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Geological structure and tectonic evolution of the Tatric Unit between Pernek village and the Pezinská Baba saddle (Malé Karpaty Mts., Slovakia)

EMA KLAMOVÁ[1,✉], RASTISLAV VOJTKO[1], DAVID MILOŠ DROPPA[1], ALEXANDER LAČNÝ[1,2] and JOZEF HÓK[1]

[1]Department of Geology and Paleontology, Faculty of Natural Sciences, Comenius University Bratislava, Ilkovičova 6, 842 15 Bratislava, Slovakia
[2]State Nature Conservancy of the Slovak Republic, Malé Karpaty Protected Landscape Area, Štúrova 115, 900 01, Modra, Slovakia

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Abstract: The geological structure of the Malé Karpaty Mountains reflects a complex, multiphase tectonic evolution. The Tatric crystalline basement and its Permian-to-Cretaceous sedimentary cover have been thrust over the Jurassic formations of the Borinka Subunit. The basement comprises Lower Paleozoic metamorphic rocks of the Pezinok and Pernek groups, intruded by Lower Carboniferous granitoids. Variscan deformation, particularly the development of pervasive foliation (S_2^V) and mineral and stretching lineations (L_{2t}^V), records syn-metamorphic processes predating granitoid emplacement. Later Variscan phases (D_3^V, D_4^V) introduced folding and localised structural overprints. Alpine deformation overprinted the older structures through several discrete deformational phases. Early Alpine deformational phase (D_1^A) was marked by NW-directed shear, asymmetric folding, and greenschist facies metamorphism (Cretaceous). Later phases (D_2^A, D_3^A) reflect exhumation and Miocene compression, with the latest deformation associated with south-vergent folding and reverse faulting. Together, these events document a long-lived tectonic history shaped by both Paleozoic and Cenozoic orogenic processes.

Keywords: Pezinok Group, Pernek Group, Borinka Subunit, Alpine deformation, Variscan deformation

Introduction

The Western Carpathians are part of the European Alpine orogenic belt, which extends westward into the Eastern Alps and eastward into the Eastern Carpathians. The mountains are traditionally divided into the Outer, Central, and Inner Western Carpathians (e.g., Andrusov et al. 1973; Froitzheim et al. 2008; Plašienka 2018). Some authors have also employed a simplified division model, distinguishing only the External and Internal Western Carpathians (e.g., Mišík et al. 1985; Hók et al. 2014, 2019).

The Malé Karpaty Mts. represent the westernmost core mountains of the Internal Western Carpathians (*sensu* Hók et al. 2014), characterised by the allochthonous position of the Tatric crystalline basement over the Borinka Subunit (Fig. 1; Koutek & Zoubek 1936; Plašienka et al. 1991; Bielik et al. 1992; Plašienka 2018; Hók et al. 2022). This basement is overlain by Permian to Cretaceous sedimentary cover sequences, which include a stratigraphic hiatus during the Late Triassic. The Fatric and Hronic thin-skinned nappes are restricted to the northern part of the mountain range (Fig. 1; Mahel' 1986; Polák et al. 2011, 2012). The present study focuses on the central segment of the Malé Karpaty Mts., encompassing the Tatric Unit.

The principal aim of this study is to perform a comprehensive analysis of deformation structures, with an emphasis on their spatial orientation and geometrical patterns. Previous interpretations have frequently offered divergent views, attributing the origin of these structures either to the Variscan or Alpine orogeny. The data presented herein serve as an important basis for reconstructing the tectonic evolution of the study area. Nevertheless, interpretations concerning the geometry of these structures must be approached with caution, given the complexity of overprinting deformation phases. Additionally, this study attempts to identify the sense of displacement of rock complexes in the westernmost part of the Western Carpathians.

Geological setting

The Malé Karpaty Mts. comprise four principal Eo-Alpine tectonic units. Structurally, the lowermost unit is the Borinka Subunit, composed predominantly of Jurassic sediments. This unit has been variably interpreted as a part of the (Infra)Tatric tectonic domain (e.g., Plašienka 1987; Plašienka in Polák et al. 2012) or Tatric tectonic domain (e.g., Hók et al. 2022). A substantial portion of the range is occupied by Tatric granitoid and metamorphosed rocks, along with sub-autochthonous Permian to Mesozoic sedimentary sequences. Crystalline basement of the Tatric Unit was thrust over the Borinka Subunit (Figs. 1b, 2). The highest structural levels are represented by

✉ corresponding author: Ema Klamová
ema.klamova@gmail.com

the Fatric and Hronic thin-skinned nappe systems (Polák et al. 2011, 2012).

The Tatric crystalline basement is composed of Lower Paleozoic metamorphic volcano-sedimentary complexes, which are subdivided into the structurally distinct Pernek Group and Pezinok Group (Ivan et al. 2001; Ivan & Méres 2006). The Pernek Group consists predominantly of metamorphosed basalts, dolerites, and gabbros, accompanied by minor cherts and associated sedimentary rocks. This assemblage is interpreted as a metamorphosed and dismembered ophiolitic complex. In contrast, the Pezinok Group, interpreted as having originally infilled a rift-related basin, is composed mainly of metamorphosed clastic sediments, locally containing organic matter, carbonates, and subordinate basaltic intrusions (Fig. 2).

The Bratislava Massif, predominantly located in the southern part of the mountain range, intrudes mainly into the Pezinok Group and is composed of S-type granodiorites to

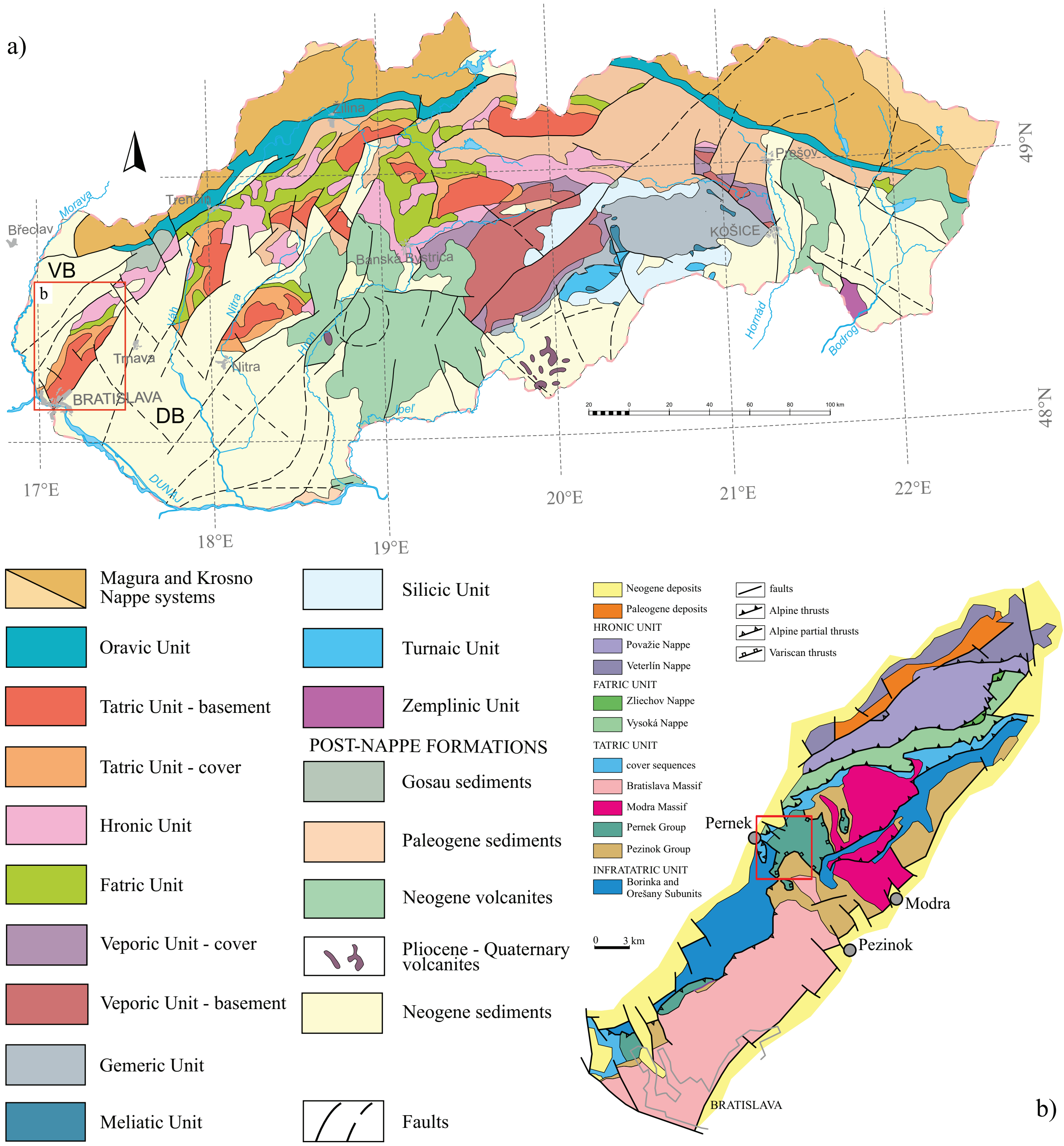

Fig. 1. Simplified tectonic map of the investigated area: **(a)** Tectonic map of the Slovak part of the Western Carpathians. The Malé Karpaty Mountains are highlighted by a red rectangle (adapted from Biely et al. 1996). **(b)** Detailed tectonic map of the Malé Karpaty Mountains, indicating the specific study area (modified after Polák et al. 2011). Note: VB – Vienna Basin; DB – Danube Basin.

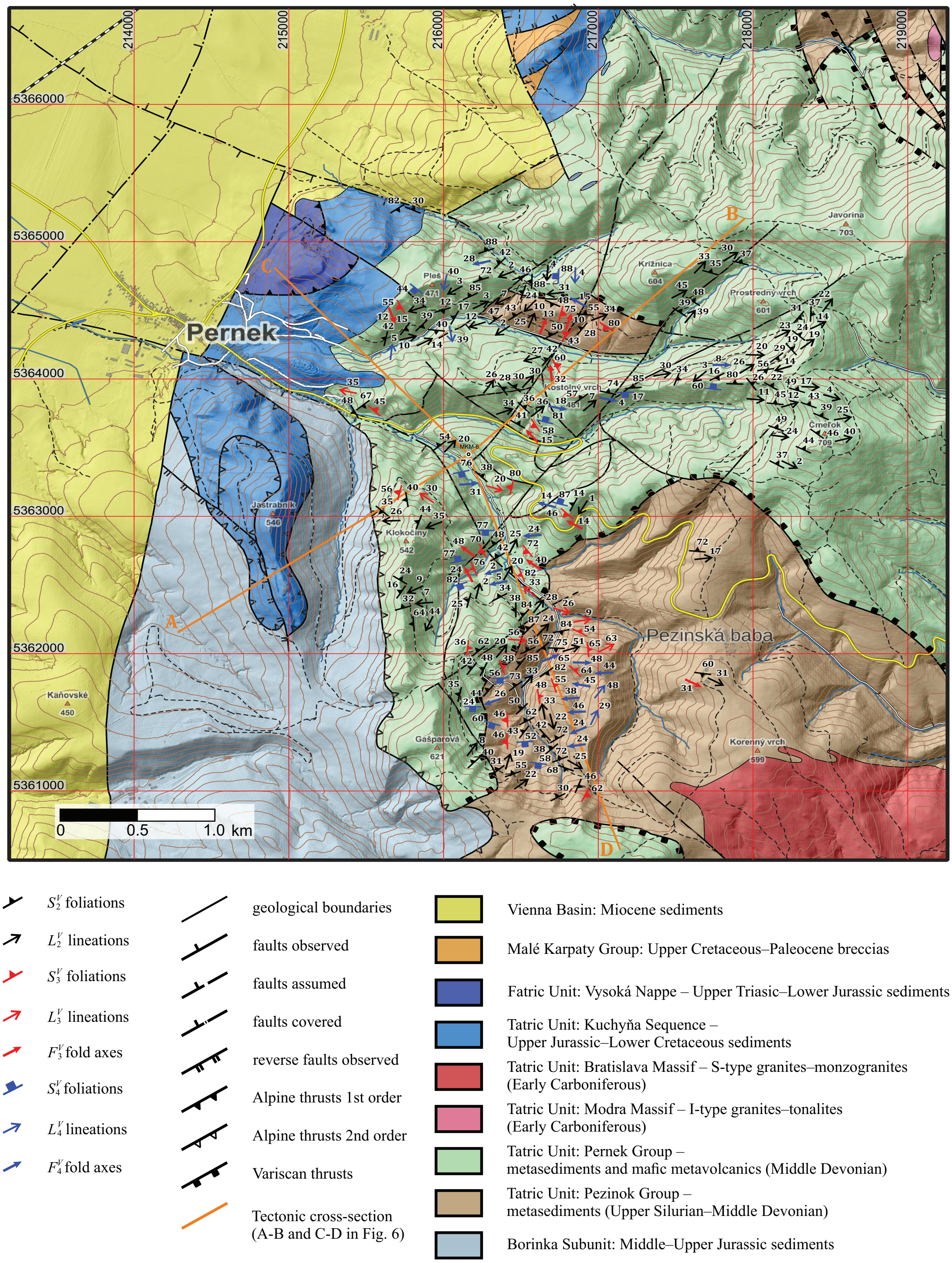

Fig. 2. Tectonic map of the Pernek and Pezinská Baba area illustrating Variscan deformation structures. Coordinate reference system: WGS84/UTM zone 34N, EPSG: 32634 (modified after Polák et al. 2011).

monzogranites, commonly associated with pegmatite and aplite dykes (Cambel & Vilinovič 1987; Kohút in Polák et al. 2012). In contrast, the Modra Massif, situated in the northern part of the mountains, was emplaced at a higher structural level, primarily within the Pernek Group, and is characterised by I-type granodiorites to tonalites. The age of the granitoids has been constrained using multiple geochronological methods to between 345 and 355 Ma (e.g., Kohút et al. 2009; Kohút & Larionov 2021; Uher et al. 2024).

The Variscan-consolidated crystalline basement of the Tatric Unit is overlain by a variety of cover sequences, which are primarily distinguished based on differences in Jurassic lithostratigraphy and their tectonic position relative to the underlying Tatric crystalline basement. Based on these criteria, six distinct cover sequences have been identified (Plašienka et al. 1991; Polák et al. 2011, 2012). The Borinka Subunit and Orešany Subunit are tectonically located beneath the Tatric crystalline basement. The Devín, Kuchyňa, Kadlubek, and Solírov sequences represent the autochthonous sedimentary cover of the Tatric crystalline basement (Fig. 1b).

In the northern part of the mountain range, the structural pattern incorporates the thin-skinned nappes. Directly overlying the Tatric successions and crystalline basement is the Fatric Unit, which is subdivided into two distinct structural subunits (Vysoká and Zliechov partial nappes). The Hronic Unit occupies the highest structural position. Similar to the Fatric nappe system, the Hronic Unit is also divided into several discrete nappe bodies (Považie and Veterlín nappes within this area (cf. Havrila 2011; Polák et al. 2011, 2012).

Methods

The study area is characterised by scarce outcrops, which typically occur as small exposures and, occasionally, as rock cliffs. However, structural features are reliably observable only within these outcrop domains. The succession of tectonic structures identified within these accessible areas forms the foundation for subsequent structural analysis. Structural observations, including kinematic analysis (cf. Passchier & Trouw 2005; Pelech & Hók 2017), were conducted at 134 sites, covering the Borinka Subunit, the Tatric crystalline basement, and the Kuchyňa Cover Sequence.

The research was focused on determining the orientation of planar and linear structural elements. Distinct sets of these structures were designated using letter symbols (foliation as *S*, lineation as *L*) and were indexed according to their relative chronological order. The relative ages were inferred based on the ages of the host rocks and the cross-cutting or overprinting relationships observed between structures. Numerical indexing based on relative age is conventionally applied as follows: S_0 denotes the primary planar fabric, typically representing bedding planes, while S_1, S_2, ..., S_n correspond to successive tectonic foliations arranged in order of their superposition, from the oldest to the youngest (e.g., McClay 1992; Fossen 2016; Kriváňová et al. 2023; Vojtko & Kriváňová 2024). Throughout the text, the orientation of planar structures is given using the dip direction versus dip notation.

Analogous to foliations, linear structures within the rocks are designated as *L*-structures. When multiple generations of lineations occur within the same rock, they are assigned numerical suffixes according to their relative chronological order: L_0 denotes the primary (sedimentary) lineation, while L_1, L_2, ..., L_n correspond to successive tectonic lineations, arranged by superposition. Linear structures are further classified based on their orientation relative to tectonic transport: those parallel to the direction of tectonic transport (L_t), such as mineral or stretching lineations, and those perpendicular to the direction of shortening (L_c), including intersection or crenulation lineations that are parallel to fold axes (*F*). Fold axes are indexed as F_1, F_2, ..., F_n. A comparable indexing scheme is used for the associated deformation stages (D_1, D_2, ... D_n) and metamorphic phases (M_1, M_2, ... M_n) responsible for the evolution of these tectonic structures.

The analysed tectonic structures, ranging from mesoscopic to macroscopic scales, can be grouped into two principal deformation cycles. The earlier deformation phase is attributed to the Variscan orogeny and is designated as Variscan deformation (D^V), whereas the later phase corresponds to Alpine deformation and is denoted as (D^A).

For the computation of plane intersections, construction of planes containing linear features, bisecting planes between two surfaces, and the correction of line–plane pairs, the GeolCalc software (developed by R. Vojtko) was used. All structural data were further processed and visualised using Stereonet v. 11 software (Allmendinger et al. 2012; Cardozo & Allmendinger 2013).

The digital terrain model (DTM) utilised in this study was derived from airborne LiDAR data, specifically from the Digital Model of Relief 5.0 (DMR 5.0) and the Digital Model of Surface 1.0 (DMP 1.0), both provided by the Geodetic and Cartographic Institute Bratislava. These products originate from LLS: ÚGKK SR – The Geodesy, Cartography and Cadastre Authority of the Slovak Republic (available at: https://zbgis.skgeodesy.sk). All spatial datasets were managed and analysed using the GeoPackage format within Quantum GIS (QGIS) version 3.40 'Bratislava' (QGIS.org 2025).

Results: Structural analysis

In the results were identified multiple phases of deformation, which were classified according to their relative chronological order. Overall, two principal deformation stages can be distinguished: the Variscan and the Alpine.

The Variscan structural fabric (D^V) is preserved exclusively within the Pezinok and Pernek groups. A clear and well-documented structural discontinuity exists between the granitoids of the Bratislava and Modra massifs and the Pezinok and Pernek units (Fig. 2). The associated contact metamorphism is of limited extent and has exerted only a minor influence on the deformation of surrounding host rocks.

The presence of Alpine deformation is less pronounced compared to the pervasive Variscan structures (D_2^V). However, it can generally be noted that the closer the observed basement rocks are to the thrust surface of the crystalline basement of the Tatric Unit over the Borinka Subunit, the more systematically Alpine deformations are observed in the Tatric crystalline rocks. However, the Alpine deformational structures were observed, measured, and analysed primarily in Jurassic and Lower Cretaceous sediments of the Borinka Subunit and Kuchyňa Cover Sequence.

Variscan deformation

The most significant deformation of the Tatric crystalline rocks is the pervasive foliation (S_2^V), which developed during the Variscan metamorphism (M_2^V) of originally sedimentary siliciclastic rocks, basic volcanic rocks, and, to a lesser extent, carbonates. Within the Malé Karpaty Mts., Variscan deformation (D^V) exerted a significantly greater influence on the geological evolution of the Tatric crystalline complex than the subsequent Alpine deformation (D^A) (Figs. 3, 4).

The volcano-sedimentary complex has undergone multiple deformation phases and metamorphic overprints. Consequently, the primary stratification (S_0) and the earlier older Variscan planar fabric (S_1^V) could not be clearly identified in most localities. Nevertheless, in certain areas within the Pezinok Group sediments, isoclinally folded quartz veins and, potentially, relics of primary sedimentary surfaces (S_0), together with the earlier Variscan foliation (S_1^V), were observed (Fig. 3a). Where these older structures were observable, they were significantly transposed and parallelised within the metamorphic foliation (S_2^V). The parallelisation of structures predating the S_2^V foliation is well-developed, and, as previously noted, the unambiguous identification of primary structures remains difficult. These closed and isoclinal folds are markedly more frequent in the Pezinok Group than in the Pernek Group, where such structures are practically absent, most likely due to contrasting rock rheology.

The principal planar structure of the metamorphic rocks is the pervasive foliation (S_2^V), which is characterised by material heterogeneity and formed during syn-metamorphic crystallisation of rock-forming minerals in greenschist facies reaching at most the biotite subfacies (e.g., Krist et al. 1992), with their preferred orientation aligned parallel to the foliation planes during progressive Variscan metamorphism (M_2^V). The earlier Variscan deformation phase (D_1^V) was not accompanied by any recognisable regional metamorphic overprint, and therefore no distinct M_1^V metamorphic assemblage has been identified. This pervasive foliation (S_2^V) represents the most prominent planar structural element within the metamorphic rocks of the Pernek and Pezinok groups within the Tatric crystalline basement (Figs. 3b, 4a, b).

In addition to foliation (S_2^V), stretching and mineral lineations (L_{2t}^V) are relatively common and record the direction of tectonic transport during the Variscan deformation in both the Pezinok and Pernek groups. The orientation of foliation (S_2^V) and associated tectonic transport lineations (L_{2t}^V) displays a gradual spatial variation across the study area, influenced by subsequent deformation events (Figs. 4a, b, 5a). In the eastern part of the region, S_2^V foliation generally exhibit an E–W orientation, gradually rotating to a NE–SW trend toward the west, and shifting to a S–N orientation in the southwestern sector (see Fig. 2).

The relatively wide range of L_{2t}^V lineation orientations is attributed to the overturning of metamorphosed volcano-sedimentary sequences of the Tatric crystalline basement during later folding events. The dip angles of these lineations (L_{2t}^V) typically vary between 15° and 30°.

The Variscan deformation process (D_2^V) led to the development of pervasive metamorphic foliation (S_2^V) in black shales, as well as phyllitic foliation in rocks originally associated with the volcano-sedimentary complex of the Pernek Group. This structural fabric is also distinctly expressed in the schists and paragneisses of the Pezinok Group. In contrast, it is absent in the Lower Carboniferous granitoid rocks of the Bratislava and Modra massifs. These observations suggest that the deformation event occurred before the Early Carboniferous.

The chronologically younger, non-pervasive (spaced) Variscan deformation (D_3^V) is characterised by NE–SW-directed shortening. This deformation is commonly manifested by folds with NW–SE-trending axes (F_3^V) and steeply inclined axial planes (S_3^V), whose strike is also oriented in the NW–SE direction (Figs. 3c, 4c, d, 5c). During the deformation phase (D_3^V), the rocks of the Pezinok and Pernek groups were deformed into a fan-like structure (Fig. 6), accompanied by the frequent occurrence of NE–SW-trending stretching lineations (L_{3t}^V) (Fig. 5b). The associated cleavage surfaces (S_3^V) correspond to the axial planes of folds with a NW–SE-striking and steep dips toward the NE and SW (Figs. 2, 3c, 4c, d). It is hypothesized that this deformation event is younger than the emplacement of the granitoid bodies of the Bratislava and Modra massifs, which occurred during the Lower Carboniferous period (Kohút & Larionov 2021). These granitoid rocks are incorporated into this fabric.

The final phase of distinct, non-pervasive Variscan deformation (D_4^V) is less intense and is primarily characterised by the development of folds (F_4^V), which are predominantly open to closed and symmetrical, with asymmetrical folds occurring only rarely. The strike of axial planes (F_4^V) is in E–W direction (Figs. 3d, 4e, f) These structures likely reflect top-to-the-SSE tectonic transport. The axes of F_4^V folds generally exhibit an E–W orientation, with dips of up to 30° in the northern part of the study area (Fig. 5d).

In contrast, closer to the Bratislava granitoid intrusion in the southern sector, the dip of the fold axes increases, ranging from 25° to 50°. These structural features suggest that this folding phase also falls within the Variscan deformation cycle in terms of its relative chronology. This interpretation is further supported by the fact that the folds do not continue into the Bratislava granitoid and are instead deflected around its margin, indicating that the folding predates the emplacement

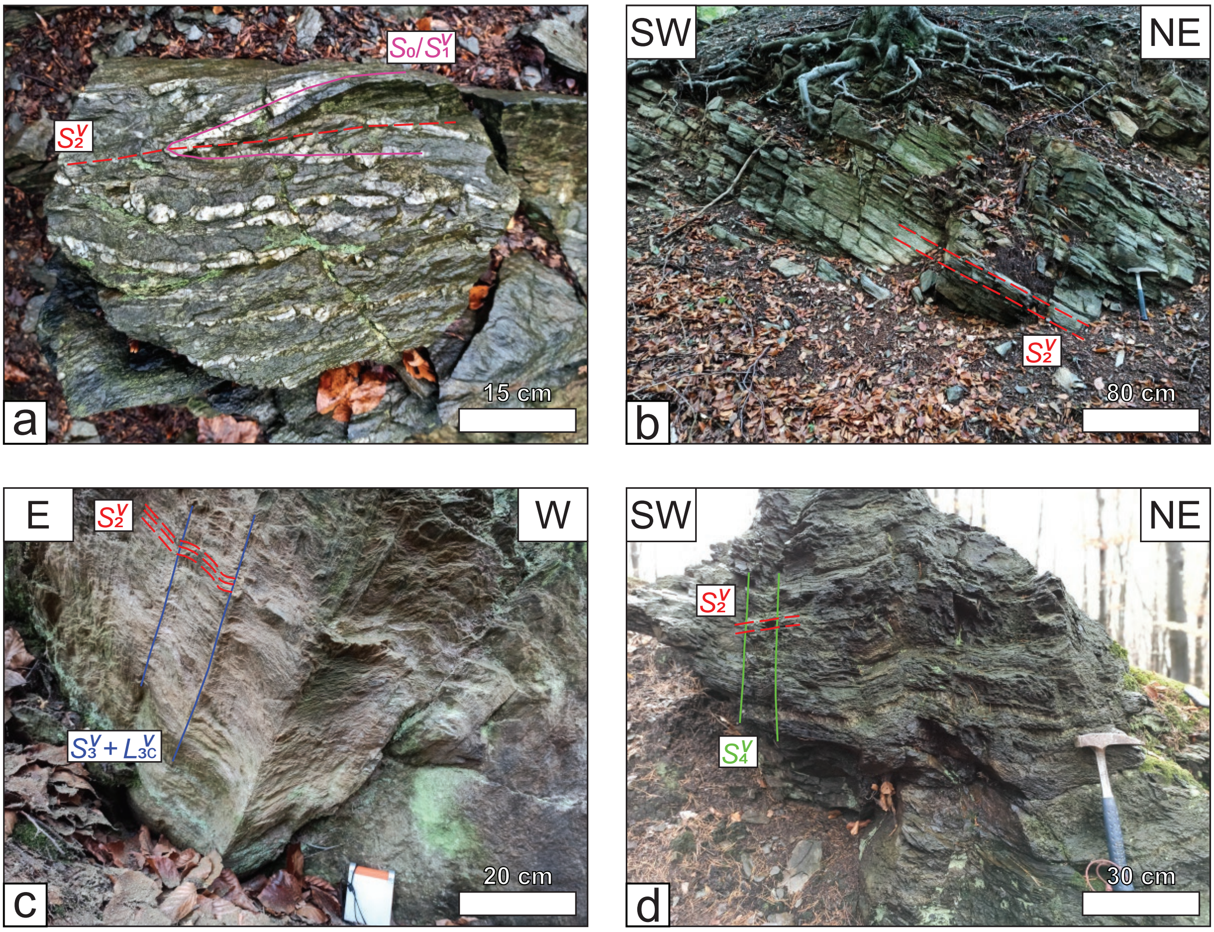

Fig. 3. Photographic documentation of key Variscan deformation structures (D^V) observed in the metamorphosed volcanic-sedimentary complex of the Pernek and Pezinok groups within the Tatric crystalline basement: **(a)** isoclinally folded quartz veins in metasedimentary rocks of the Pezinok Group, displaying well-developed Variscan planar structures; **(b)** pervasive Variscan metamorphic foliation (S_2^V 036/39°); **(c)** pervasive Variscan foliation (S_2^V 138/72°) crosscut by a well-developed cleavage (S_3^V 085/65°); crenulation cleavage ridges (L_{3c}^V 060/62°) are evident, formed in metasandstones to metagreywackes of the Pezinok Group. **(d)** structural relationship between subhorizontal pervasive metamorphic foliation (S_2^V 336/24°) and subvertical cleavage (S_4^V 346/82°), parallel to axial planes of gently open folds.

of the intrusion. The geometrical relationship between the deformed host rocks and the undeformed granitoid body therefore provides one of the key arguments for assigning this deformational event to the Variscan age.

Alpine deformation

Alpine deformation structures were identified within the Mesozoic sedimentary rocks of the Borinka Subunit, the Kuchyňa Cover Sequence, and the crystalline basement of the Tatric Unit (Fig. 7). In the Jurassic to Lower Cretaceous strata, the primary bedding surfaces (S_0) are predominantly subhorizontal, with dip angles generally not exceeding 35° (Fig. 8d).

The first Alpine deformation phase (D_1^A) is characterised by a tectonic foliation (S_1^A) is typically subhorizontal to gently dipping (Fig. 9a, b) and is closely linked to the transport-related lineations (L_{1t}^A) (Fig. 10). The observed folds (F_1^A) are generally open to closed in style, and range from symmetrical to asymmetrical, with overturned folds (F_1^A) occurring only rarely. The stretching and mineral lineations (L_{1t}^A) (Fig. 8a, b), are oriented perpendicular to the intersection lineations (L_{1i}^A), which are in some places defined by the intersection of bedding planes (S_0) and tectonic foliation (S_1^A). The intersection lineations are subparallel to the fold axes (F_1^A).

Kinematic indicators consistently reveal top-to-the-NW-directed tectonic transport, which corresponds with the orientation of the crenulation lineations (L_{1c}^A) and fold axes (F_1^A). The transport lineations (L_{1t}^A) together with asymmetric structures and tectonic duplexes in cover sequences also indicate the top-to-the-NW sense of shear, with an average azimuth of 306° (Fig. 10), suggesting deformation under simple shear conditions during NW–SE-oriented shortening (Fig. 8a, b). The Alpine deformation phase (D_1^A) significantly intensified the foliation within the affected rocks and was accompanied by low-grade Alpine metamorphism (M_1^A), corresponding to the lower part of the greenschist facies (Krist et al. 1992).

The identification of planar and linear deformational structures within the metamorphic rocks of the Pezinok and Pernek

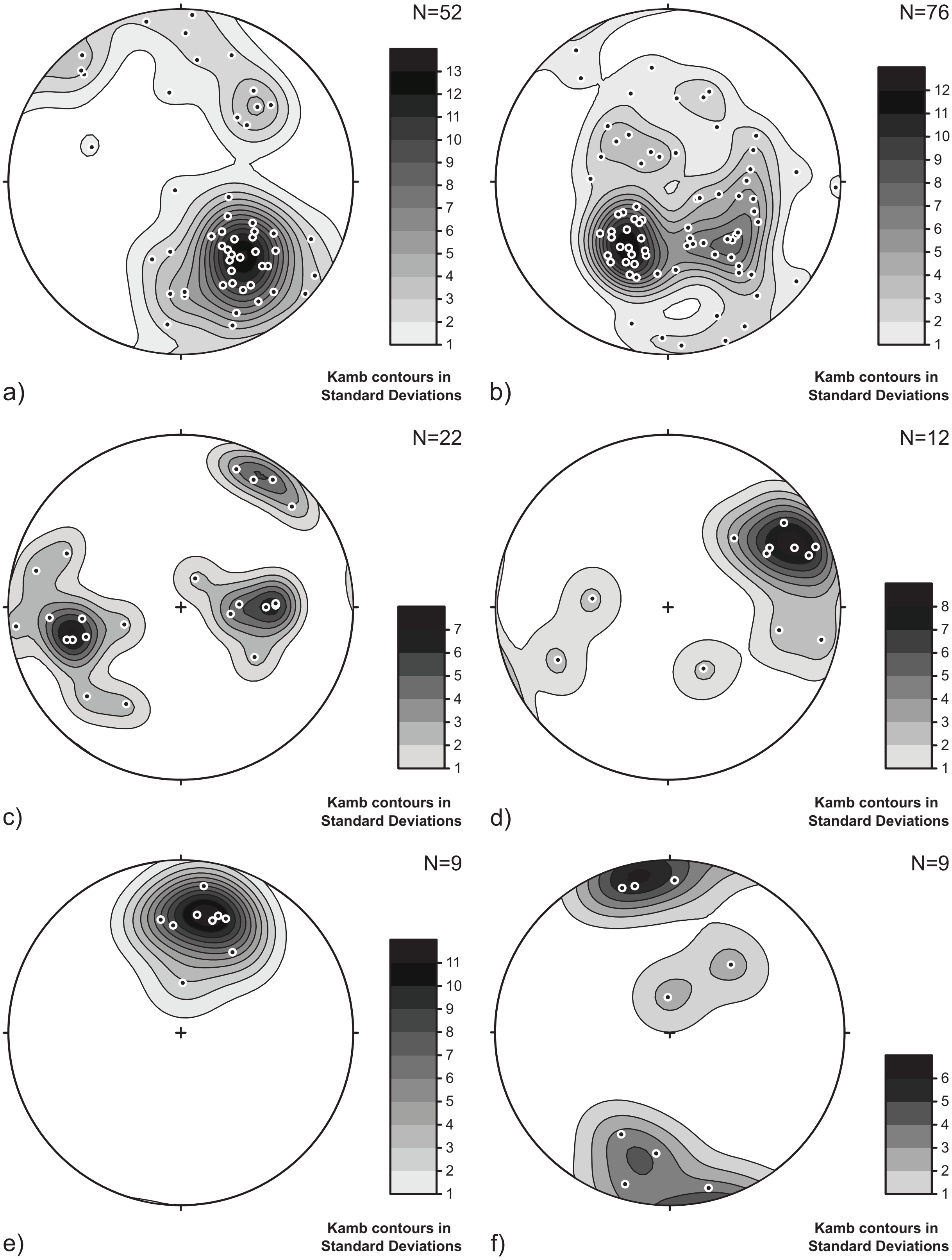

Fig. 4. Contour plots of Variscan foliations and cleavages in the Tatric crystalline basement, represented by poles to planar structures: **(a)** Variscan S_2^V foliation in the Pezinok Group; **(b)** Variscan S_2^V foliation in the Pernek Group; **(c)** Variscan S_3^V cleavage in the Pezinok Group; **(d)** Variscan S_3^V cleavage in the Pernek Group; **(e)** Variscan S_4^V cleavage in the Pezinok Group; **(f)** Variscan S_4^V cleavage in the Pernek Group. Note: Lambert projection, lower hemisphere, N – number of poles.

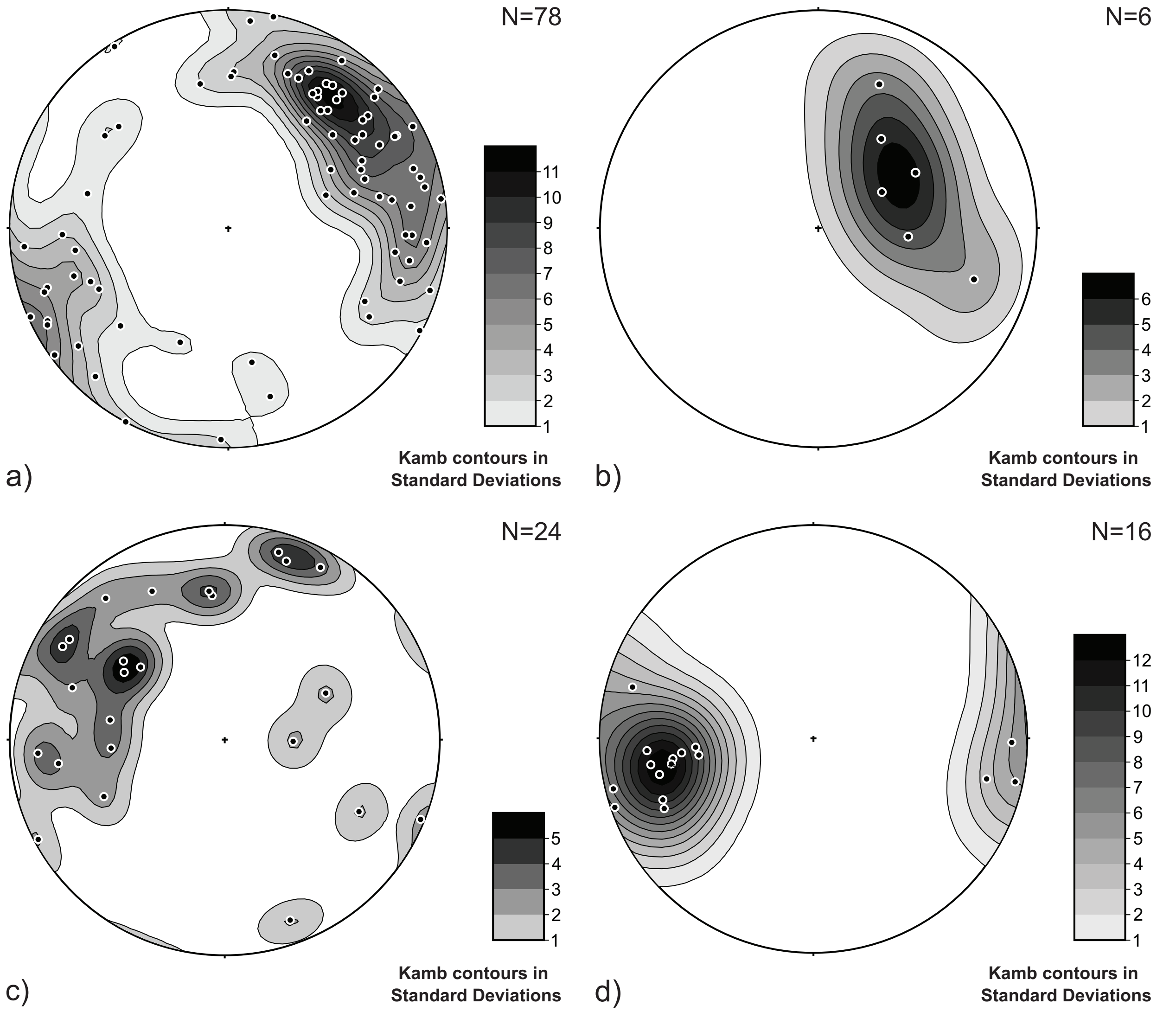

Fig. 5. Variscan stretching and crenulation lineations of the Pezinok and Pernek groups: **(a)** Variscan L_{2t}^{V} lineations; **(b)** Variscan L_{3t}^{V} lineations; **(c)** Variscan L_{3c}^{V} lineations and **(d)** Variscan L_{4c}^{V} lineations. Note: Lambert projection, lower hemisphere, N – number of lineations.

groups, forming part of the crystalline basement of the Tatric Unit, is considerably more complex. Alpine deformation is not pervasive throughout these units but is instead localised within relatively narrow shear zones, typically several tens of meters thick. Within these zones, spaced to mylonitic foliation (S_1^A) has developed, predominantly oriented in a NE–SW direction with SE-ward dipping (Fig. 9d). Alpine stretching and mineral lineations (L_{1t}^A) are also observed within these shear zones and together with crenulation cleavage (S_1^A), bend folds (F_1^A), and tectonic duplexes consistently indicate top-to-the-NW-directed tectonic transport.

The second Alpine deformation (D_2^A) is weak and is expressed by the development of spaced to mylonitic foliation (S_2^A), accompanied by stretching lineations (L_{2t}^A) trending WNW–ESE. This deformation stage (D_2^A) is associated with the post-Eo-Alpine exhumation processes and is characterised by top-to-the-ESE-directed kinematics. Its limited intensity suggests deformation at relatively low metamorphic grades, most likely sub-greenschist facies. The fabrics produced during (D_2^A) document the progressive strain localisation reflecting a shift to more heterogeneous, partitioned deformation and the extensional overprint superimposed on earlier compressional fabrics of (D_1^A).

The youngest recognized Alpine deformation stage (D_3^A) is defined by a general NNW–SSE-directed shortening, which led to the formation of predominantly open to closed asymmetric folds exhibiting a top-to-the-south tectonic transport (F_3^A). The axial planes of these folds (F_3^A) are steeply inclined towards the north (S_3^A), while the fold axes (F_3^A) are subhorizontal, generally oriented at F_3^A 098/05° (Fig. 9c). Field investigations indicate that these folds are closely associated with south-verging reverse faults. Transport lineations (L_{3t}^A) are represented by slickenside lineations, which exhibit a general N–S orientation.

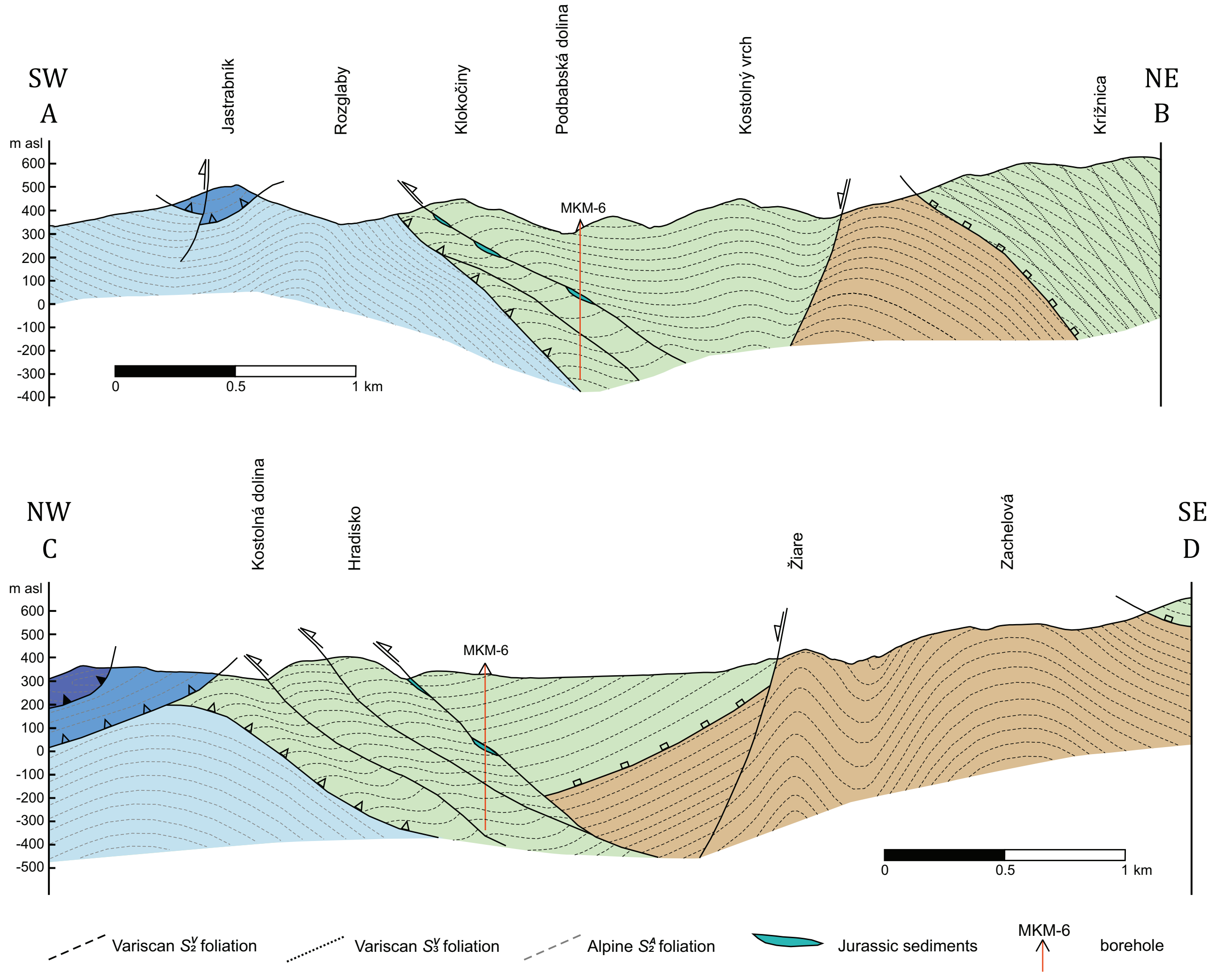

Fig. 6. Tectonic cross-sections with spatial distribution of the Variscan and Alpine fabric in the study area. Note: for the legend, see Fig. 2.

Interpretation and discussion

The pre-Cenozoic tectonic framework of the Malé Karpaty Mountains is characterised by a complex nappe structure, primarily resulting from Alpine (Cretaceous) compressional processes within the Western Carpathians. Consistent with other core mountain ranges in the region, the geological architecture comprises major tectonic units of the first order, namely, the Tatric, Fatric, and Hronic units. Additionally, the Borinka Subunit, located in the Infra-Tatric position, is incorporated into the regional tectonic classification (Polák et al. 2012). Among these, the Tatric Unit is the most extensive and geologically significant within the study area. Its crystalline basement also exhibiting evidence of Variscan deformation (Figs. 1b, 2, 7).

Variscan structural evolution

The crystalline basement of the Tatric Unit is composed of complexes of metabasalts and metasedimentary rocks that have undergone low- to medium-grade metamorphism (e.g., Korikovskij et al. 1984; Krist et al. 1992; Ivan et al. 2001; Ivan & Méres 2006). These metamorphosed basement rocks are of Early Paleozoic age, specifically ranging from the Late Silurian to the Middle Devonian (Ivan & Méres 2006). The dominant Variscan planar secondary structure is a pervasive metamorphic foliation (S_2^V), which has been the subject of detailed investigation in previous studies (e.g., Putiš 1987). This pervasive structure is associated with decimetre-scale isoclinal folds, which are interpreted to represent either an older tectonic foliation (S_1^V) or remnants of the original primary stratification (S_0). However, the original primary structures (S_0) have not yet been reliably identified at the outcrop scale within the metamorphic rocks of the Pezinok and Pernek groups (Fig. 3a).

The most prominent pervasive planar structure (S_2^V) has frequently been interpreted in earlier studies as the original tectonic fabric subsequently affected by deformation (D_2^V), implying that the S_2^V foliation is subparallel to the earlier S_1^V or primary stratification surfaces (S_0). However, structural

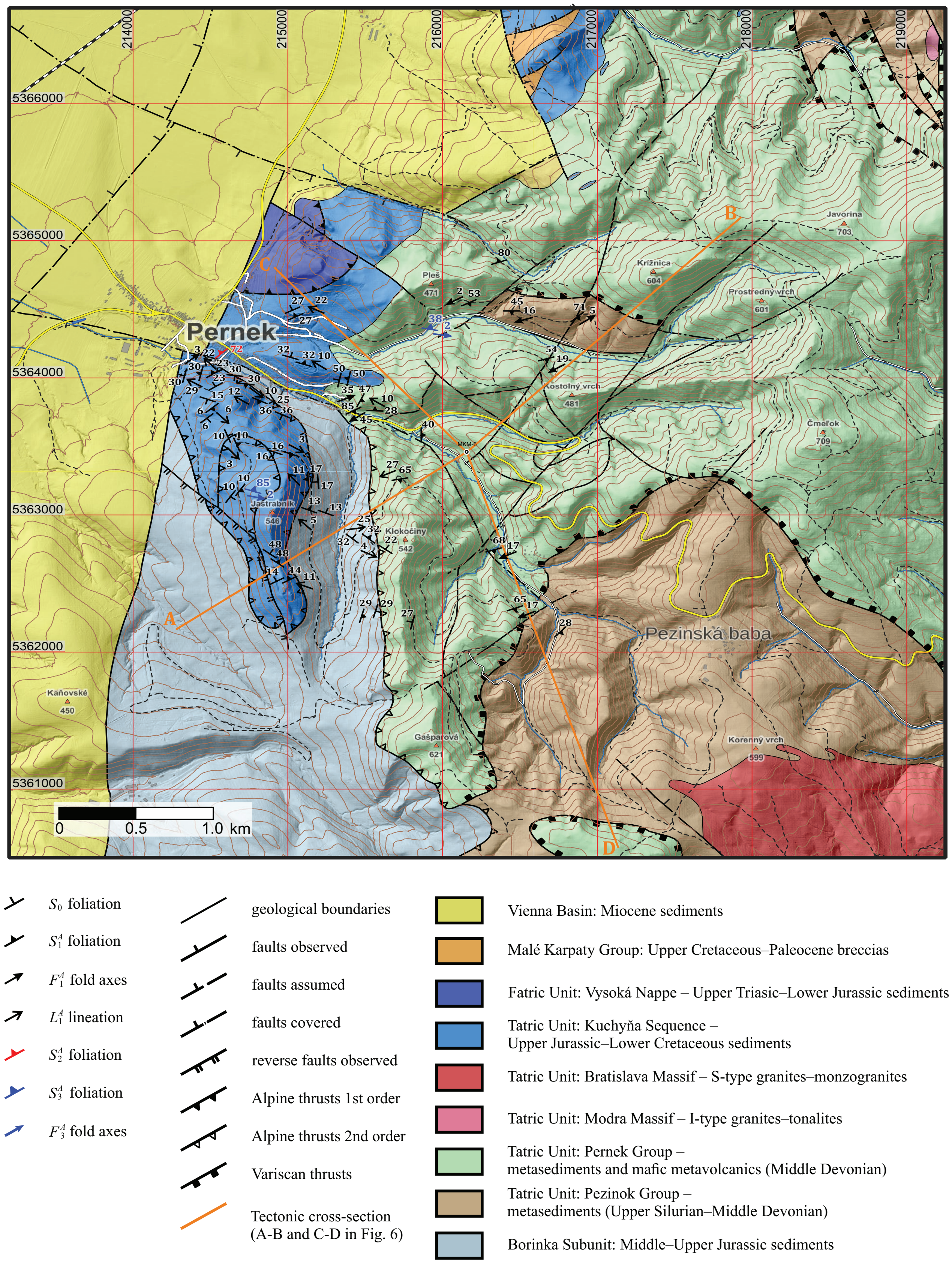

Fig. 7. Tectonic map of the Pernek and Pezinská Baba area illustrating Alpine deformation structures. Coordinate reference system: WGS84 / UTM zone 34N, EPSG: 32634 (modified after Polák et al. 2011).

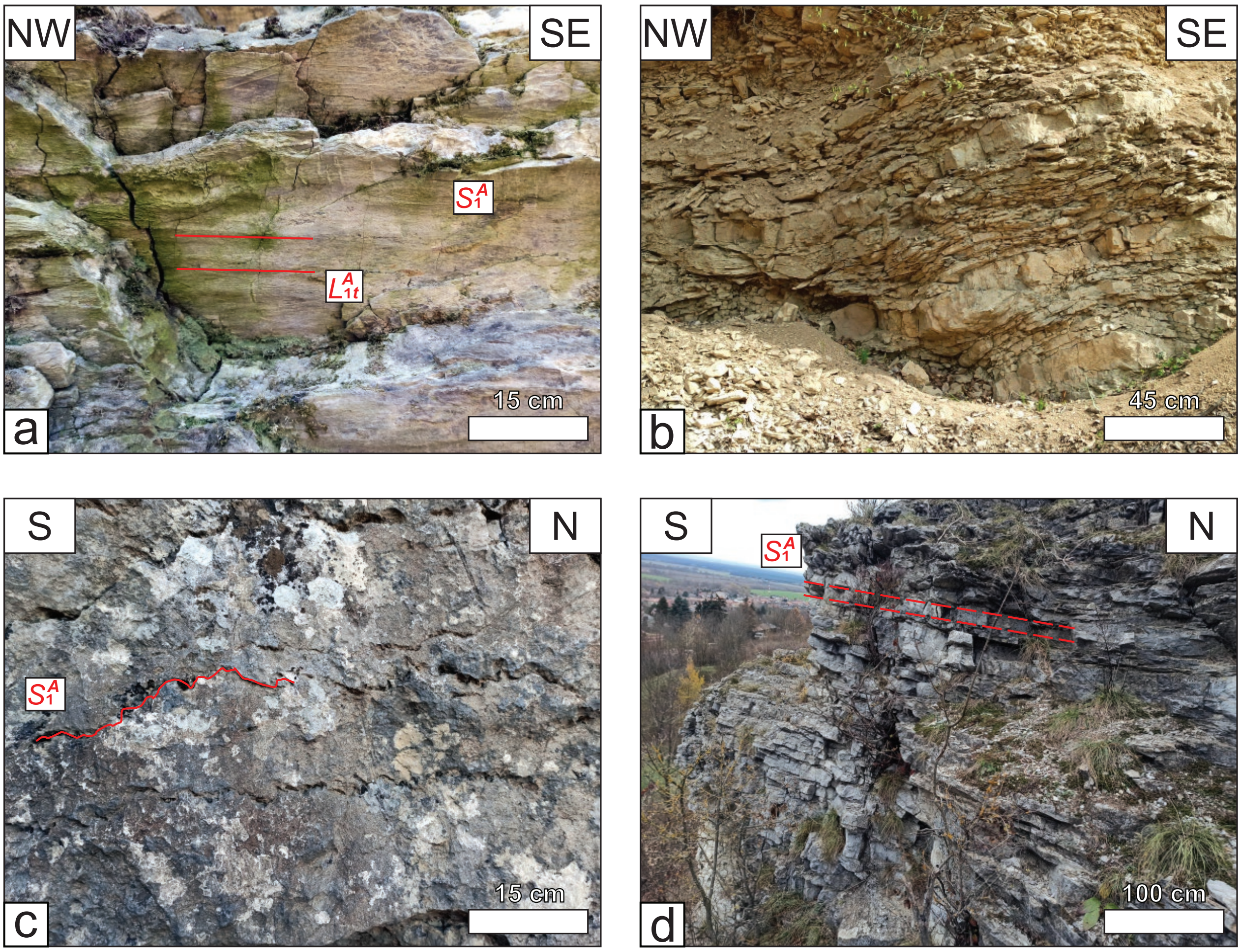

Fig. 8. Photographic documentation of key Alpine fabric observed in Jurassic and Lower Cretaceous limestones of the Borinka Subunit and Kuchyňa Cover Sequence within the Tatric Unit: **(a)** mineral and stretching lineations (L_1^A 115/08°) developed under anchimetamorphic conditions in limestones of the Borinka Subunit, indicating top-to-the-west-NW transport; **(b)** tectonic duplexes of the (D_1^A) deformation exhibiting top-to-the-west-NW transport (Kuchyňa Cover Sequence); **(c)** irregularly developed stylolitic foliation (S_1^A 266/17°) in Jurassic limestones of the Borinka Subunit; **(d)** Alpine pervasive foliation (S_1^A) parallel to bedding (S_0) in Lower Cretaceous marlstones of the Kuchyňa Cover Sequence.

evidence from certain localities indicates a significant transposition of the older S_0 (S_1^V) structures into the S_2^V fabric. This is demonstrated by the presence of strongly isoclinal folds, whose limbs are parallel to the S_2^V foliation, as well as by the occurrence of rootless folds (see Figs. 3a, b, 4a, b). Nevertheless, it remains the case that planar structures predating the S_2^V foliation have only been reliably identified within the Pezinok Group, likely due to its predominantly sedimentary protolith composition.

Isoclinal folds parallel to the S_2^V foliation have not been observed within the Pernek Group, which is predominantly composed of mafic volcanic rocks. The contrast between the structural development in the Pezinok and Pernek groups is likely attributable to differences in the rheological properties of their respective lithologies and should not be interpreted as evidence of an additional deformation phase affecting the Pezinok Group. However, this distinction cannot be conclusively verified at present due to almost full transposition to S_2^V fabric.

The Variscan deformation phase D_2^V represents the oldest reliably documented tectonic event, characterised by the development of well-defined pervasive metamorphic foliations S_2^V (Fig. 4a, b), as well as prominent stretching and mineral lineations L_{2t}^V, which are generally oriented E–W (Fig. 5a). The Early Carboniferous granitoid intrusions (~350 Ma; cf. Kohút et al. 2009) postdate the earlier Variscan tectonic structure (D_2^V) developed within the Tatric crystalline basement.

It appears that the chronologically younger Variscan deformation phase D_3^V, characterised by NE–SW-directed shortening, occurred only after the emplacement of the granitoid intrusions of the Bratislava and Modra massifs (~350 Ma; Kohút et al. 2009; Putiš et al. 2009; Kohút & Larionov 2021). Prior to the formation of these folds, a nappe structure had already been established, referred to by Putiš (1992) as early

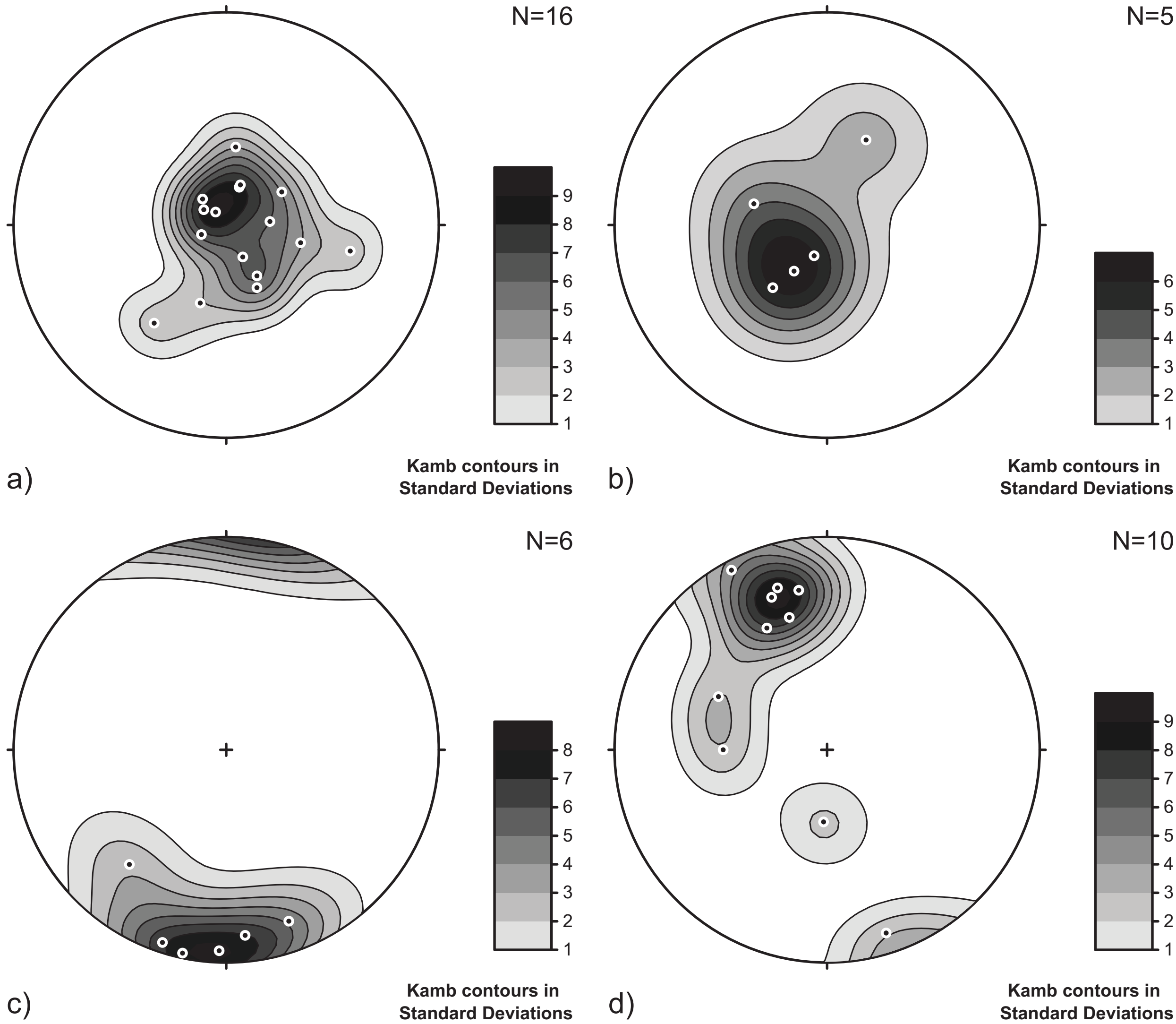

Fig. 9. Contour plots of Alpine foliations and cleavages in the cover sequences of the Tatric Unit and Borinka Subunit, represented by poles to foliation planes: **(a)** Alpine S_1^A foliation in the Kuchyňa Cover Sequence; **(b)** Alpine S_1^A foliation in the Borinka Subunit; **(c)** Alpine S_3^A foliation in the Kuchyňa Cover Sequence; **(d)** Alpine S_1^A foliation in the Tatric crystalline basement. Note: Lambert projection, lower hemisphere, N – number of poles.

Variscan in age. Within this nappe structure, the Pernek Group, positioned structurally higher (in the hanging wall), was thrust over the Pezinok Group (in the footwall; D_2^V; Fig. 2). The deformation phase (D_3^V) is marked by the development of crenulation cleavage (S_3^V) and NW–SE-trending fold axes (F_3^V) and steeply inclined axial planes on both sides (Figs. 3c, 4c, d).

The emplacement of the granitoid bodies also contributed to the folding of the earlier S_2^V foliation. The axis and axial plane of the resulting large-scale fold are conformable with the S_3^V structural orientation. During D_3^V deformation, the metamorphosed rocks of the Tatric crystalline basement were deformed into a fan-like geometry (Fig. 6), and NE–SW-oriented stretching lineations (L_{3t}^V) are also commonly observed (Fig. 5b). The metamorphic crenulation cleavage (S_3^V) is particularly well developed in incompetent metapelites, whereas it is typically less pronounced in more competent metapsamites. Locally in the contact zone with metapelites, the granitoid rocks are mylonitised by this tectonic phase (D_3^V), which denotes that this deformation must be younger than Early Carboniferous. The strike of this mylonitic zones is generally in the NW–SE direction.

The emplacement of the granitoid intrusions during the Lower Carboniferous is thought to have triggered contact and periplutonic metamorphism within the surrounding crystalline rocks of the Pernek and Pezinok groups (Korikovskij et al. 1984; Cambel et al. 1989). The metamorphic evolution of the Tatric crystalline basement in the Malé Karpaty Mountains was polyphase in character and is interpreted as a combination of regional pre-granitic (Variscan) epizonal metamorphism, contact metamorphism (Early Carboniferous), and Alpine retrograde metamorphism (Cambel in Buday et al. 1962).

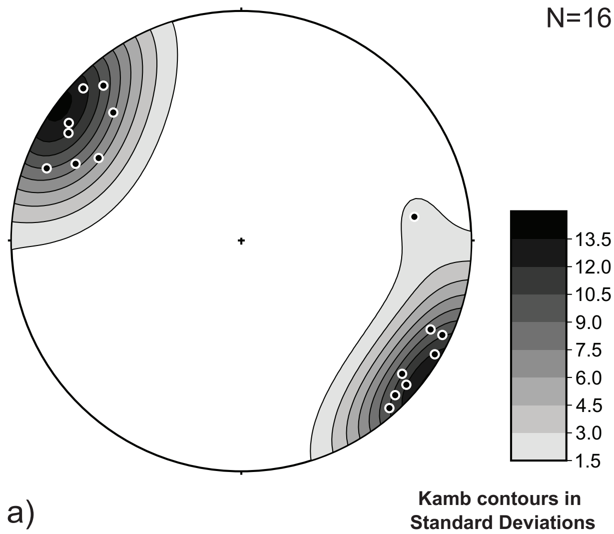

Fig. 10. Alpine mineral and stretching lineations: Alpine L_{1t}^{A} lineations in the Borinka Subunit and the Kuchyňa Cover Sequence. Note: Lambert projection, lower hemisphere, N – number of lineations.

Alpine structural evolution

The Alpine orogeny within the region of the evolving Western Carpathians commenced during the Late Jurassic and persisted into the Neogene period. In this context, oceanic domains, such as the Meliatic, Vahic, and Magura, were progressively closed through subduction processes, ultimately leading to a continent–continent collision involving the Adriatic microcontinents and the Eurasian continent (e.g., Plašienka et al. 1997; Schmid et al. 2008; Plašienka 2018).

The most significant Alpine deformation event (D_1^A) is represented by the emplacement of nappes during the Alpine orogeny. This deformational phase was marked by the development of NW–SE-oriented mineral and stretching lineations (L_{1t}^A) (Figs. 8a, 10), which are commonly observed on predominantly flat-lying foliations (S_1^A) (Fig. 8c, d). The Alpine deformation, particularly within the cover sequences of the Tatric Unit and Borinka Subunit, was accompanied by the formation of the evolution of pervasive foliation structures (S_1^A) and folds (F_1^A) with NE–SW-trending fold axes. The foliation (S_1^A) is generally subparallel to original bedding (S_0^A). These structures formed during the northwest-directed thrusting of the Alpine nappes, specifically recording the overthrusting of the Tatric crystalline basement onto the Borinka Subunit (Putiš 1987; Plašienka et al. 1991; Droppa et al. 2024).

Thrusting was accompanied by the incorporation of Mesozoic successions into the structure of the Tatric crystalline complex in its frontal zone, where tectonic lenses of these sedimentary rocks were observed at the surface in the Klokočina area (Maheľ & Cambel 1972; Klamová 2023). Additionally, Jurassic sediments of cover sequence were drilled in borehole MKM-6 (for location see Figs. 2, 7) within a depth interval of 278 to 300 m, approximately 1 km east of the village of Pernek (Hacura et al. 1987; Plašienka et al. 1989; Hanzel et al. 1993).

The F_1^A folds frequently co-occur with compressional duplex structures, which also exhibit clear indicators of top-to-the-NW tectonic transport (Fig. 8b). These structures have been identified within the Borinka Subunit and Kuchyňa Cover Sequence. The Alpine foliation (S_1^A) is also recorded within the granitoid rocks of the Tatric crystalline basement (cf. Droppa et al. 2024). This cleavage (S_1^A), ranging from spaced cleavage to mylonitic and, in certain cases, pervasive, is associated with axial plane cleavage of the accompanying folds (F_1^A).

During D_1^A deformation phase, several structural rock types, such as protomylonites, mylonites, and cataclasites, were developed from pre-existing metamorphic and granitoid rocks within the crystalline basement. The emplacement of the overlying Fatric and Hronic units onto the Tatric Unit is estimated to have occurred approximately 90 Ma ago (cf. Plašienka et al. 1997; Plašienka 1999, 2018; Putiš et al. 2009). Conversely, their identification in the rocks of the Pezinok and Pernek groups is more challenging.

Generally, the Alpine deformation (D_1^A) exhibits a progressive intensification towards the thrust contact between the Tatric crystalline basement and the Borinka Subunit. The timing of this thrusting event is constrained to the Late Cretaceous (~80–75 Ma), based on K–Ar dating of Alpine sericitic mylonites derived from granitoid bodies (Kantor et al. 1987; Putiš et al. 2009).

The resultant shear zones are inclined southeastward along the western edge of the Tatric crystalline complexes and are spatially associated with the thrust surface of the crystalline basement over the carbonate successions of the Borinka Subunit. The deformation and structural evolution within both the crystalline basement and its sedimentary cover occurred under simple shear conditions, giving rise to the formation of asymmetrical structures.

The principal outcome of the thrusting of the metamorphosed rocks of the Pernek and Pezinok groups, together with the granitoid bodies of the Bratislava and Modra massifs belonging to the Tatric Unit, onto the Jurassic–Lower Cretaceous carbonate formations, was the development of Alpine metamorphism under lower greenschist facies conditions (Plašienka et al. 1993; Ivan & Méres 2006).

The subsequent deformation phase (D_2^A) is associated with the post-Eo-Alpine exhumation process. This exhumation of the Variscan crystalline basement of the Malé Karpaty Mts. occurred exclusively during the Cenozoic era, as by the Eocene, the majority of the currently exposed crystalline rocks remained at depths of no less than 3 km (cf. Danišík et al. 2004; Králiková et al. 2016).

Exhumation ages of the crystalline rocks in the Malé Karpaty Mts., as determined by zircon fission track dating, are approximately 70–65 Ma corresponding to the Late Cretaceous–Paleocene boundary. At that time, the rocks passed through an isotherm of around 225 °C. Subsequent uplift of the Tatric crystalline basement brought these rocks to near-surface levels (depths of less than 3 km, eventually reaching the surface) between roughly 40 and 20 Ma, as indicated by apatite fission track data (Danišík et al. 2004; Králiková et al. 2016).

The present erosional surface of the Tatric crystalline rocks, however, exposes structural levels that were originally situated at depths exceeding 6–8 km, as evidenced by the partial annealing zone of zircons (240–300 °C). This interpretation is further supported by independent geothermometric indicators from the cover sequences of the Tatric Unit, including illite crystallinity, muscovite chemistry, and deformation mechanisms in carbonates, all pointing to temperatures of 250–300 °C (Plašienka et al. 1993). Changes in the configuration and kinematics of the marginal faults of the Malé Karpaty Mountains also facilitated the preservation of Miocene sedimentary relics on the uplifted margins and foothills of the range, with these sediments locally resting directly upon the Tatric crystalline rocks (Polák et al. 2012).

The youngest phase of Alpine deformation (D_3^A) is characterised by a compressional tectonic regime and the development of south-vergent fault structures (Fig. 9c). According to published studies (e.g., Marko et al. 1990, 1991; Plašienka 1990; Marko & Jureňa 1999; Lačný et al. 2025), this deformation phase is assigned to the Early Miocene age and is interpreted to reflect the soft docking of the ALCAPA Mega-Unit with the European Platform. This tectonic interaction led to the thrusting of the External Western Carpathians and the formation of reverse faults within the hinterland. The D_3^A deformation is further believed to be associated with the development of a structural fan in the broader region surrounding the Pieniny Klippen Belt (Pešková et al. 2012).

Conclusions

The structural evolution of the Malé Karpaty Mts. records a complex interplay of Variscan and Alpine tectonic processes that have affected both the crystalline basement and overlying sedimentary sequences. The Variscan deformation, particularly the D_2^V phase, was the most pervasive, producing a well-developed S_2^V metamorphic foliation and associated mineral lineations (L_{2t}^V) within the Pezinok and Pernek groups. These structures reflect syn-metamorphic conditions and significant tectonic transport prior to the emplacement of the Upper Devonian–Lower Carboniferous granitoid intrusions. Subsequent, less pervasive Variscan deformation phases (D_3^V, D_4^V) introduced folding, cleavage development, and fan-like geometries, indicating continued crustal shortening and structural reworking.

In contrast, the Alpine deformation history (D_1^A–D_3^A) is characterised by a succession of discrete deformation events, each linked to specific tectonic regimes and kinematic patterns. Early Alpine deformation (D_1^A) was associated with flattening and NW-directed tectonic transport under pure to simple shear conditions, resulting in tectonic foliations, asymmetric folding, and localised shear zones. These phases were accompanied by low-grade metamorphism (sub-lower greenschist facies) and complex deformation structures within the sedimentary and crystalline rocks. Later Alpine deformation (D_2^A and D_3^A) reflects post-metamorphic processes including exhumation and compressional reactivation, with WNW–ESE and NNW–SSE shortening directions, respectively. The D_3^A deformational phase, in particular, is linked to Early Miocene tectonics and the soft docking of major crustal units, manifesting as south-vergent folds and reverse faulting.

Overall, the deformation history recorded in the Malé Karpaty Mountains illustrates a prolonged and multiphase tectonic evolution, wherein early Variscan orogenesis established the fundamental structural framework that was subsequently overprinted by Alpine tectonics during Mesozoic to Cenozoic convergence and exhumation processes.

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