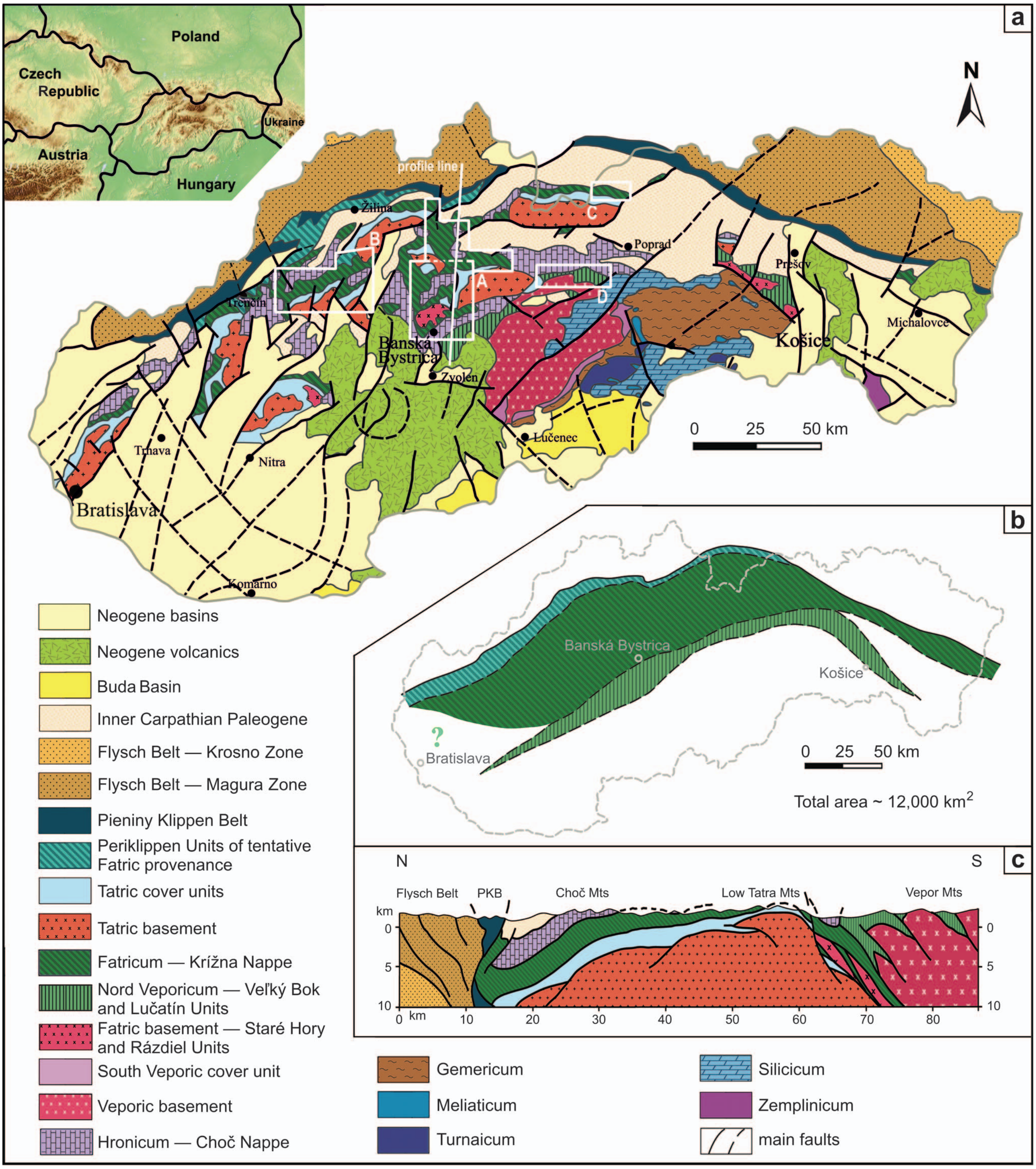

Fig. 1. a — Tectonic sketch of the Slovak part of Western Carpathians (after Vozár et al. 1998, modified) with location of the studied areas (rectangles A–C), area considered in the discussion (rectangle D) and location of profile line depicted in Fig. 1c,**b** — original areal extent of Fatric and related (i.e. Veľký Bok and Periklippen) Units; **c** — schematic cross-section displaying position of the Krížna Nappe in the Central Western Carpathian orogenic wedge.

- **T1$_B$** — the Upper Scythian (Werfen Formation) shales and evaporites. Their position between two rigid horizons — Permoscythian clastics (P–T1$_A$) and Middle Triassic massive carbonates (T2) predetermined this horizon to act as the first-order basal décollement;

- **T2** — the huge (~700 m) complex of poorly bedded or massive Middle to lower Upper Triassic carbonates (mostly Gutenstein and Ramsau Formations). High strength of the complex predetermined it to act as rigid frame of the lower part of deformed sedimentary succession;

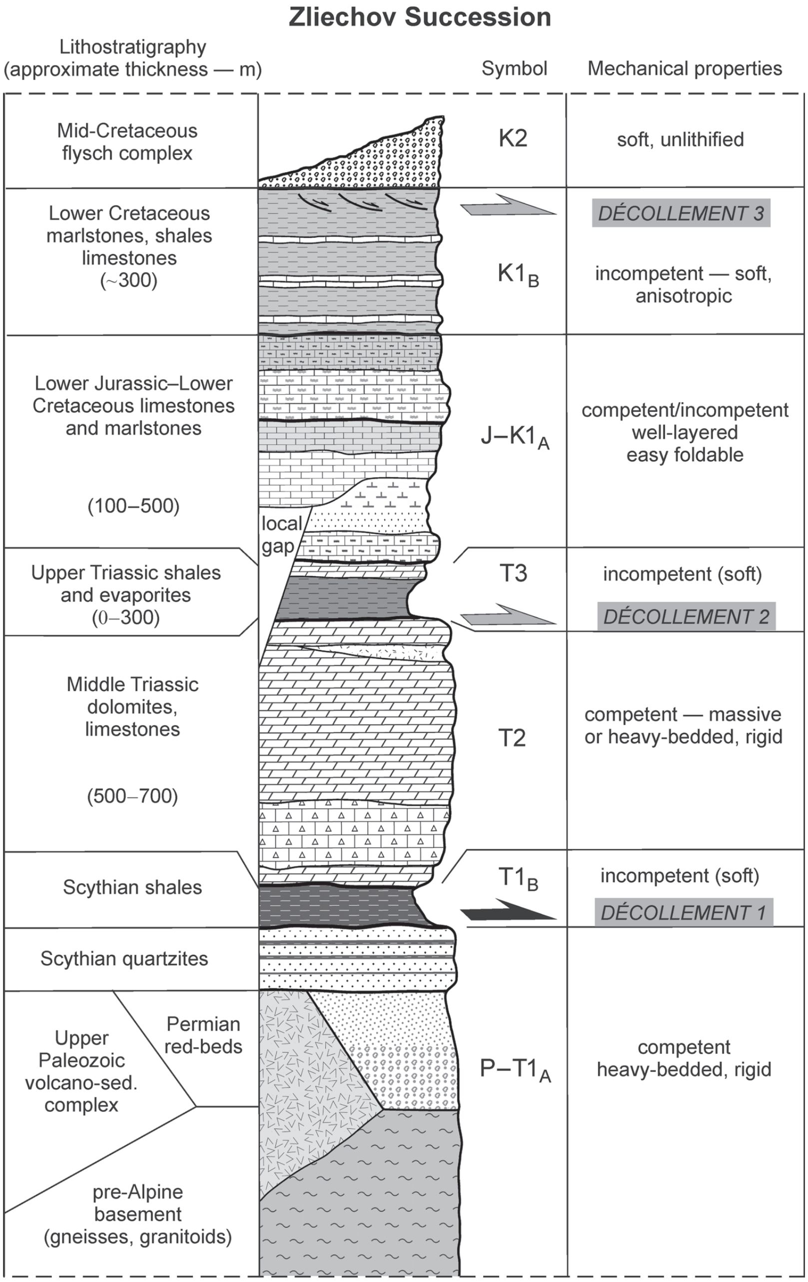

Fig. 2. Mechanical stratigraphy of the Fatric Zliechov sedimentary succession.

- **T3** — up to 300 m thick horizon of variegated shales and evaporites with dolomite and sandstone beds (Carpathian Keuper Formation) in the roof of T2. Due to its weakness and plasticity it plays a second-order décollement function;
- **J–K1$_A$** — the Jurassic (including also Rhaetian) to Lower Cretaceous (Valanginian) succession is a relatively thick (100–500 m) complex of alternating well-bedded strata (various types of limestones, cherts and marlstones, e.g. Fatra, Kopieniec, Allgäu, Osnica Formations — see e.g. Michalík 2007) of different thickness and competency with a high tendency to buckling strain and interlayer slip. Its original thickness is frequently reduced due to macroboudinage of sequences situated above the Carpathian Keuper;
- **K1$_B$** — incompetent and weak complex (~300 m) of the Lower Cretaceous (Valanginian to Aptian) marls and marly limestones (Mráznica and Párnica Formations);
- **K2** — the uppermost Middle Cretaceous (Albian–Cenomanian) syn-tectonic (syn-deformational) flysch sequence (Poruba Formation) deposited immediately before and during thrusting.

More detailed stratigraphy of the Zliechov and Vysoká type successions can be found in many works (e.g. Mahel' 1983; Lefeld et al. 1985; Michalík 2007).

Obviously three weak horizons can be defined in the Krížna Nappe successions. While the role of the T1$_B$ as basal décollement has been known for a long time, the role of the T3 and K1$_B$ has not been fully appreciated until recent time (e.g. Plašienka 1999). Especially the role of the K1$_B$ is newly recognized. It deserves more attention and will be discussed in detail, here.

Methods

To investigate the structural pattern of displaced Fatric successions with a view to the Krížna Nappe emplacement mechanisms, field profiles parallel to the XZ principal deformation plane, namely parallel to assumed nappe transport direction (S–SSE to N–NNW), were selected for the structural analysis. Field profiles were studied preferably in the area defined as "A" in Fig. 1a, although some additional profiles were also selected in areas "B" and "C". Additionally, the results of structural analysis carried out in area "D" and presented in the works of Plašienka (1983, 1995a) have been considered in the "Discussion". Conventional methods of field structural analysis (e.g. Ramsay & Huber 1983, 1987; Price & Cosgrove 1990) were used. Mesoscopic structures, including folds, cleavages, shear-band-like structures, stylolites, and stretching lineations were assembled into structural paragenesis succession. Their orientation parameters were evaluated in the Lambert's equal area projection by using software GEOrient v9.4 (Holcombe 2010).

To gain insight into the p-T regime on the Krížna sole thrust, basal cataclasites (rauhwackes) from near-root areas of the Krížna Nappe were sampled for fluid inclusion analyses. Samples were cut for macroscopic study of textures and clastic lithologies, thin sections were prepared for petrographic study and the rest of the material was digested in diluted acetic acid. Euhedral authigenic minerals were hand-picked from light and heavy fractions of insoluble residues, separated in methylbromide. Newly-formed crystals of quartz up to 1.5 mm in size were mounted in resin and doubly polished for study of fluid inclusions. Microthermometric observations were performed on a Linkam THMSG-600 heating-freezing stage mounted on an Olympus BX-51 microscope. Calibration was performed using temperature of melting in natural pure CO_2 inclusions in quartz (–56.6 °C) and synthetic $K_2Cr_2O_7$ (398 °C). Low temperature data (<100 °C) were measured with the precision of ±0.2 °C at a rate of 1 °C/min. An uncertainty of ±2 °C is estimated for the temperatures above 100 °C measured at a rate of 10 °C/min.

Results

Structural analysis

In consequence of the above described lithological aspects, downward increasing competence and upward increasing ability to fold may be expected in the Fatric successions. Since different structural styles and different deformation mechanisms reflect the same tectonic history in the above defined rock complexes, they are characterized separately in this section.

Permoscythian complex P–T1$_{(A,B)}$

The Upper Scythian shales and evaporites ("Werfen" Formation) have long been regarded as the main décollement along which the Fatric sedimentary succession was detached. Unfortunately, rare preservation and scarce outcropping of Werfenian shales does not allow us to study the strain in rocks comprising this primary basal décollement. Nevertheless, the structural overprint of underlying Lower Scythian clastics was studied at several localities near Banská Bystrica where tectonic slices of the Fatric basement (Staré Hory Unit) are present. In some horizons the quartzites with shale intercalations are refolded to recumbent folds (Fig. 3a,b) with roughly E–W trending sub-horizontal folds axes. Their character and localization suggest a passive amplification of initial perturbations during shearing (Cobbold & Quinquis 1980; Hanmer & Passchier 1991) and can be a result of differential movements during decoupling of Krížna sedimentary successions. The plastic behaviour of quartzite beds was conditioned by their (original?) gypsum cement.

Interestingly, the thickness of the Permoscythian sediments is highly variable in this area (it ranges from 100 m to 800 m) but their absence is also not uncommon (Jaroš 1965). Although it cannot be definitely stated whether this absence is due to primary (sedimentary) or secondary (tectonic) reasons, the second one seems to be more probable.

Carbonate complex T2

Thick (up to 700 m) T2 carbonate complex constitutes a lower rigid frame of the Krížna sedimentary succession. The

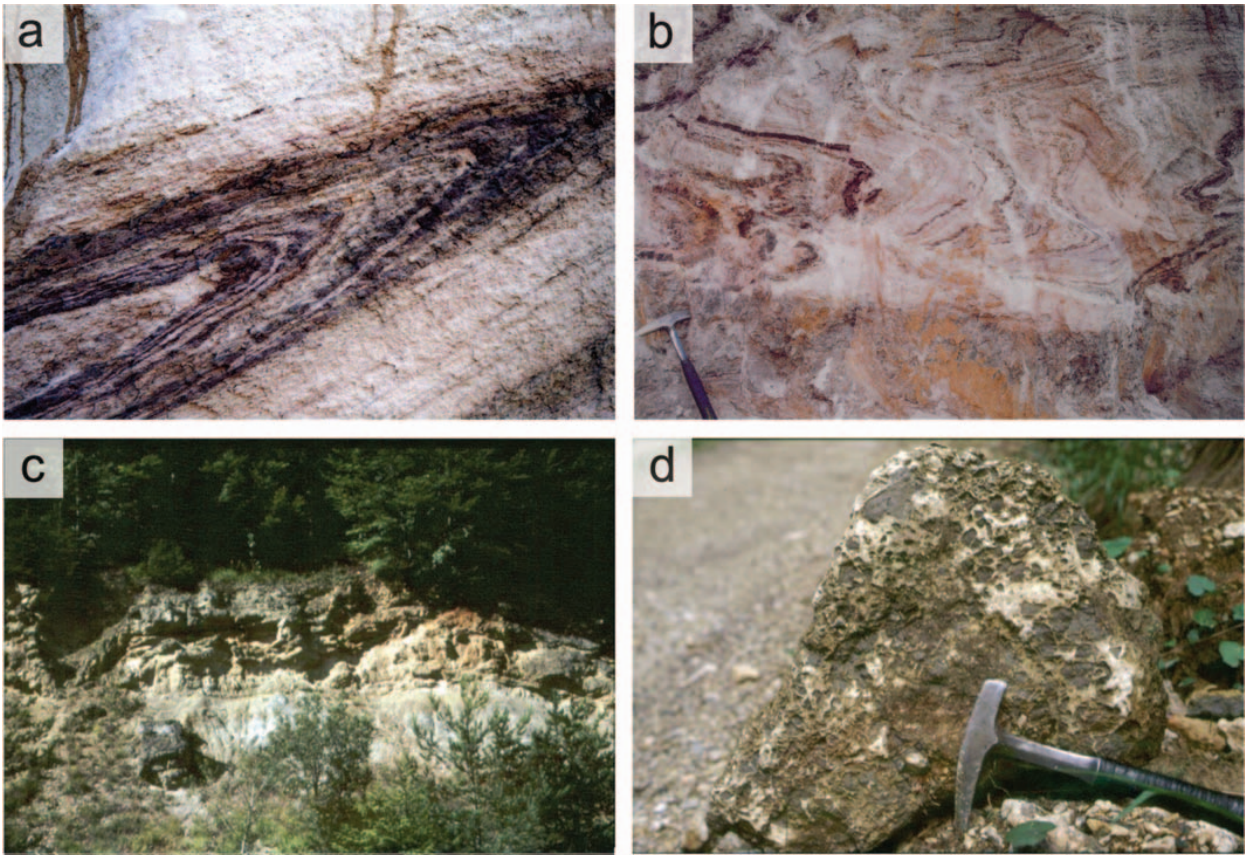

Fig. 3. Typical structural pattern of the Krížna near sole-thrust rocks: **a, b** — folds in Lower Scythian clastics near Baláže village; **c** — rauhwackes outcropping in the Donovaly road-cut; **d** — carbonate tectonic breccias (rauhwackes) — the same locality as "c".

high proportion of dolomites, poor bedding and insignificant content of incompetent beds caused the whole complex to act as a huge single layer (the C-type multilayer cf. Ramsay & Huber 1987, p. 418) controlling the micro- and mesostructural character of lower part of the nappe — namely low buckling instability and high ability to brittle deformation. Large-scale duplexes and megafolds are typical map-scale features mainly in the frontal and rear parts of the Krížna Nappe where they were described as northward plunging "digitations" (e.g. Polák et al. 1979; Maheľ 1985) and partial thrust units and megafolds (e.g. Plašienka 1983, 2003). All Mesozoic Fatric and North Veporic successions (together with massive T2 carbonates and basement rocks) suffered more ductile strain in the rear areas (i.e. in the Veľký Bok and Lučatín Units — Plašienka 1995a; Soták & Plašienka 1996) where low-grade metamorphism was established (Plašienka et al. 1989).

Unlike these rear zones, the mesostructural character of the T2 complex in allochthonous Fatric units (i.e. Krížna Nappe System) reflects solely the brittle strain (Fig. 3c). Several generations of contractional (stylolites, weak fracture cleavage), shear and extensional brittle structures with rather complicated cross-cutting relationships are widespread in this complex and indicate a changeable stress regime which is best explainable by fluctuating fluid pressure. The intensity of brittle overprint increases toward the base (that is the sole of the nappe) where fine-grained cataclasites, tectonic breccias and/or rauhwackes as a final result are common (Fig. 3d). Some authors (e.g. Plašienka & Soták 1996) envisaged that high pore-fluid pressure was the main mechanism of their development. Moreover, in several frontal areas "megastylolitic" contact of T2 carbonates with underlying massive limestones of the autochthonous Tatric successions (described also by Jaroszewski 1982 and Jurewicz 2005, 2007) apparently resulted from complete dissolution of the carbonate breccia bodies. All these facts suggest a significant role of overpressured fluids at the sole of transported Krížna thrust sheet. Therefore, special attention has been devoted to such phenomena in a chapter below.

Carpathian Keuper Formation (T3)

Regardless of its high original anisotropy (shales with evaporites alternate with dolomite and/or sandstone beds), structures originating from buckling instability are rare in this complex. Instead, monoclinal position is typical except in the areas where these rocks are incorporated into T2-megastructures (i.e. duplexes and/or megafolds in the frontal and rear zones of the nappe system). Thus the structural character of the T3 seems to be partly conditioned by the underlying rigid T2 complex by impeding small-scale folding (Treagus & Fletcher 2009). Instead folds, low-angle (with respect to original layering) planar fabric (cleavage, partly pervasive) in the shales and small thrusts in the competent beds are common. En-echelon types of fractures, slightly elongated pebbles and fine stretching lineation suggest that differential movements and shearing occurred along this horizon. The role of the T3 complex as a secondary detachment horizon is revealed by several partial nappe units occurring in the frontal parts of the Krížna Nappe System (e.g. Ďurčiná, Drietoma, Manín or Belá Units containing the Vysoká-type successions), which do not contain the T2 complex and were fully detached along the T3 layer (Plašienka 1999).

Jurassic to Lower Cretaceous complex (J–K1)

Evolution of a rich spectrum of mesostructures (i.e. outcrop-scale structures) in this complex was conditioned by its rheological properties. Obvious pre-existing planar anisotropy was further intensified by layering rotation and development of secondary foliations as deformation proceeded. This led to an increase of J–K1 heterogeneity, which was originally induced by variable thickness and viscosity contrast of deformed beds. Numerous planar discontinuities prone to slip resulted in complicated structural overprint. Thus apparently unrelated structures could have originated during the same deformational event as a result of rotation of pre-existing planar anisotropies from contractional to extensional sector of incremental strain ellipsoids.

Although the structural successions described below are really the result of progressive deformation history, we are using the traditional deformation stages approach for their description as the most practical for further interpretations.

The oldest widespread mesostructural paragenesis D1 comprising the F_1 folds, S_1 cleavage and related structures, is markedly developed in the J3–K1 sub-complex consisting of well-layered and foldable micritic limestones. Rotated (now overturned or recumbent), flattened and segmented F_1 mesofolds (Fig. 4a,b and h) are the most frequent remnants of the D1 stage. They mostly represent later strongly sheared, flattened and rotated small-scale folds related to large-scale folds and thrusts. They are associated with pressure solution cleavage S_1 moderately south-dipping in the normal and sub-horizontal in the inverted fold limbs, where it is also more pervasive — intensified due to a later deformational event. Sub-horizontal to gently plunging L_1 lineations (fold axes or hinge lines and cleavage/bedding intersection) with mean E–W to ENE–WSW trends (Figs. 5a,d and 6a,b) suggest an origin in compressional stress field with N–S to NNW–SSE (in present coordinates) oriented maximal compression axis δ_1.

Reorientation of primary layering (S_0) and development of secondary foliation (S_1) during the D1 stage led to an increase of anisotropy and heterogeneity in the J–K1 complex and enhanced its ability to slip. Therefore, deformation frequently occurred by sliping along suitably oriented pre-existing (mainly S_0) planes. Thus besides rotation, flattening and segmentation of F_1 folds, new associations of shear-like structures and/or thrust-related F_2 folds are the most common results of the D2 stage. Sub-horizontal to gently south-dipping (compressional) shears with "top to the N–NW" kinematics (Fig. 5b) are either reactivated $S_0(C_2)$-planes (Fig. 4c) or newly formed C_2-shears in domains with steeply dipping S_0/S_1 fabric (Fig. 4d,e). NW-directed tectonic transport may also be indicated by mineral or object stretching lineation and/or S_0-plane striations (Fig. 4f,g) observed mainly in J1-J2 successions (see also Kováč & Bendík 2002).

The bedding-cleavage relationships in this case correspond well to the "flexural flow" model of a thrust sheet overcoming a frontal ramp (Sanderson 1982). As will be shown later, this

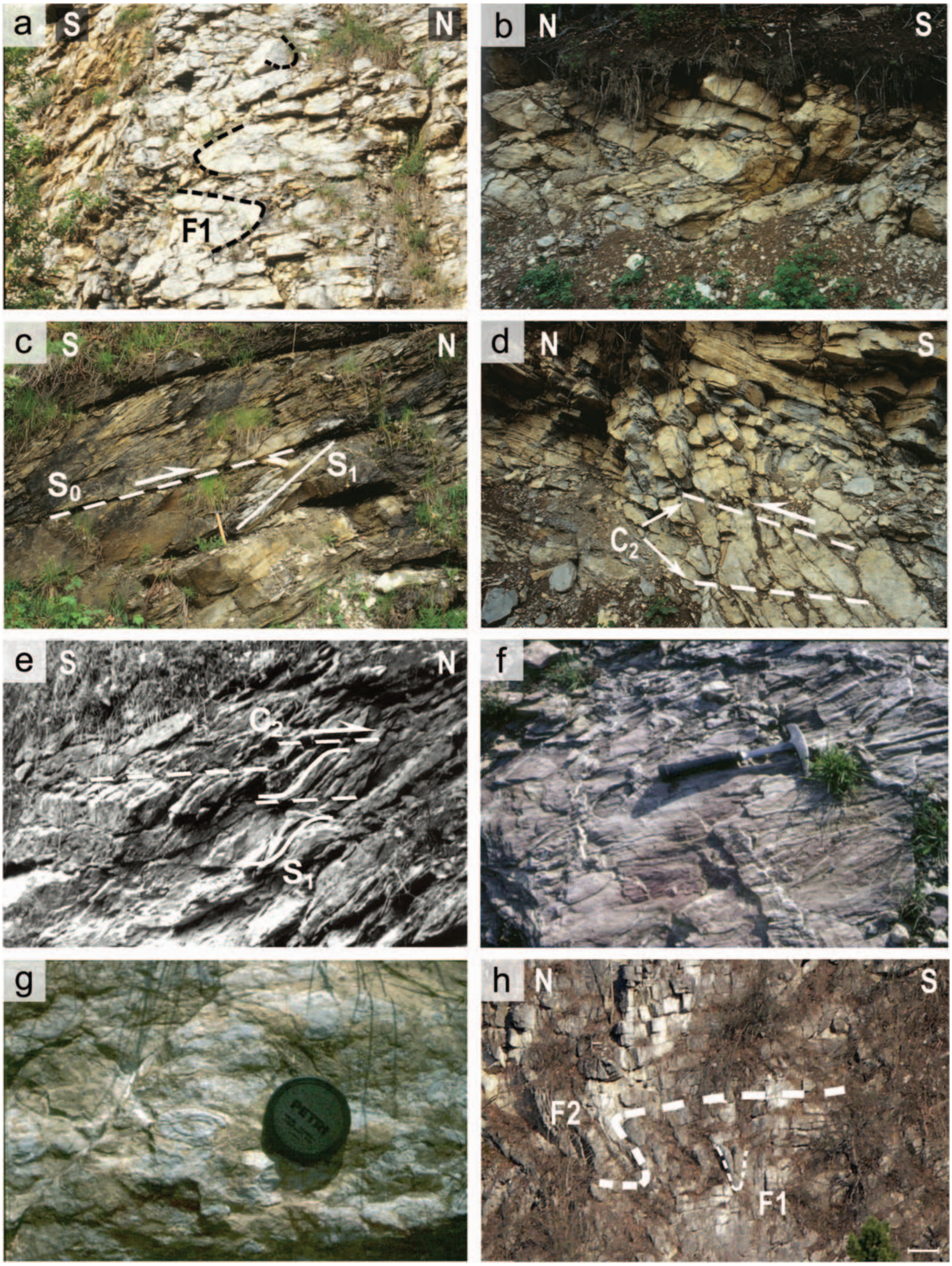

Fig. 4. Typical D1 and D2 mesostructures in Jurassic to Lower Cretaceous Krížna Nappe rocks: **a** — F1 folds — Banská Bystrica-Kostiviarska quarry; **b** — F1 folds — Staré Hory; **c, d, e** — C2 shear-like structures — Rybô-Staré Hory-Turecká; **f** — stretching lineation, Kostviarska; **g** — stretched ammonite in the Toarcian Adnet limestone, Rybô; **h** — F1 and F2 folds — Banská Bystrica-Urpín (scale bar is ~1 m).

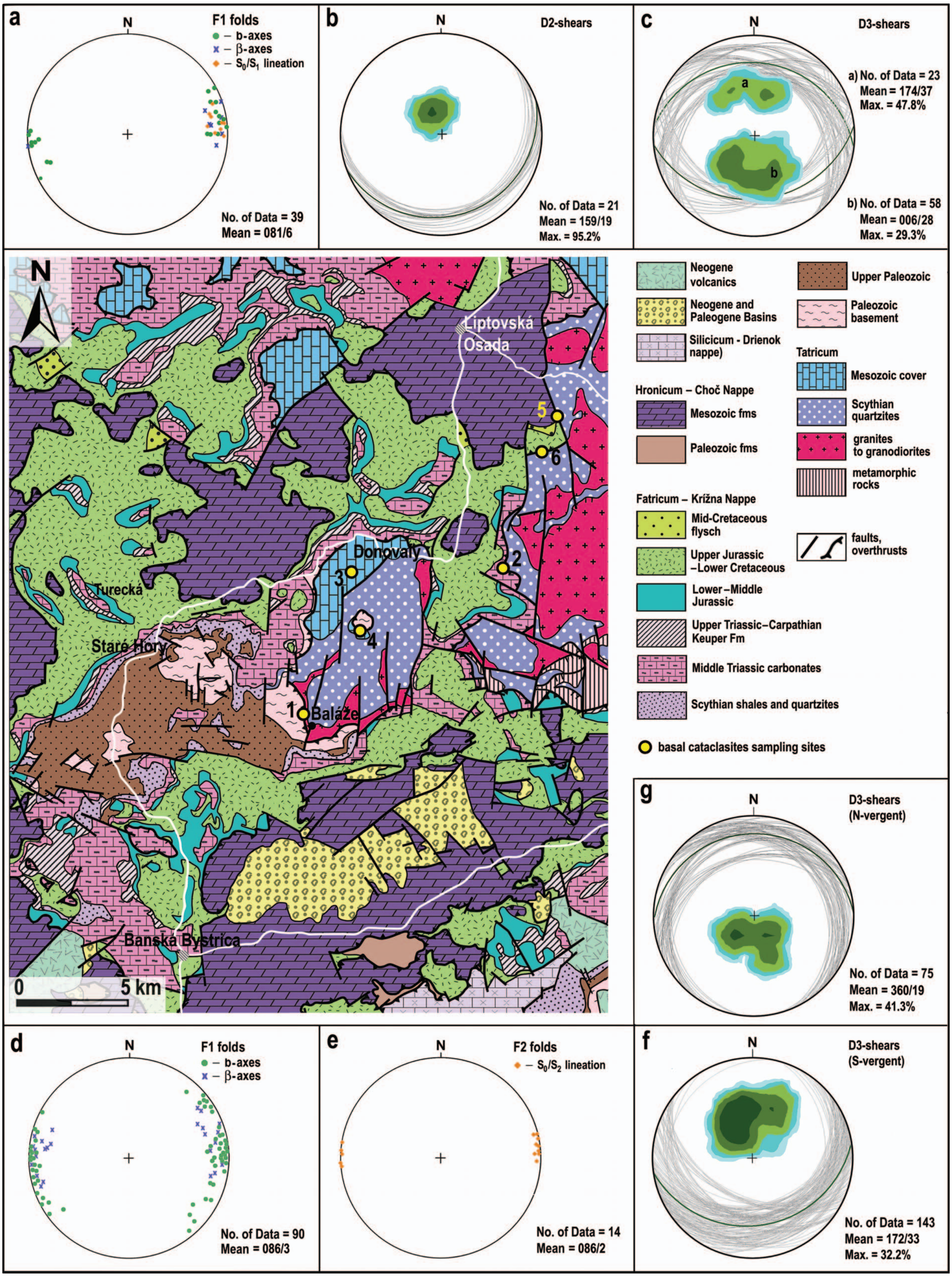

Fig. 5. Geological map of the study area between Banská Bystrica and Liptovská Osada (lower part of area "A" in Fig. 1a; after Biely et al. 1992; Polák et al. 1997a, 2003, modified) with FI microthermometry sampling sites (1 — Baláže, 2 — Barboriná, 3 — Donovaly, 4 — Kalište-Hrubý vrch, 5 — Liptovská Lúžna-Čierny vrch, 6 — Patočiny) and stereograms showing orientation of main tectonic mesostructures in the Krížna Nappe (lower hemisphere of Lambert's equal-area projection): **a–c** — Staré Hory-Turecká-Donovaly; **d–g** — Banská Bystrica surrounding.

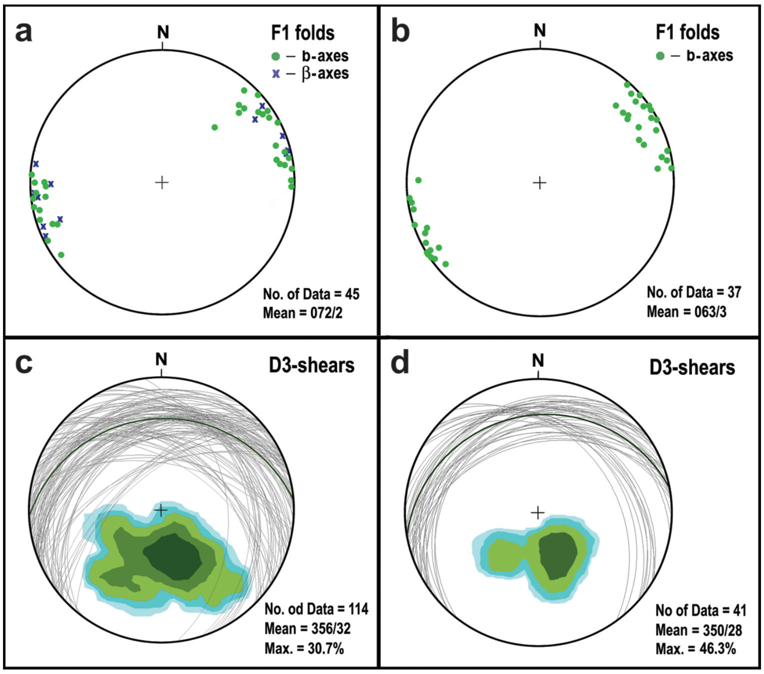

Fig. 6. Stereograms showing orientation of main D1 and D3 tectonic mesostructures in dorsal and near-frontal areas of the Krížna Nappe (lower hemisphere of Lambert's equal area projection): **a, b** — F1 fold axes — Ružomberok surrounding (a), Strážovské vrchy Mts and Krivánska Malá Fatra — East (b); **c, d** — D3 shear bends with "top to the North" kinematics — Nízke Tatry Mts (Northern slopes) and Ružomberok surrounding (c), Strážovské vrchy Mts (d).

frontal ramp might be paleogeographically identified with the South Tatric Ridge, which the Krížna Nappe had to overcome during the early stages of thrusting, namely the D_1 deformation stage (Fig. 12b). It might also be inferred, that remagnetization of the Krížna Nappe body in a southward inclined position (hinterland dipping duplex — Grabowski 2000; Grabowski et al. 2009) occurred during this "ramp" stage.

North-vergent thrust-related F_2 folds (associated with S_2 cleavage steeply inclined to the south) are frequent in more competent (e.g. majolica and biancône type) limestones in the rear zone of the Krížna Nappe (Banská Bystrica surroundings). Axial directions of F_2 folds (accompanied by S_0/S_2 cleavage-bedding intersection lineation) are sub-horizontal with E-W trend, and so nearly homoaxial with the F_1 folds (Fig. 4h). All the types of D2 structures are more obvious in the near-rear and dorsal parts of the Krížna Nappe.

Extensional shear-like structures with generally "top to the N" kinematics referred to as D3 structural association have the position of reactivated $S_0(C_3)$ planes slightly to moderately inclined (10–50°) towards the NW–NE and/or newly formed S-C-like shears (C_3) slightly inclined (10–35°) towards the NW–NE in areas with strong south-dipping cleavage S_1 (Figs. 5, 6 and 7). Their origin in the stress field with vertical to steeply foreland-inclined σ_1 is most probable, although their slightly variable kinematics (from "top to the NW" to "top to the NE") can be a result of partly unrestricted (both laterally and frontward) forward movement. North-vergent D_3 shears are the most conspicuous in the dorsal and near-frontal areas of the Krížna Nappe (Fig. 6c,d). Towards the rear zone two conjugate systems appear (Fig. 5c,f,g) that, along with crenulations (Fig. 7f) and boudinage of more competent beds, suggest sub-vertical flattening component of strain in this area during D3. Segmentation and boudinage of competent members is more obvious at map-scale, where they are revealed by the lack of some stratigraphic members in the deep-water Jurassic successions. They have been identified from many areas in the CWC (Bujnovský 1979; Maheľ 1985; Nemčok et al. 1993; Polák et al. 1997b). The fact that boudinaged formations are situated mostly between two incompetent complexes — the Carpathian Keuper Formation below and the Lower Cretaceous marlstones above — supports this suggestion.

Numerous extensional faults with variable orientation and other related brittle structures should be associated with the post-emplacement D4 stage. Most of them can be related to the Paleogene/Neogene gravitational collapse and lateral extension of the CWC nappe stacks leading to fast cooling and exhumation of CWC crystalline complexes confirmed by fission track data (e.g. Kováč et al. 1994; Danišík et al. 2008, 2010) and/or by movements in the Central Slovak Fault System (Kováč & Hók 1993).

Mid-Cretaceous flysch complex — K2

The Albian–Cenomanian Poruba Formation is accumulated mostly in the frontal parts of the Krížna Nappe. Foreland-ward increase of thickness and coarsening upward indicate the syntectonic nature of this flysch complex. The geometry of synsedimentary structures such as olistoliths, slump breccias and slump folds together with paleo-current markers in the Vlkolinec Breccia Formation (Jablonský & Marschalko 1992) situated on the base of the Poruba Formation indicate NNW paleoslope inclination as a result of compression and thrusting in the rear part of the Krížna Nappe accompanied by foreland flexing (Plašienka 1999). At the same time, the Poruba Formation shows a structural independence from the underlying Krížna complexes, which indicates its partial detachment and a relative forward movement during the final stages of the nappe emplacement.

p-T regime on the nappe sole

Basal tectonic breccias — occurrence and petrography

Since the carbonate hydraulic breccias (so-called rauhwackes) are a common rock type in the soles of all the CWC cover nappes including the Krížna Nappe, some authors proposed that overpressured fluids must have played an important role during their emplacement (Plašienka & Soták 1996). Rauhwackes are valuable nappe-base material because they are able to provide information on the p-T regime at the time of the nappe displacement. Supra-lithostatic pressures determined from the basal rauhwackes of the Muráň Nappe

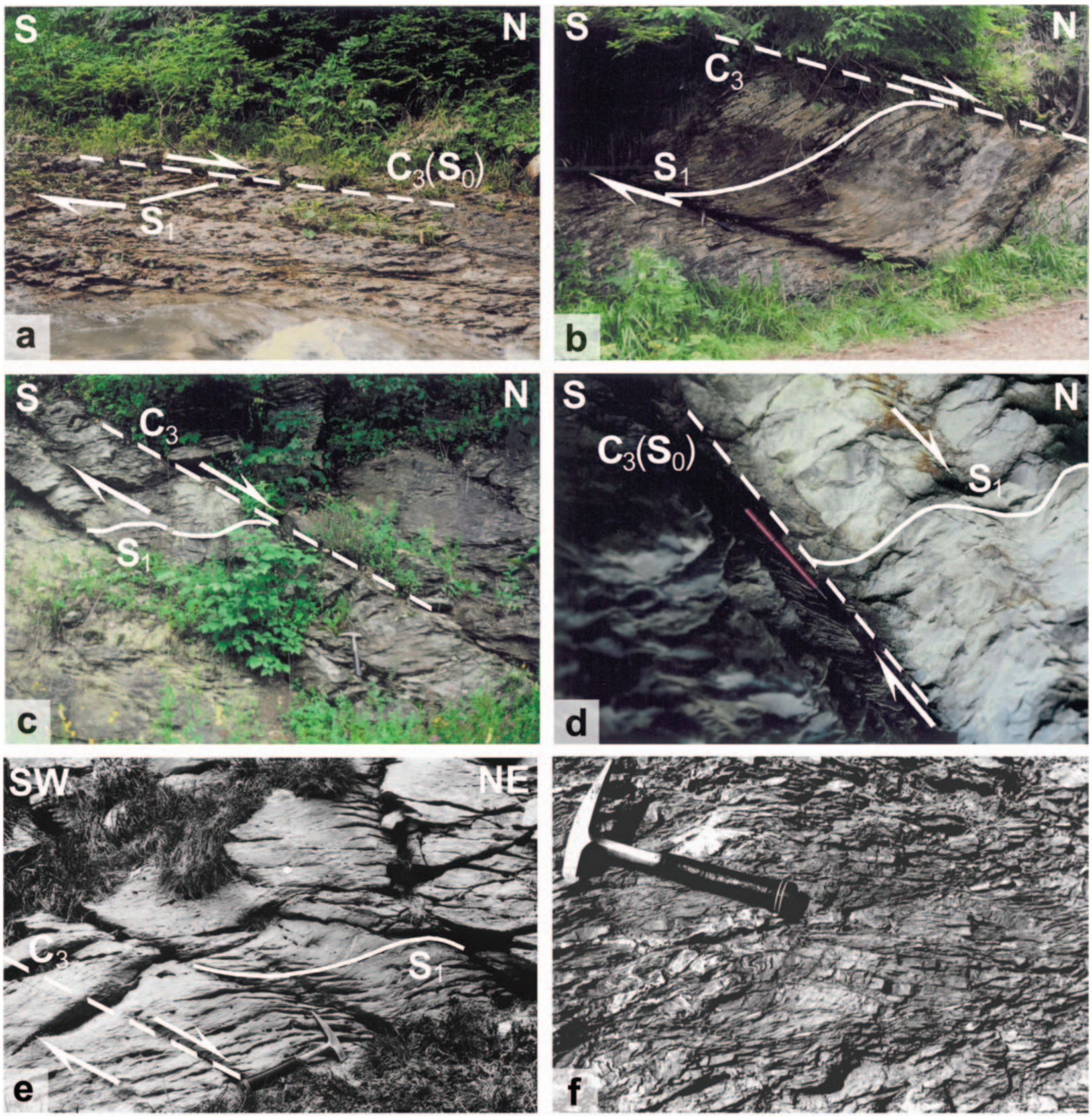

Fig. 7. Typical D3 structures in Jurassic to Lower Cretaceous Krížna Nappe rocks: **a–e** — shear-like D3 structures: Nízke Tatry Mts — Iľanovo Valley (a, b) and Ľupčianska dolina Valley (c, d), Belianske Tatry — Kopské sedlo-Hlúpy (e); **f** — subvertical flattening crenulation cleavage (Banská Bystrica-Kostiviarska).

(Milovský et al. 2003) challenged us to obtain analogous data from the sole of the Krížna Nappe to detect the p-T regime accompanying its emplacement.

Basal cataclasites, similar to those described from the Muráň Nappe (Milovský et al. 2003), were also observed on the foot of the Krížna Nappe, mainly in its rear zones, where it reposes on anchizonally metamorphosed Tatric cover units (Fig. 5a). The cataclasites are very variable in appearance, from monomict varieties with boxwork textures and leached dedolomite fragments to highly polymict breccias, containing fragments of carbonates and shales, scarcely of crystalline rocks (gneiss in breccias from Kalište — Hrubý vrch Hill). Textures of hydrofracturing and dedolomitization are ubiquitous. The newly-formed mineral assemblage comprises quartz, pyrite, dravite tourmaline, microcline, albite and anhydrite (which is only present as inclusions in other minerals). The matrix consists of newly-crystallized calcite cement, contaminated by microclasts and clay minerals. We propose that basal tectonic breccias have formed during partial nappe movements by grinding wallrocks of the thrusting plane and reworking of frontal debris of the advancing nappe. The characteristic petrographic features of basal rauhwackes are illustrated in Fig. 8a–c.

Fluid inclusions

The quartz, tourmaline and feldspars from basal tectonic breccias contain numerous fluid inclusions (FI), which were

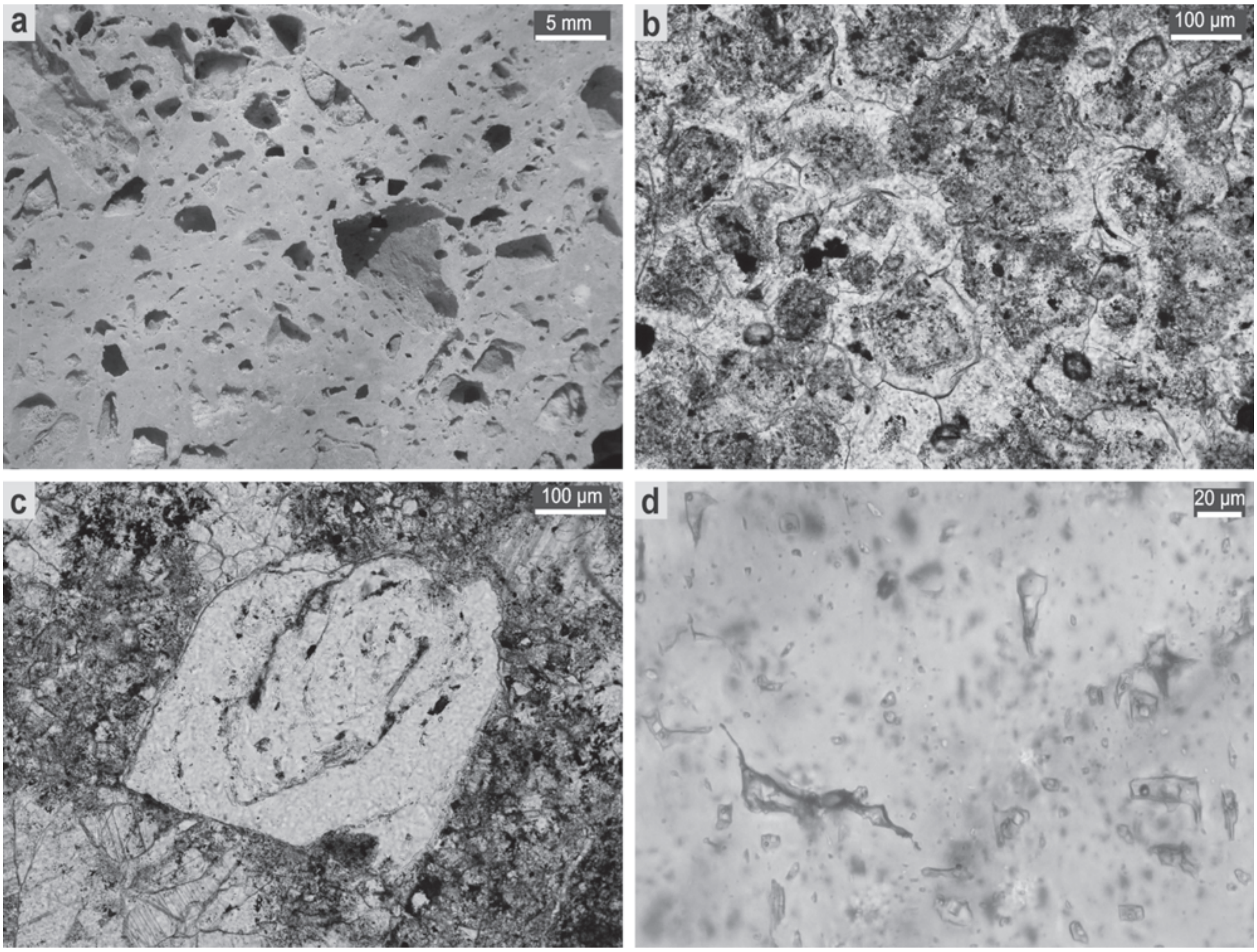

Fig. 8. Characteristic petrographic features of basal rauhwackes: **a** — typical texture with cavities after leached dolomite fragments in calcite matrix (Patočiny); **b** — newly crystallized calcite cement of incompletely dedolomitized clasts often encloses relic rhombs of dolomite (Kalište-Hrubý vrch); **c** — large crystal of newly-formed quartz, growth zones marked by solid inclusions of anhydrite, tourmaline and mica hint at a polyphase growth (Kalište-Hruhý vrch); **d** — array of fluid inclusions in crystal of newly-formed quartz (Patočiny).

investigated (in quartz only) to constrain the p-T conditions and chemical properties of included fluids. Clearly neoformed minerals are devoid of matrix calcite inclusions and they appear as crystallized into open space, yet they are often fractured and besides primary FI (trapped during crystal growth) they contain secondary inclusions, trapped along healed fracture planes. These features (analogous to those studied previously by Milovský et al. 2003) lead us to conclude that fluids were trapped in crystallizing minerals synkinematically, and thus refer to conditions of thrusting events.

Primary fluid inclusions (FI) are either scattered or form small isolated groups. Secondary FI are arranged in planar arrays along healed cracks. Inclusions are of irregular shape, typically up to 10 micrometers in size (Fig. 8d). At room temperature, they contain aqueous liquid (L), vapour bubble (V) and crystal of halite (H). All populations showed homogeneous volumetric phase ratios of individual FI (Fig. 9), and no other coevally trapped phases were observed, thus ruling-out entrapment of heterogeneous fluid.

Phase transformations were observed upon heating of completely frozen fluid inclusions, from approximately −100 °C up to temperature of total homogenization. Homogenization successions were invariably as follows:

- T_e — first melting or "eutectic" temperature at −65 to −40 °C;
- Gradual hydration of halite above the first melting temperature;
- T_mI — melting of ice at −25.3 to −12.2 °C;
- T_mHh — metastable dissociation of hydrohalite up to +15 °C;
- T_h — homogenization of vapour bubble in liquid phase from 65 to 192 °C;
- T_mH — dissolution of halite crystal at 193 to 344 °C.

Temperature ranges for particular samples are given in Table 1. First melting temperatures are equal to, or slightly lower than true eutectic temperatures and depend on association of coexisting solid salt species with liquid electrolyte (abbreviations of daughter-phase mineral names are used here as follows: I — ice, H — halite, Hh — hydrohalite $NaCl \cdot 2H_2O$, Ca4 — $CaCl_2 \cdot 4H_2O$, Ca6 — antarcticite $CaCl_2 \cdot 6H_2O$,

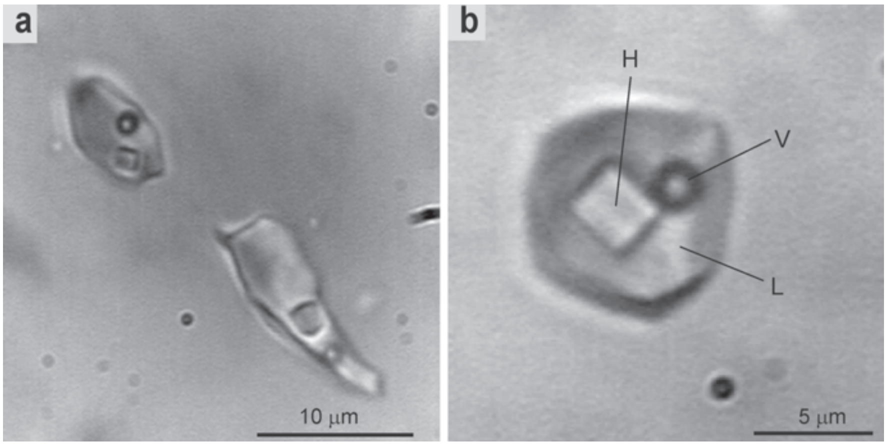

Fig. 9. Fluid inclusions in newly formed quartz crystal at room temperature (Patočiny): **a** — nearly identical phase ratios of three-phase fluid inclusions suggest trapping of homogeneous fluid; **b** — three-phase FI contain an NaCl-saturated aqueous liquid (L), vapour bubble (V) and cubic crystal of halite (H).

Table 1: Summary of temperatures of important phase transformations, calculated salinities (Sterner et al. 1988) and pressures (Brown & Lamb 1989).

Sample	T_e (°C)	T_mI (°C)	T_h (°C)	T_mH (°C)	wt. % NaCl	*P* (kbar)
Bal	–47 to –40	–13.6 to –12.2	107–192	198–297	31.8–37.9	0.25–2.42
Bar			117–175	269–344	35.9–41.9	2.02–4.03
Dono	–62 to –43	–25.3 to –21.9	83–123	211–294	29.4–37.7	1.78–3.55
KalHV	–62 to –41		119–161	240–324	34.1–40.1	1.61–2.97
LLČV	–65 to –44	–23.0	65–152	193–318	31.5–39.6	1.83–2.97
Pat	–44.5	–44.5	90–137	241–307	34.1–38.7	1.83–3.79

Explanations: **Bal** — Baláže, **Bar** — Barboriná, **Dono** — Donovaly, **KalHV** — Kalište-Hrubý vrch, **LLČV** — Liptovská Lúžna-Čierny vrch, **Pat** — Patočiny, $\mathbf{T_e}$ — first melting or "eutectic" temperature, $\mathbf{T_m}$**I** — melting of ice, $\mathbf{T_h}$—homogenization of vapour bubble in liquid phase, $\mathbf{T_m}$**H** — dissolution of halite crystal at 193 to 344 °C.

Mg8 — $MgCl_2 \cdot 8H_2O$, Mg12 — $MgCl_2 \cdot 12H_2O$). In our samples they cluster between A) –65 and –55 °C, B) –55 and –53 °C and C) –52 and –40 °C. Groups A) and B) may refer to eutectic melting in metastable associations Ca4+H+I at –70 °C and Mg8+H+I at –55 °C, respectively (Davis et al. 1990). Span of the group C) covers eutectic temperatures in stable associations Mg12+Ca6+I at –52.2 °C, Ca6+Hh+I at –51.6 °C and Ca6+I at –49.8 °C (Linke 1965a,b; Spencer et al. 1990). Summarizing this, trapped fluids contain oversaturated brines from the system Na-Ca-Mg-Cl. Salinity expressed in wt. % of NaCl equivalents was calculated using the equations of Sterner et al. (1988) at the homogenization temperature of halite and is denoted on the right y-axis of the diagram in Fig. 10. Overall range is 29.4 to 41.9 wt. %.

In one inclusion (LLČV-2-1-1) a sylvite daughter crystal was present at room temperature, but it dissolved in aqueous liquid at 106 °C after bubble homogenization and prior to halite dissolution. This succession allowed us to determine the NaCl/KCl weight ratio to 0.99 and overall NaCl+KCl salinity to 42.3 wt. % (Sterner et al. 1988).

Final homogenization temperatures are dispersed in an unusually wide range, stretching over 150 °C, between 193 and 344 °C (Fig. 10). Spans for particular localities Bal-1, Bar-1, Dono-62, KalHV-1, LLČV-1, Pat-1 are 99, 75, 150, 84, 98, 66 °C, respectively. The *T*mH spans for individual FI populations in quartz grains are mostly within 30 °C, exceptionally more, up to 147 °C (Dono 62-3).

Pressure determination is based on the equation of the state for system H_2O–NaCl of Zhang & Frantz (1987), modified by Brown & Lamb (1989), using the *T*h and T_mH to calculate molar volume and isochore slope in two-phase L+H field. The values of pressure at *T*mH must be taken with a certain caution due to approximation of complex natural brine to the theoretical NaCl–H_2O binary. In the overall *T*mH span, the pressure also has an abnormally wide span from 0.25 to 4.03 kbar, with variations for particular localities up to 2.17 kbar and for particular FI populations up to 1.62 kbar (Fig. 11a).

The whole p-T dataset as well as the plots for particular localities scatter in elongated fields approximately parallel to isochores in the liquid field of the NaCl-H_2O system (Fig. 11a). In p-T plots for particular FI populations in individual quartz crystals, two distinct patterns appear repeatedly: (i) a transverse, nearly isochore-parallel trend, and (ii) a vertical, nearly isothermic trend (Fig. 11b). However, the directions of these trends remain unclear, as we do not know the trapping succession of individual FI.

Discussion

The evolution of the Krížna Nappe has been discussed in several papers (e.g. Biely & Fusán 1967; Jaroszewski 1982; Maheľ 1983; Jacko & Sasvári 1990; Plašienka & Prokešová 1996; Plašienka 1999). Evolutionary models presented there are based mainly on, indisputably important, paleogeographic and paleotectonic evidence. However, results obtained by structural analysis together with p-T data providing basic information about the nappe-base regime can be crucial for detection of emplacement mechanisms of shallow-crustal thrust units. Several stimulating discussions have been written on this topic (e.g. Coward & Kim 1981; Sanderson 1982; Merle 1986, 1989,1998; Geiser 1988; Gray & Willman 1991; Grant 1992; Schulz-Ela 2001) from which the following most important issues for such debate arose:

- Character of the nappe sole and p-T regimes operating on the basal thrust plane;
- Degree of tectonic inversion;
- Strain partitioning, deformation gradient and progressive deformation history;

- Displacement gradient and trajectory;
- The scale of observation.

Character of the nappe sole and p-T regime in the basal thrust zone

Existence of a weak décollement is the most important feature of all the nappe emplacement models. A weak base can be formed by easily-deformable rocks such as evaporites or shales (e.g. Kehle 1970; Davis & Engelder 1985; Jaumé & Lilie 1988), mylonites with pseudo-viscous behaviour (Schmid et al. 1981; House & Gray 1982; Wojtal & Mitra 1986), "superplastic" calcite tectonites (Schmid et al. 1977; Schmid 1982), high fluid pressure (Hubert & Rubey 1959) or other softening mechanisms.

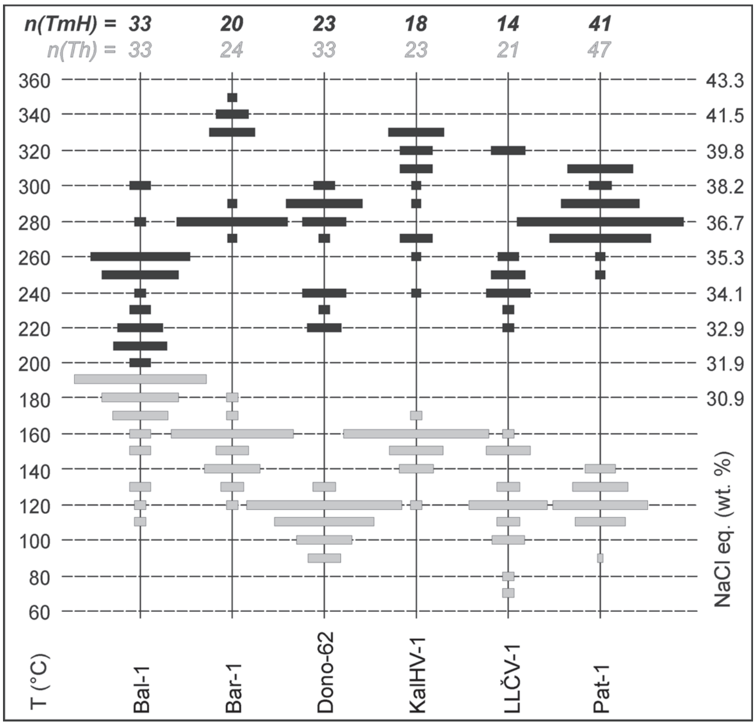

Fig. 10. Histograms of *T*h (dashed bars) and *T*mH (solid bars) in fluid inclusions. Salinity expressed in NaCl equivalents is on the right y-axis. Sample names are indicated below histogram axes, numbers of measurements above them — in dashed letters for *T*h and in solid letters for *T*mH.

The concept of the Krížna Nappe detachment along the weak horizon of the Upper Scythian (Werfenian) shales and evaporites is almost classical in the Slovak geological literature. This role of the Werfenian shales can be inferred from their rheology and stratigraphic position between two rigid members. Since these rocks are only rarely preserved, the base of the Krížna Nappe is more frequently formed by massive Triassic carbonates (T2) with a thin horizon of carbonate tectonic breccias (rauhwackes) at their sole. Processes of pressure solution, recrystallization and alteration have been recognized in the Krížna Nappe-base (Bac-Moszaszvili et al. 1981; Jaroszewski 1982; Jurewicz 2005, 2007) also in its frontal position where classic rauhwackes are not present.

The widely occurring phenomena of hydraulic brecciation and reaction-softening due to dedolomitization point to high activity of pervasively circulating fluids along the basal thrusting plane. Fluid inclusions (FI) in newly-formed minerals were trapped in the course of these fluid-rock interactions and thus record their dynamics.

In the studied FI populations, no obvious evidence of heterogeneous trapping of brine and solid halite was observed. This suggests trapping at the halite liquidus by temperature decrease. Thus they do not necessarily represent exact trapping temperatures, and may also be regarded as their lowest limit. The extremely wide p-T ranges may then be explained in two ways: (i) only the high-

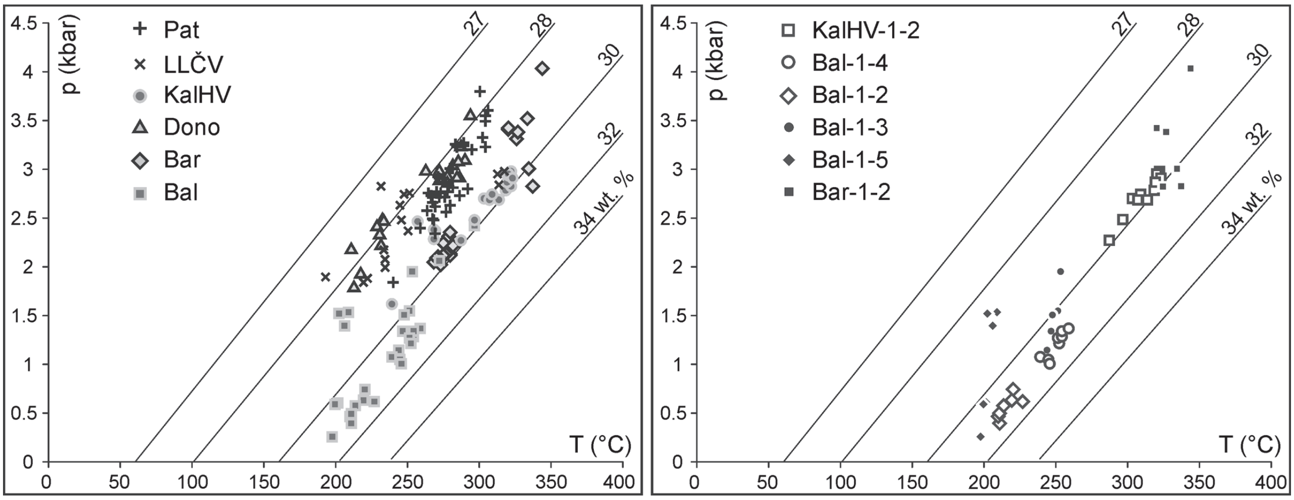

Fig. 11. Pressure calculated at temperatures of total homogenization according to equations of Brown & Lamb (1989) for NaCl–H_2O system. Dashed curves represent isochores in one-phase liquid field. Left — data for all studied samples, right — example of two prevailing p-T trends in FI populations: open symbols — "transverse" trend, solid symbols — "vertical" trend.

est data reflect true trapping p-T conditions, namely trapping at, or close to halite liquidus, while all other inclusions trapped unsaturated brines. Large variations in salinity are expected during trapping of individual FI populations; (ii) the p-T data represent the true trapping conditions, which implies trapping at NaCl saturation level. It may be achieved either by steady saturation of circulating fluids in the course of temperature increase, or oversaturation/precipitation in the course of cooling.

With the first alternative, the trapping conditions come constrained at some 2.4 to 4.0 kbars and 290 to 340 °C. The second alternative proposes large p-T variations during entrapment, mostly along "transverse", or "vertical" trends described in the results section. The "vertical", nearly isothermal trends may represent either the pressure rise, or drop. They are typically recorded in populations of secondary FI on healed crack planes, that is trapped at episodic cracking of quartz grains. On the other side, "transverse", near-isochoric trends dominate among primary inclusions, and may represent either gradual cooling or gradual heating during grain growth. Considering the usual orogenic geothermal gradients of 25–30 °C in the upper crust and published illite-crystallinity data (Plašienka et al. 1989) the lower temperature limit is roughly consistent with diagenetic overprint of the Krížna Nappe, but the upper temperature limit is anomalous and should be interpreted in terms of focused hydrothermal fluid flux.

Two sources of heat come into account, which may also combine: (i) intrinsic — frictional heating by pervasive cataclasis in course of kinematic events; (ii) external — injections of hot overpressured metamorphic fluids from the underlying Tatric basement units. The latter involves an external fluid budget, which presumably mixed with autochthonous fluids, circulating in basal formations. Both may well explain the observed trends, if we putatively link (or loop) them in the sense: "transverse" upwards — "vertical" downwards. We suggest two different mechanisms responsible for such hypothetic fluid p-T pulsing: a "frictional heating", whereby thrusting is a driving force for p-T pulse; and a "hot injection" of overpressurized fluid, which in turn triggers the thrusting. Causalities of both mechanisms are summarized in Table 2.

Since we do not have time-series of FI p-T data, the preferred scenario must be deduced from indirect hints. The "frictional heating" mechanism is simpler, as it only assumes one fluid budget. On the other side it can hardly explain coeval precipitation of quartz, anhydrite and calcite, which have opposite temperature dependence of solubility (quartz prograde while anhydrite and calcite retrograde). The "hot injection" mechanism however expects mixing of deep hot fluids, rich in silica, with cooler formation waters, saturated by sulphate and carbonate. The silica may thus precipitate due to temperature drop and sulphates due to temperature increase at the same time. Pressure and temperature spans would then mirror various mixing ratios of basement fluids with formation waters.

Another hint may be the spatial distribution of basal tectonic breccias. We found them exclusively in the rear-part of Krížna Nappe, where it is thrust over anchizonally metamorphosed South Tatric complexes (Donovaly cover unit — e.g. Rakús et al. 2003) capable of generating large amounts of hot overpressured fluids. Moreover, the South Tatric realm created an elevated area in the time of the Krížna Nappe translation. Thus a compressional regime of nappe emplacement can be proposed to overcome this frontal ramp (i.e. South Tatric Ridge). Since a compressional stress field helps to contain overpressured fluids (Sibson 2004) due to higher pressure gradient in convergent tectonic settings (Petrini & Podladchikov 2000), supralithostatic pressures (fluid vs. lithostatic pressure ratio $\lambda v > 1$) could have been achieved episodically at this stage. The scarcity of typical rauhwackes in more frontal parts may be explained by insufficient temperature gradient between substrate and nappe rocks. Cavernous calcitic rocks with evidence of leaching and pressure solution present in these frontal zones (Jaroszewski 1982; Plašienka & Soták 1996; Jurewicz & Słaby 2004) confirm that fluids surely played a key role also during the northward translation of the nappe from the South Tatric Ridge. However, p-T conditions at the nappe sole during this stage remain unknown. If the gravitational regime of the nappe emplacement is applied, a maximal fluid overpressure had to be limited by overburden pressure (e.g. Sibson & Scott 1998). On the other hand, hydrostatic to lithostatic fluid pressure fluctuation ($0.4 > \lambda v < 1.0$) could have effectively facilitated nappe movements via acceleration of load-weakening of the basal zone leading to its episodic failure (Sibson 1993) in the gravitational regime.

Degree of tectonic inversion

Although tectonic inversion is probably very common in compressional orogens at all scales, its intensity is not easily recognizable due to the high intensity of compression (e.g McClay & Buchanan 1992).

Table 2: The two hypothetical mechanisms of p-T pulsing on Krížna Nappe base — synopsis of events, their causes and p-T regime of fluids. The terms *adiabatic* and *isochoric* are approximative.

Mechanism	**Frictional heating**	**Hot injection**
Drive	**Thrusting**	**Fluid injection**
1. standstill 190–210 °C 1.6–1.7 kbar	**Pre-kinetic:** basinal brines in basal formation (Scythian shales and sandstones with evaporites), circulating or stagnant at "ambient" diagenetic conditions	
2. prograde transverse path upwards	**Kinetic:** detachment and thrusting → frictional heating → *adiabatic* thermal pressuring	**Pre-kinetic:** injections of hot overpressured basement fluids: fluid mixing → *isochoric* heating + pressuring
3. peak 300–340 °C 3–4 kbar	**Kinetic:** main thrusting, maximum frictional heat production	**Pre-kinetic:** culminating fluid influx from the basement
4. collapse transverse or vertical path downwards	**Post-kinetic:** thrusting arrest → breakdown of p-T peak by gradual *isochoric* cooling of fluid in sealed porosity	**Kinetic:** fluid pressure surpassed the shear strength of basal rocks → detachment → collapse of p-T peak by *adiabatic* decompression

In the case of the Krížna Nappe, the north-south oriented (in the present geographical coordinates) Jurassic extension of the Zliechov Basin has been predicted (e.g. Plašienka 2003). Michalík (2007) proposed a transtensional, pull-apart model for the Zliechov Basin formation. Accordingly, the extensional faults in the northern part of the Zliechov Basin were inclined to the south, and so compatibly with Cretaceous compression. Huge north-ward plunging recumbent folds (so-called "digitations") in the frontal zone of the nappe (e.g. Polák 1979; Maheľ 1985, 1986) were probably initiated by contractional reactivation of originally extensional faults associated with roll-over anticlines. On the other hand, inclination of extensional faults at the southern part of the Zliechov Basin should not be estimated with doubt because both cases, symmetrical or asymmetrical extension, were possible. Although extensional faults were inclined against the direction of Cretaceous compression (i.e. to the north) in the case of symmetrical extension and their simple reactivation was thus improbable, rotation and turnover of these faults, softened by underthrusting to greater depth beneath an advancing orogenic wedge, have been proposed by Plašienka (1999, 2003).

The present tectonic situation in the "root" area of the Krížna cover nappe reveals a total inversion of the Zliechov Basin and detachment of its sedimentary infill followed by diminishing of its former basement substratum by underthrusting below the overriding Veporic thrust wedge (Plašienka 2003). In places, the toe of the Veporic thrust sheet directly overthrusts the southern Tatric margin, which meant that the former basinal area was entirely sutured. This thrust fault is known as the Čertovica "line" in the Carpathian literature (Biely & Fusán 1967; Andrusov 1968).

Progressive deformation history, strain partitioning, deformation gradient

Concerning progressive deformation history, two aspects seem to be important: i) structural associations developed as a consequence of rear compression are typical for the first two deformational stages D1 and D2, although the structural pattern of D2 can be characterized by larger tendency to slip (i.e. compressional shear). Together with increasing intensity of contractional strain towards the rear part of the nappe these facts suggest rear compression as the driving force at early stages of the Krížna Nappe's evolution; ii) the structural association linked to the extensional shear mode of strain, typical of the D3 deformation stage, is connected with a changed tectonic regime moving the Krížna Nappe from rear compression to gravity-controlled modes of emplacement. Distribution of extensional shears over the whole thrust unit (although concentrated to mechanically suitable horizons) most closely matches with the gliding-spreading emplacement mechanism (cf. Merle 1998) during this stage. Both additional attributes of D3, namely gradually varying character of extensional shears from conjugate system in the near-rear zones to clearly "top to the N" kinematic types towards the frontal zones, as well as increasing intensity of D3 from the base towards the top is in agreement with this model.

Deformed Krížna successions are a typical example of partitioned deformation. Strain partitioning along the vertical profile primarily depended on the rheological properties of the deformed multilayer (i.e. existence of weak and strong complexes), thus above all it is manifested by concentration of strain in mechanically suitable horizons. Position in the thrust unit (e.g. base vs. upper level) is crucial for the vertical deformation gradient, which means the concentration of simple-shear component in the basal zone and pure shear component in the top (mainly in the rear zone).

The deformation gradient along the longitudinal profile (parallel to the XZ principal plane of deformation) reflects several important aspects. (i) Primarily facies and lithological variability (deep-water vs. shallow-water succession and well-bedded incompetent vs. mostly massive competent strata, respectively), as well as the existence of extensional features (mainly faults) suitable for compressional reactivation should be noted. Northward plunging recumbent folds and duplexes in the frontal part of the nappe reflect contractional reactivation of extensionally weakened margins of the Zliechov Basin at early stages of the nappe's evolution (controlled by compression) followed by their rotation and forward rigid translation controlled by gravity. Partial units detached along higher weak horizons (i.e. Carpathian Keuper Formation) primarily reflect the facial changes in the Fatric sedimentary area emphasized by the increasing importance of higher décollements induced by the gradually changed regime of deformation in a substantial part of the Krížna Nappe. (ii) Position within the thrust unit coupled with variability of both the basal slope angle and mechanical properties of the nappe base — are the most important from this point of view and can be accommodated by a changing mode of internal strain in a transported wedge-shaped thrust unit. (iii) Changing emplacement mechanisms also play an important role. Stronger and multi-stage contractional deformation recorded in the rear part of the nappe and its North Veporic backstop (Veľký Bok and related units, Plašienka 1983, 1995a, 1999) reflects the "rear compression" acting on this zone for the whole time the of the nappe's evolution. Extensional shear strain with strong pure-shear component in the near-rear areas and simple shear with distinct "top to the ~N" kinematics towards the frontal zones developed as a result of the gravity controlled final emplacement.

Displacement gradient and displacement trajectory

The displacement gradient is considered one of the key features differencing the two main genetic categories of the nappe units, namely those generated by rear compression from those driven by gravity (Merle 1998). Although this criterion can be simply applied for thrust units considered in isolation, a problem should arise if the same unit is assessed in a broader context (i.e. in orogen scale).

Simply, studying amounts of displacement in the Mesozoic Fatric successions seems to make clear that the maximum displacement (up to 60 km) should be set for the Krížna Nappe front while travelling to the rear zone these successions create an autochthonous sedimentary cover of the North-Veporic basement (i.e. zero displacement should be set with respect to this basement). Such a displacement gradient would be characteristic for gravity controlled emplacement mechanisms, especially for gravity spreading. However, evaluating displacements on a larger scale, the Krížna Nappe must be considered as the frontal part of the joint Fatric-Veporic thrust system overriding the Tatric Superunit during the mid-Cretaceous shortening. The basal displacement plane did not fade out in the rear part of the Krížna Nappe. Instead it slopes downward to the base of crustal-scale Veporic thrust wedge (i.e. thin-skinned thrust unit passes into the thick-skinned one). Consequently, amount of displacement at the Tatric-Veporic Čertovica suture should be roughly approximated by the width of the disappeared Fatric substratum originally separating these two realms, which was at least 100 km (a minimal width of the Zliechov Basin, cf. Plašienka 1999). From this point of view, the displacement gradient problem appears to be more complex and needs to be evaluated not only spatially, but also temporally.

Obviously, the Krížna Nappe has been translated in front of the Veporic Superunit during the early stages when the rear compression was the main driving force. After the Tatric-Veporic collision, the forward movement of the Veporic thick-skinned sheet stopped and the Krížna Nappe moved forward independently due to gravity on a foreland-inclined paleoslope.

Retracing the exact displacement path of an allochthonous unit is an even more complex problem. Main complications summarized by Merle (1998) arise from the character of displacement of shallow-crustal thrust units which typically combines two components: internal strain and rigid translation. Frequently the displacement related to internal strain can be negligible in comparison with the displacement produced by rigid translation and their directions can be very different. In addition, there can be no particular relationship between the displacement achieved by internal strain and the displacement accomplished by rigid translation. Therefore, the displacement produced through rigid translation, very important in cover nappes, is hardly determined (in direction) or quantified by the methods of structural geology and can be studied only by means of paleogeographic reconstructions and paleomagnetic measurements.

Pre- or syn-thrusting paleomagnetic data from the Krížna Nappe were reported by Kruczyk et al. (1992), Grabowski (1995, 2000) and Grabowski et al. (2009, 2010). These data show a systematic variation from the west (Malé Karpaty Mts) to the east (Tatra Mts) — the western localities show Cretaceous paleodeclinations rotated counterclockwise (CCW) up to 70°, further east in the Strážovské vrchy and Malá Fatra Mts this CCW rotation decreases to 60–25°, in the Nízke Tatry Mts it is only 20°, then no rotation was detected in the Chočské vrchy and Western Tatra Mts, while the easternmost sites in the Eastern Tatra Mts and the Ružbachy "island" have already shown a clockwise (CW) rotation 20–50°. This fanwise arrangement of paleomagnetic declinations remains preserved also after subtracting the Late Tertiary CCW rotation of the whole Western Carpathian orogenic system by some 80° (Grabowski & Nemčok 1999; Márton et al. 1999; Grabowski 2010). Although particular directions might have been affected also by local tectonic phenomena, such as the vertical axis block rotation within wrench fault zones, or slight relative rotations of individual "core mountains" (Hrouda et al. 2002), the fanwise pattern of paleomagnetic directions might be interpreted in terms of oroclinal bending (Kruczyk et al. 1992; Grabowski 2010). Since the paleodeclinations are also subparallel to the presumed transport directions of the Krížna Nappe deduced from the kinematic criteria (Prokešová 1994; Kováč & Bendík 2002; Plašienka 2003), it is highly probable that they are also roughly parallel to the translation pathways of the Krížna Nappe System. Furthermore, the paleomagnetic and transport directions are normal to the trace of a suture after closure of the Zliechov Basin — the Čertovica line, which is also slightly northward-convexly bended. The Krížna Nappe directions are also comparable to those from the underlying Tatric Mesozoic complexes, at least in the Tatra Mts (Grabowski 1997). All these data collectively indicate that the Krížna Nappe was emplaced in its recent position as a coherently moving body without any considerable internal distortions at the orogenic scale. After emplacement, the Krížna Nappe created an originally straight belt that was bent shortly afterwards, namely during the Late Cretaceous but before the onset of sedimentation in the Central Carpathian Paleogene Basin.

The scale of observation

As it was pointed by Schultz-Ela (2001), this problem is highly underestimated in structural geology and appears sporadically in the literature. Nevertheless, the scale of observation appears to be a very important factor, which may markedly influence our subjective assessment of the problem (for example: cataclastic flow, which is the brittle deformational mechanism on the microscale, is regarded as a ductile process on the macroscale).

In our discussion, the scale of observation is important for the evaluation of the final mechanism of the Krížna Nappe's emplacement. We have relevant evidence that it was gravity-controlled. In the shallow crustal environments, which are characteristic of the Krížna Nappe's evolution, gravity gliding is conventionally proposed as a typical nappe emplacement mechanism. For this mechanism concentration of strain solely at the base of the nappe is typical. In the Krížna Nappe, however, strain is more distributed across the moving thrust unit mainly in the final emplacement-related stages (D3). Therefore, gravity spreading should be proposed as a contributory emplacement mechanism.

Usually, the main argument that restricts this mechanism to "very weak or very hot" rocks is a doubt that rocks can behave viscously in shallow crustal conditions (e.g. Mandl 1988). However, there are at least two higher weak horizons in the Krížna Succession for which spreading processes are possible — the Carpathian Keuper and Lower Cretaceous marls. In addition, the problem of gravity spreading appears differently when changing the scale of appreciation. Gravity spreading of the whole orogenic wedge is a widely accepted event that may be accommodated by a number of processes. Gravity gliding of small undistorted blocks of rocks as well as faulting, deformation along deformation bands or brittle shear zones and/or pressure solution are some of them. Especially the last named process, which is one of the most important deformation mechanisms in carbonate rocks, is considered analogous to the deformation of a viscous material (Rutter 1976, 1983).

Bearing this in mind and taking into account that a large part of the Krížna Nappe has been translated as a foreland slopped wedge (accumulation of the flysch of the Poruba Formation in its frontal areas) over a foreland inclined plane after overcoming the South Tatric Ridge (frontal zones of the Krížna Nappe rest on deep-water Tatric Poruba flysch, while its rear parts lie on the South Tatric Ridge) it is more than possible that the final emplacement of the Krížna Nappe has been accommodated by interaction of both gravity mechanisms (i.e. gliding–spreading).

Conclusions

The Krížna cover nappe of the Central Western Carpathians was characterized as an areally extensive, but comparatively thin allochthonous body continuously overriding the Tatric substratum. Originally, the Krížna Nappe sedimentary complexes were deposited in a broad basin that originated by Lower Jurassic rifting and subsequent subsidence of a portion of the widespread Triassic carbonate-clastic shelf area. The central part of this rift furrow is known as the Zliechov Basin with the Jurassic–Lower Cretaceous pelagic Zliechov Succession. The northern margin of the Zliechov Basin juxtaposed the southern edge of the present Tatric Superunit, which was represented by the South Tatric Ridge domain passing into another rifted basinal domain further northwards. The Vysoká-type, comparatively shallow-water successions, which also became constituents of the Krížna Nappe later, were deposited on this northern slope. The southern margin was also represented by more shallow-water successions (Veľký Bok, Lučatín). These mostly remained confined to their basement substratum and formed the northern toe of the thick-skinned Veporic thrust sheet afterwards. The Zliechov Succession is terminated by the synorogenic flysch complex — the Albian–Cenomanian Poruba Formation, which heralded the onset of the basement shortening due to underthrusting of its basement substratum below the prograding Veporic thrust wedge. The basin closure was completed by the Turonian. This was also the time of the final emplacement of the Krížna Nappe in superposition over the youngest sediments of the Tatric Superunit — basinal shales and turbidites of Early Turonian age.

On the basis of analysis and interpretation of both the small-scale and large structures, the structural evolution is partitioned into several stages of progressive deformation that record the changing boundary conditions in different parts of the nappe body at different time levels. At the same time, the nappe body is regarded as a lithologically variable and rheologically stratified multilayer unit with presence of three potential décollement horizons exhibiting a downwardly increasing significance for the nappe transport. The basal décollement followed the horizon of Upper Scythian shales and evaporites and was transformed into a nappe sole during the later stages of emplacement. The middle décollement horizon occurred in the Upper Triassic shales and evaporites (Carpathian Keuper Formation) and was important for detachment of some frontal, Vysoká-type partial units. The highest décollement allowed a partially free movement of the youngest member of the Zliechov Succession — the Poruba Formation.

Considering the available data, we have defined the most important phenomena that would constrain further thoughts about the origin and emplacement of the nappe. These are as follows: (1) complete inversion and suturing of a broad rifted basinal area bounded by elevated domains; (2) strain partitioning within a mechanically stratified multilayer unit; (3) décollement horizons; (4) weak nappe

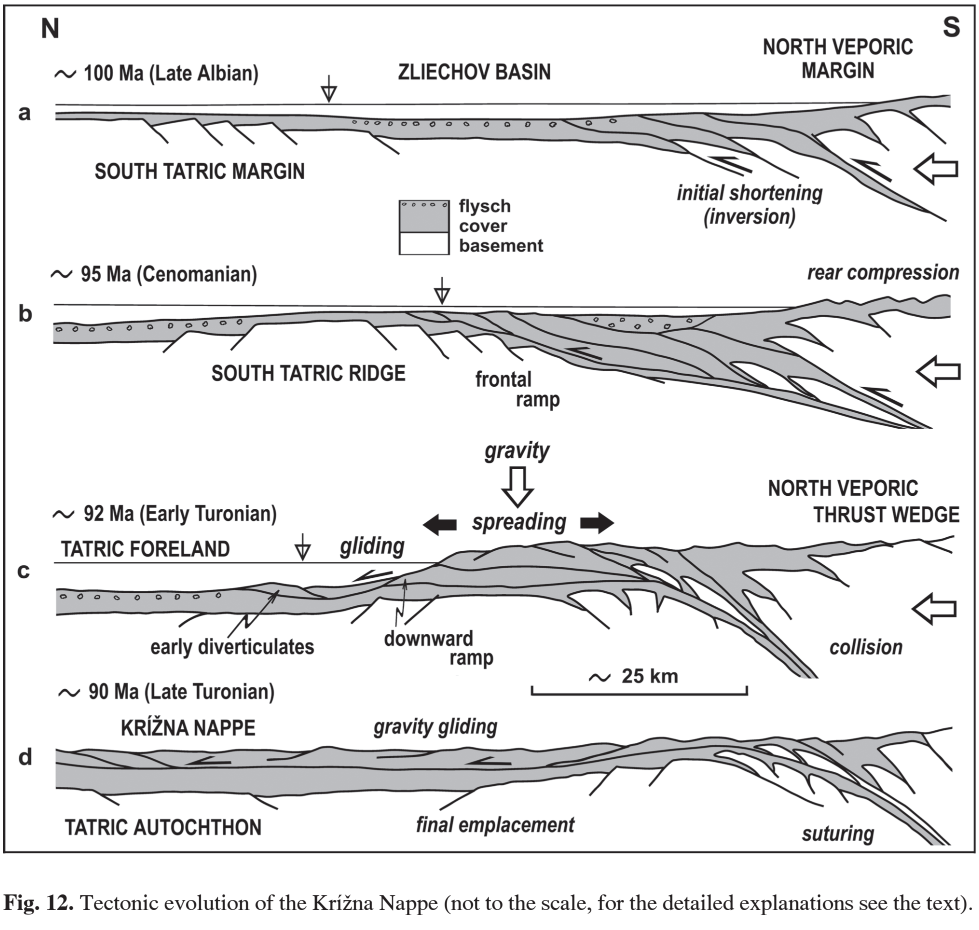

Fig. 12. Tectonic evolution of the Krížna Nappe (not to the scale, for the detailed explanations see the text).

sole; (5) stress and strain gradients, both vertical and horizontal; (6) structural associations of several deformation stages; (7) external constraints for the nappe movement.

In general, no simple mechanical model for the nappe emplacement can be applied. It appears that all potential emplacement mechanisms and driving forces temporally and spatially participated in the progressive structural evolution of the nappe. The rear compression provided by the backstop Veporic thrust sheet operated during the early stages, when the sedimentary succession of the Zliechov Basin was detached, shortened and transported over the frontal Tatric ramp. Subsequently, gravity spreading and gliding governed the final nappe emplacement over the unconstrained Tatric basinal foreland. In other words, the nappe was first pushed to overcome the frontal ramp (Fig. 12a,b), which was in fact a narrow ridge elevation. In this high structural position, the nappe body experienced gravity spreading and partial detachment of small diverticulates that glided furthest to the north (Vysoká, Manín, Klape and analogous units — cf. Plašienka 1995; Fig. 12c). After the Zliechov Basin was completely closed, the main nappe body was pulled downslope by gravity and glided to its final position (Fig. 12d).

This doubled up-down ramp model seems to be unique worldwide and makes the Krížna Nappe a model structure of thin-skinned thrust tectonics.

Acknowledgments: This research was supported by the Scientific Grant Agency of the Ministry of Education of the Slovak Republic and the Slovak Academy of Sciences (VEGA Projects 1/0388/10, 1/0157/10 and 1/0744/11) and Slovak Research and Development Agency (APVV Projects 0081-10, 51-008305). We are also thankful to Edyta Jurewicz and Jacek Grabowski who improved the quality of the paper with their comments and corrections from their review of the paper.

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