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Structural evolution of the Fatric Unit in the Malé Karpaty Mountains (Slovakia) during the Cretaceous–Early Neogene Alpine Orogeny: Insights from field-based orientation analysis

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Abstract: This study investigates the internal deformation of the Fatric Unit in the Malé Karpaty Mountains during the Alpine orogeny, with the aim of clarifing the structural evolution and thrusting history of the Vysoká and Zliechov nappes. A comprehensive dataset of primary and deformation-related planar structures was collected and analysed to reconstruct the tectonic evolution of the Fatric Unit. Three main Alpine deformation phases ($D_1^A – D_3^A$) were identified, reflecting significant changes in the regional stress field. (1) The earliest phase (D_1^A) is associated with northwest-directed thrusting and NW–SE crustal shortening during the Eo-Alpine orogeny, as documented by asymmetric folds, stretching lineations, and large-scale recumbent folding. (2) The subsequent phase (D_2^A) reflects a shift to a W–E compression axis during the Late Cretaceous to Early Eocene and is expressed by the development of extensional structures, predominantly calcite-filled veins. (3) The youngest phase (D_3^A) records a return to the N–S-oriented compression associated with south-vergent backthrusting during the Late Oligocene to Early Miocene, probably related to the soft docking of the ALPACA Mega-Unit with the European Platform. Overall, the tectonic analysis of the Fatric Unit in the Malé Karpaty Mts. characterises three principal Alpine deformation stages of the Western Carpathians by constraining their timing and kinematics.

Keywords: fold, cleavage, lineation, kinematics, Western Carpathians

Introduction

The Western Carpathians constitute a segment of the Alpine–Carpathian orogenic belt and are conventionally interpreted as a product of the Cretaceous (Eo-Alpine) to Cenozoic (Neo-Alpine) crustal shortening. This tectonic evolution is associated with the formation of thin-skinned nappe stacks comprising Mesozoic sedimentary sequences (Andrusov et al. 1973; Plašienka et al. 1997; Hók et al. 2014; Plašienka 2018).

The Malé Karpaty Mountains represent the westernmost of the so-called core mountains within the Internal Western Carpathians (Fig. 1a; Maheľ 1986; Hók et al. 2014, 2019), also referred to as the Central Western Carpathians (e.g., Plašienka 2018). Geomorphologically, the range is subdivided from southwest to northeast into the Devínske Karpaty, Pezinské Karpaty, Brezovské Karpaty, and Čachtické Karpaty Mountains (cf. Mazúr & Lukniš 1978). The region is characterised by an allochthonous position of the Tatric crystalline basement overlying the Borinka Unit (Koutek & Zoubek 1936; Plašienka et al. 1991; Bielik et al. 1992; Hók et al. 2022), as well as by Permian to Cretaceous cover successions of the Tatric Unit that are predominantly discontinuous and reduced, with a notable hiatus during the Late Triassic (cf. Plašienka et al. 1991).

Additionally, the Fatric and Hronic cover nappes are present exclusively in the northern part of the mountain range and represent a thin-skinned nappe system located in the tectonic overburden of the Tatric Unit (Fig. 1b; Andrusov et al. 1973; Maheľ 1986; Polák et al. 2011, 2012).

Deformed rocks represent a crucial source of information for the observation and reconstruction of the tectonic evolution within the study area. However, the analysis and interpretation of structural geometries in such rocks must be approached with caution. These deformed lithologies typically reflect the final stage of a complex deformation history, often obscuring earlier events. Consequently, it is frequently only possible to reconstruct the most recent phase of deformation. Structural elements such as folds, foliations, lineations, and boudins can originate through a variety of mechanisms, and relying solely on geometrical data to decipher their evolution presents inherent challenges. Some degree of misinterpretation is, therefore, inevitable and should be regarded as an inherent part of the iterative process of refining our geological understanding.

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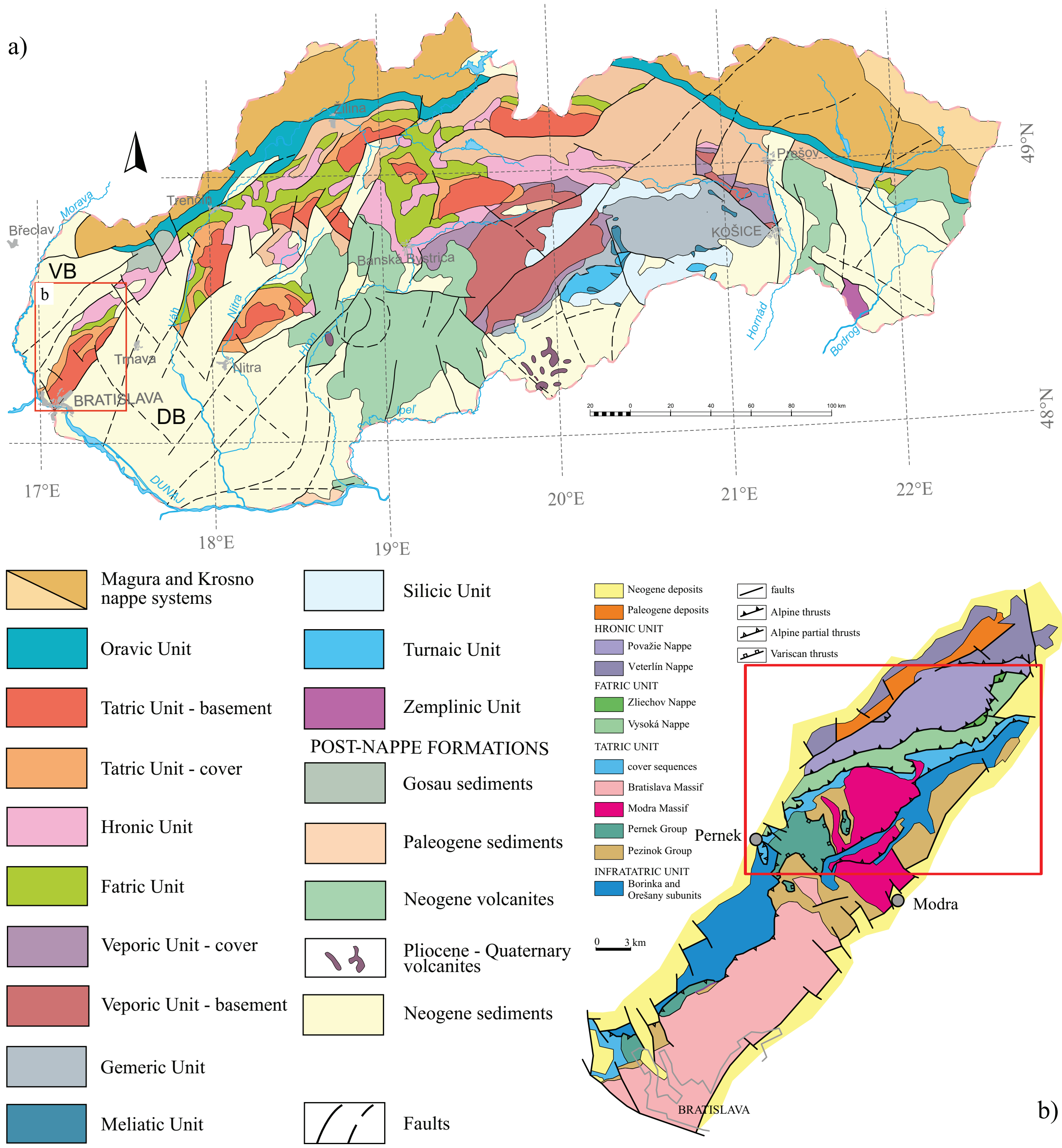

Fig. 1. Simplified tectonic map of the investigated area: **a** — Tectonic map of the Slovak sector of the Western Carpathians. The Malé Karpaty Mountains are highlighted by a red rectangle (adapted from Biely et al. 1996). **b** — Detailed tectonic map of the Malé Karpaty Mountains, indicating the specific study area within the Pezinské Karpaty Mountains drawn on Fig. 2 (modified after Polák et al. 2011). Note: VB – Vienna Basin; DB – Danube Basin.

The study area is characterised by outcrops that generally present as small exposures, and less frequently, as rock cliffs. Nevertheless, primary structural features can be reliably observed only within these outcrop zones. The sequence of tectonic structures documented in these accessible locations serves as the basis for further structural analyses.

The primary objective of this study is to synthesise, evaluate, and interpret an extensive dataset of structural measurements obtained from the Fatric Unit (specifically the Vysoká and Zliechov partial nappes), and investigates the internal deformation of the Fatric Unit in the Malé Karpaty Mountains during the Alpine orogeny. Our motivation arises from the tectonic position of the Fatric Unit in the Malé Karpaty Mountains as the most external element of the nappe system, combined with its pronounced backthrust-related overprint, which superimposes earlier deformation patterns.

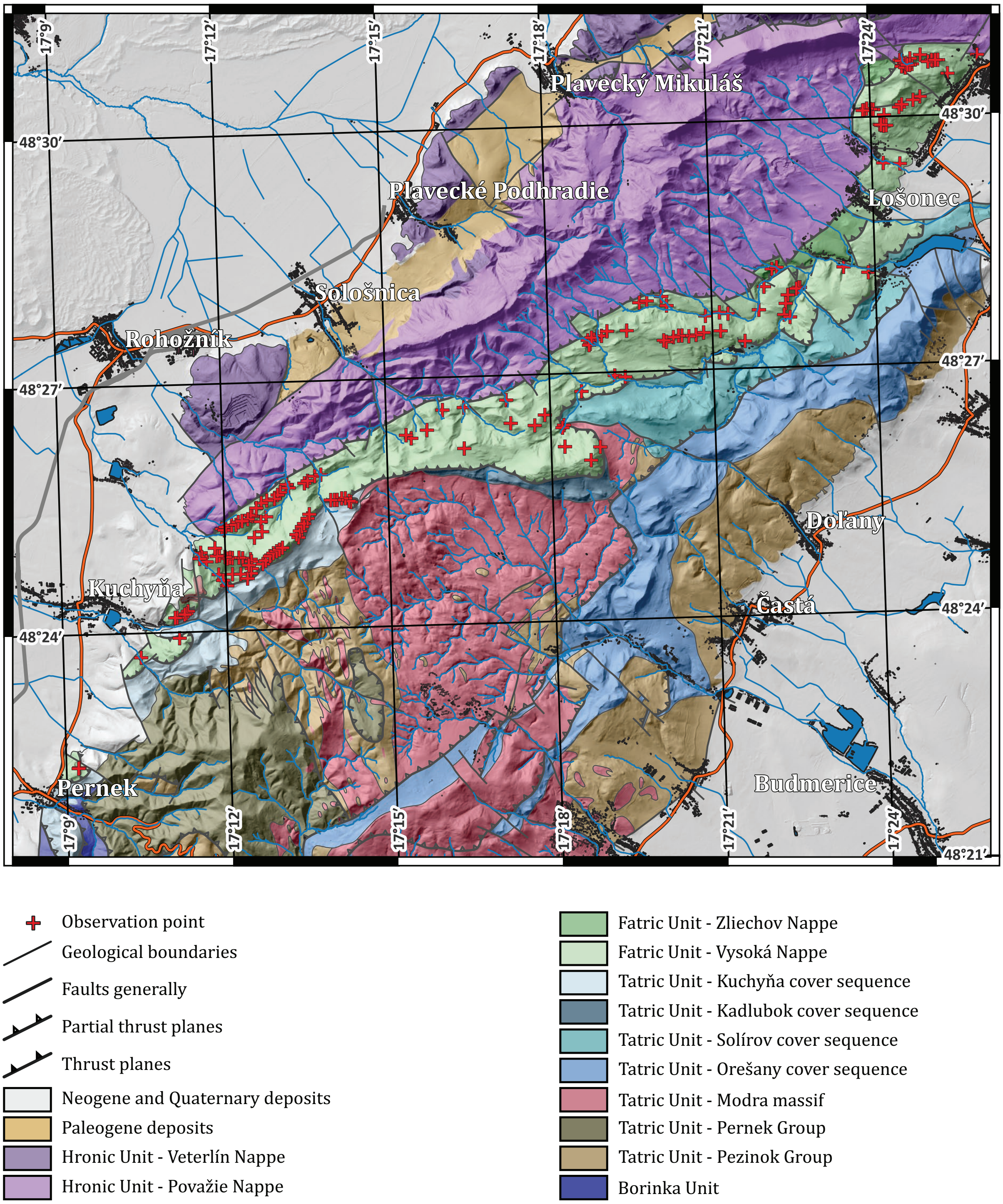

Fig. 2. Tectonic map of the central part of the Malé Karpaty Mts. with documented observation points (modified after Polák et al. 2011).

Geological setting

The Malé Karpaty Mountains form part of the Tatra–Fatra Belt, which represents the outer zone of the Central Western Carpathians (e.g., Plašienka et al. 1997; Plašienka 1999, 2018). This mountain range constitutes a key segment at the junction between the Western Carpathians and the Eastern Alps and is structurally composed of Paleoalpine complexes, specifically the Tatric, Fatric, and Hronic tectonic units and transitional Borinka and Orešany subunits (Figs. 1b, 2).

The Malé Karpaty Mts. extend over 100 km in length and approximately 15 km in width, forming a SW–NE-trending ridge that separates the Neogene Vienna Basin to the west from the Danube Basin to the east. On the northwestern side, the boundary between the mountains and the Vienna Basin is defined by the Vienna Basin Transfer Fault (VBTF), a lower Miocene to Quaternary structure segmented into several fault strands (Decker et al. 2005; Beidinger & Decker 2011; Hinsch & Decker 2011). On the southeastern side, the range is bounded by the Malé Karpaty Fault, interpreted as an early Neogene to Quaternary normal fault (Marko & Jureňa 1999).

The current geomorphological and tectonic configuration of the Malé Karpaty Mts. was established in the Late Neogene, during which time the range became fully separated from the surrounding Neogene basins, both tectonically and morphologically (Minár et al. 2011).

The Tatric Unit comprises Variscan crystalline basement rocks overlain by a Mesozoic sedimentary cover, which is predominantly exposed in the southern and central parts of the mountain range (Plašienka et al. 1991; Ivan & Méres 2006). In contrast, the northern part is primarily formed by the nappe systems of the Fatric and Hronic units. Post-nappe Upper Cretaceous sediments are represented by the Brezová Group (Salaj et al. 1987), while Paleogene (Eocene–Oligocene) deposits located in the northwestern part of the region are assigned to the Malé Karpaty Group (Buček in Polák et al. 2012).

The Fatric Unit (*sensu* Andrusov et al. 1973) represents a thin-skinned nappe system within the tectonic framework of the Western Carpathians, positioned structurally above the Tatric Unit. In the Malé Karpaty region, it crops out in the northern part of the area (Fig. 2), forming a 2–4 km wide belt that extends from the village of Smolenice in the northeast to the village of Kuchyňa in the southwest. A substantial portion of the Fatric Unit in this region is composed predominantly of the Vysoká Nappe, which structurally underlies the Zliechov Nappe (also referred to as the Krížna Nappe). The latter is locally preserved in small erosional remnants exposed in the northeastern part of the study area (cf. Mahel' & Cambel 1972; Mahel' 1986; Polák et al. 2012).

The lithostratigraphic succession of the Vysoká Nappe corresponds to a stratigraphic range from the Middle Triassic to the Cenomanian (Polák et al. 2012). The lower parts of the nappe are formed by typical Vysoká Limestone of Anisian age, overlain by Ladinian Ramsau Dolomite. A distinctive feature is the prominent development of the Carpathian Keuper, characterised by a succession of variegated claystones, dolomites, and quartzites of Norian age. The Late Triassic is classically developed in black biodetrital, lumachelle, and often coral-bearing limestones and marls.

The Jurassic to Lower Cretaceous Vysoká sequence serves as a reference model for the shallower-water sedimentary sequences of the Fatric Unit. At the base lies a formation of dark, sandy crinoidal limestones and shales of Lower Liassic age, with an approximate thickness of 100 meters. The overlying variegated sandy crinoidal limestones transition into nodular limestones of the Adnet or Prístodolok Formation, dated to the Late Liassic (Koša 1998). These are followed by Dogger-aged variegated crinoidal limestones, radiolarian limestones, radiolarites, and red nodular limestones of Late Jurassic age. The Lower Cretaceous succession is represented by a massive cherty and brecciated limestone (Padlá Voda Formation), shaly, marly cherty limestone (Hlboča Formation), and bioclastic limestone of the Barremian–Aptian Bohatá Formation (cf. Plašienka et al. 1991). The Albian–Cenomanian Poruba Formation consists predominantly of silicified marlstones, with intercalations of turbiditic sandstones occurring only in the uppermost parts.

The Zliechov Nappe is only marginally present, with a stratigraphic range from the Lower Jurassic to the Upper Cretaceous. The most characteristic lithostratigraphic unit is the Allgäu Formation (Fleckenmergel), composed of dark grey marly spotted limestones and marly shales of Lotharingian age, which gradually transition into siliceous Fleckenmergel of the Aalenian. The Middle Jurassic is represented by the Ždiar Formation, while the Late Jurassic is composed of the Jasenina and Osnica formations. The Lower Cretaceous lithostratigraphic units are represented by the Mráznica Formation, which consists of marly laminated limestones and marly shales ranging from the Berriasian to the Hauterivian (e.g., Polák et al. 2012).

Methods and data used

Standard methods of field-geological research were applied during this study. Measurements of structural elements were conducted using a Freiberg-type geological compass. All structural data were further processed and visualised using *Stereonet* version 11 (Allmendinger et al. 2012; Cardozo & Allmendinger 2013). The structural elements are presented in lower hemisphere projections of the Lambert (Schmidt) net. For accurate determination of GPS coordinates, a Garmin GPSmap 62sc device was used. Structural data were collected across the Fatric Unit at 177 documented observation points. The position of these points is indicated in the Fig. 2 and addition data are in Supplementary Table S1.

The analysed mesoscopic and macroscopic structures are attributed to the Alpine orogeny and collectively referred to as Alpine deformation (D^A). The field-based geological research focused on determining the attitude, in some cases the kinematics, of planar and linear structural elements. Planar structures were designated by letter symbols (S), and lineation by (L), with both indexed according to their relative chronological sequence. Relative ages were inferred from the ages of the host rocks and from observed cross-cutting or overprinting relationships among the structures. Numerical indexing based on relative age is conventionally applied as follows: S_0 represents the primary planar fabric, which typically corresponds to bedding planes in this context, while S_1, S_2, ..., S_n denote successive tectonic foliations arranged in order of superposition, from oldest to youngest (e.g., McClay 1992; Fossen 2016; Kriváňová et al. 2023; Vojtko & Kriváňová 2024).

Analogous to foliations, 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 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), predominantly stretching lineation, and those perpendicular to the direction of shortening (L_c), including intersection or crenulation lineations that are parallel to the fold axes (F). Macrofold 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) responsible for the evolution of these tectonic structures.

For the computation of plane intersections, construction of planes containing linear features, angles between lines and planes, bisecting planes between two surfaces, the correction of line-plane pairs, rotations, and spatial calculations, the GeolCalc 1.16 software (developed by R. Vojtko) was used.

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) 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 using the GeoPackage format within Quantum GIS (QGIS) version 3.40 'Bratislava' (QGIS.org 2025).

Structural observations

Bedding

In many areas comprised by Jurassic to Cretaceous successions, the S_0 planes are folded (Fig. 3a), whereas in the Triassic carbonate formations, they exhibit stylolitisation, as evidenced by the presence of stylolitic seams (Fig. 4a). The measured planes in Jurassic–Cretaceous formations generally dip steeply, at angles between 50° and 80°, towards the northwest. A general trend and plunge of poles to bedding planes is P_0 158/42° (Fig. 3a). In the more homogeneous Middle Triassic lithologies located further south, the bedding tends to be more gently inclined than in the Jurassic–Cretaceous formations, which are semi-ductile deformed – a result of their rheological properties (the formations are predominantly composed of shales and marls). These units are often steeply dipping, occasionally subvertical, and commonly folded into the ductile behaving rocks of the Carpathian Keuper.

In the field, the carbonate rocks of the Jurassic–Cretaceous sequence typically form characteristic steeply dipping ridges (*"klippen"*). The klippen-like pattern of the Jurassic–Cretaceous successions is well-preserved in the area of Buková hora (542 m asl.) and Kuchyňa-Vývrat settlement.

Conversely, elsewhere, the massive Middle Triassic carbonate behaved more rigidly and are more gently inclined, generally dipping north-westward at angles of up to 50°, in some places reaching subhorizontal positions (e.g., Kŕč – 409 m asl. or Geltek – 594 m asl.), with a consistent north-westward dip. Bedding served as the reference plane for the identification and analysis of secondary tectonic structures, which are described in detail in the following sections.

D_1^A *Alpine deformation*

Structural association of D_1^A deformation stage is represented by F_1^A folds, primarily associated with S_1^A cleavage and L_1^A lineations, which are primarily developed within the rheologically predisposed Jurassic–Cretaceous succession.

The cleavage planes (S_1^A)are generally steeper than the S_0 bedding planes. With a northwest or southeast dip direction, they form a characteristic fan-like pattern of axial plane cleavage. In the streonet, a distribution of poles to cleavage planes is characterised by a well-defined maximum density P_1^A with a mean orientation of 292/06° (Fig. 3b).

In several outcrops, open to closed folds, occasionally overturned, have been observed, displaying both symmetrical and asymmetrical geometries, often reaching metre- to tens of metre-scale dimensions (Fig. 4b). These folds predominantly verge to the northwest, although the opposite, southeast vergence was also observed. The fold-related axial plane cleavage (S_1^A) typically dips toward the east-southeast to subvertical orientations and is closely associated with transport-parallel lineations (L_{1t}^A) with WNW trend (Figs. 4c, 5, and 6). The orientation of fold b-axes is generally in the NNE–SSW direction and is parallel to crenulation lineations, which are locally developed in lithologically suitable rocks of Jurassic and Cretaceous age (Fig. 5).

Foliation S_1^A in combination with bedding planes (S_0) form *S-C*-like structures (Fig. 4f). In these structures, the S planes correspond to bedding (S_0) , while and the *C* planes represent newly formed foliations (S_1^A). This *S–C* fabric clearly indicates top-to-the-northwest-directed transport, with an azimuth of approximately 305°. In some locations, recumbent folds with a north-westward vergence have also been observed and documented (Fig. 4b).

D_2^A *Alpine deformation*

During this deformation stage, both symmetrical and asymmetrical folds were formed, with their axes inclined towards the north (Fig. 4e). The asymmetrical F_2^A folds are of decimetric scale and exhibit vergence towards the east, which is associated with W–E compression. The measured and calculated axial planes (S_2^A) correspond to the orientation of the documented folds. The S_2^A planes, which exhibit an almost subvertical orientation, with dips toward both the west and east (Fig. 3c). These planes can be classified as spaced and fold axial cleavage; however, in several outcrops, they may be mistaken for very young systematic extensional joints. Nonetheless, these structures are frequently associated with meso-scale open folds (F_2^A), whose axes trend approximately north–south (Figs. 7 and 8). In such cases, their fold-related origin allows for a clear distinction from joints.

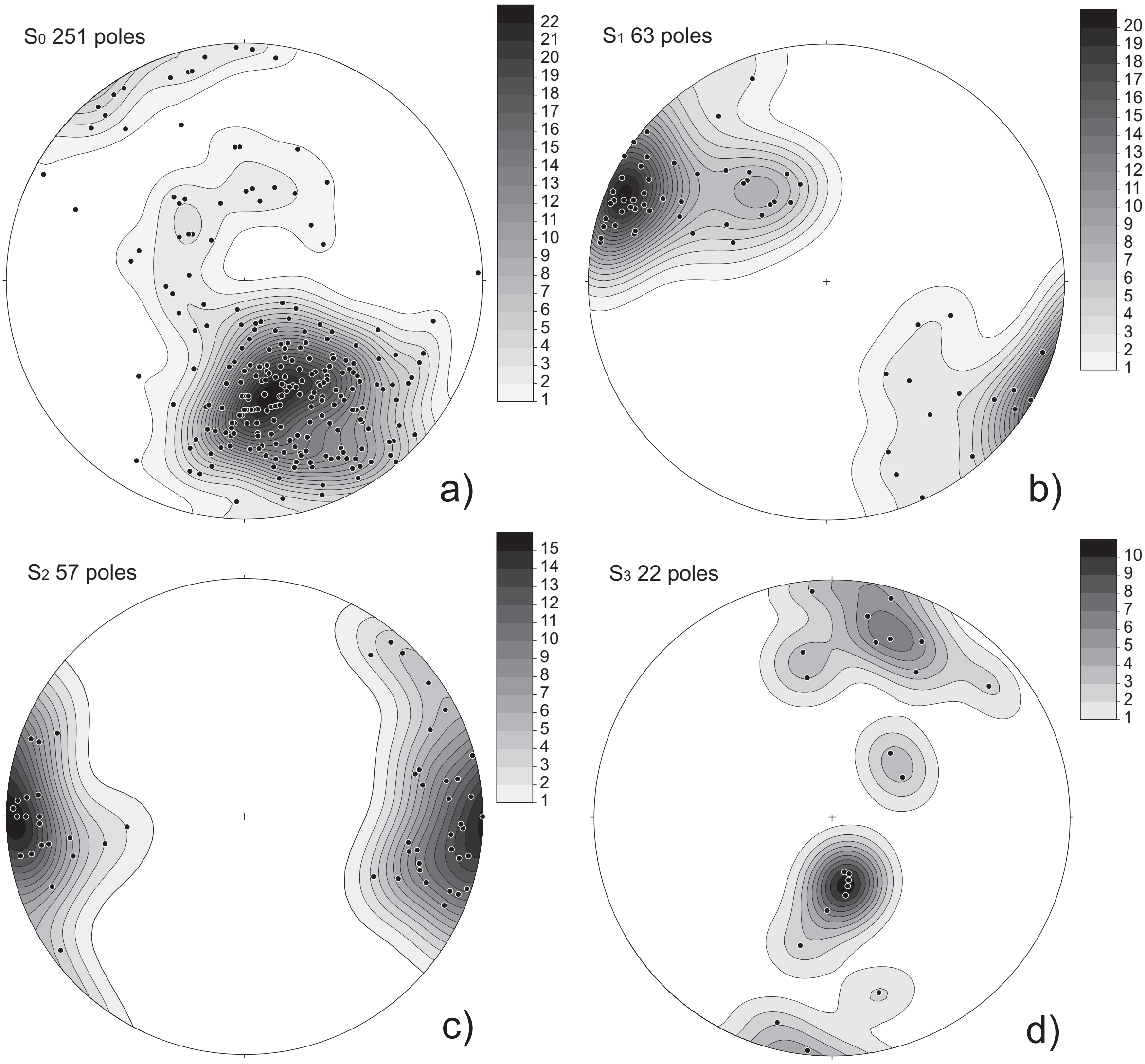

Fig. 3. Contour plots of Alpine primary and tectonic planar structures of the Fatric Unit, represented by poles to planes (Kamb contours in standard deviations, Kamb 1959; Lambert projection, lower hemisphere): **a** — Primary sedimentary planes – beddings (S_0^A) with well-visible point to girdle distribution. **b** — Alpine S_1^A foliations and cleavages with point distribution linked to top-to-the-northwest tectonic transport. **c** — Alpine S_2^A cleavages. **d** — Alpine S_3^A cleavages related to top-to-the-south tectonic transport.

D_3^A *Alpine deformation*

The youngest identified Alpine deformation phase (D_3^A) is characterised by a general NNW–SSE shortening, associated predominantly with the development of open to tight folds (F_3^A) with southward vergences indicating a top-to-the-south transport. The axial planes of these folds which are parallel with cleavages (S_3^A) are steeply inclined towards the north (Fig. 3d), while the fold axes are subhorizontal (Fig. 7), with a general trend and plunge of F_3^A 092/02°. Field investigations revealed a close spatial and genetic relationship between the folds and south-vergent reverse to thrust faults (Fig. 4d). No transport lineations (L_3^A) were observed in the rocks except for slickenside lineations present on the reverse fault planes, which exhibit a north–south orientation.

Interpretation of structures and discussion

In this contribution, an extensive dataset of planar primary structures associated with bedding (S_0) and deformation-related features (D_n^A) was documented within the Triassic to Cretaceous sedimentary sequences of the Fatric Unit. Structural analysis revealed a heterogeneous assemblage of measured structures. The geometry and overprinting relationships of secondary planar elements (cleavages, fracture cleavages, and fold axial surfaces, various types of lineation as well as fold hinge lines or axes) indicate the presence of three principal Alpine deformation phases.

The first deformation stage (D_1^A) is characterised by the enhancement of bedding through pressure-solution processes under pure shear conditions, followed by the development of

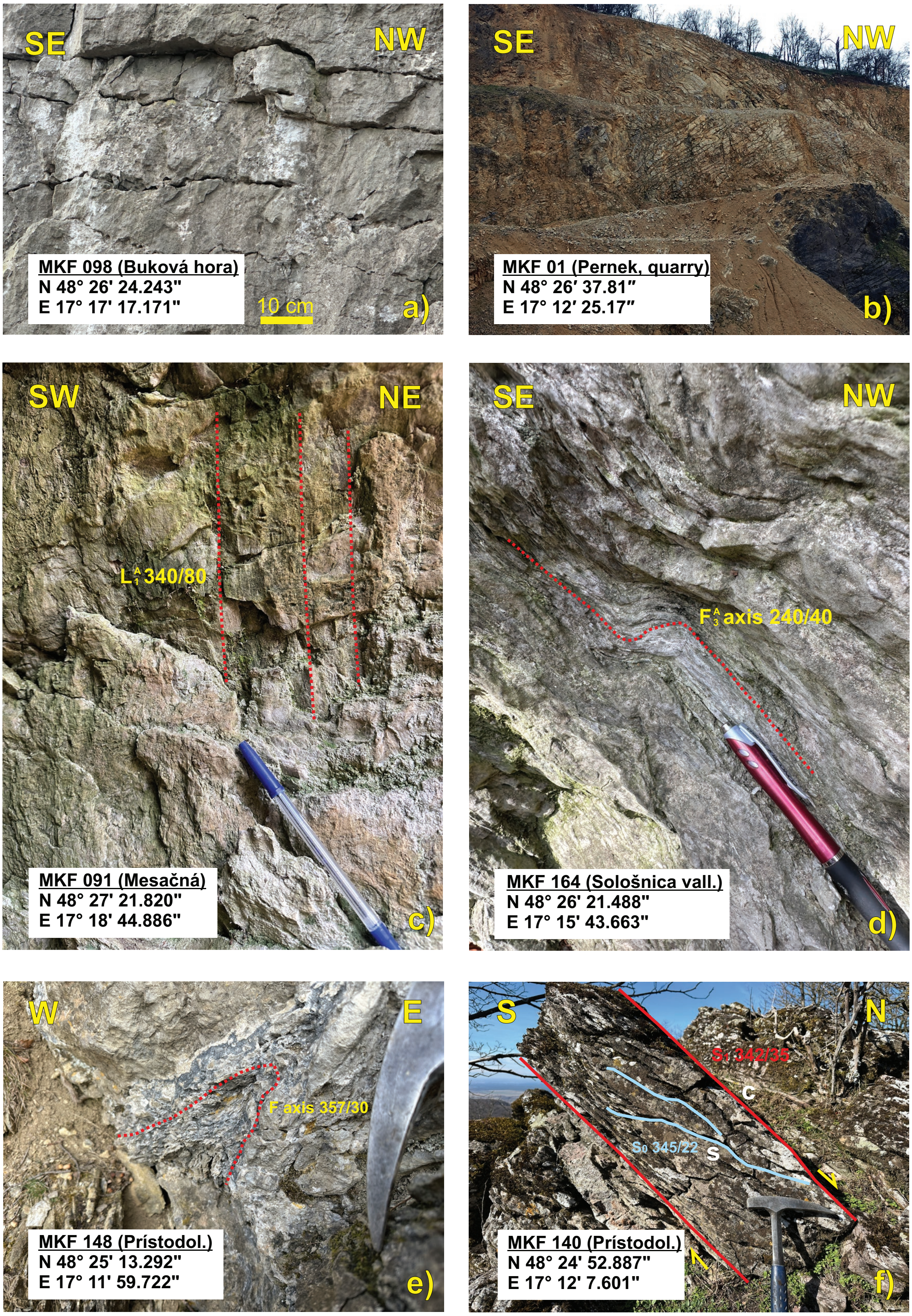

Fig. 4. Alpine deformation structures of the Fatric Unit: **a** — Irregularly developed stylolitic foliation within Middle Triassic limestone, interpreted as evidence of pure-shear deformation. **b** — Recumbent fold affecting Jurassic limestone, indicating tectonic transport directed top-to-the-northwest (Pernek quarry). **c** — Alpine stretching lineation (L_{1t}^A) with a NW–SE orientation in the Lower Cretaceous limestone. **d** — South-vergent asymmetric fold (F_3^A). **e** — East-vergent asymmetric fold (F_3^A) in the Lower Cretaceous limestone. **f** — Discontinuous cleavage (S_1^A) within Jurassic marly limestone with preserved S-C fabric and indicating tectonic transport toward the northwest.

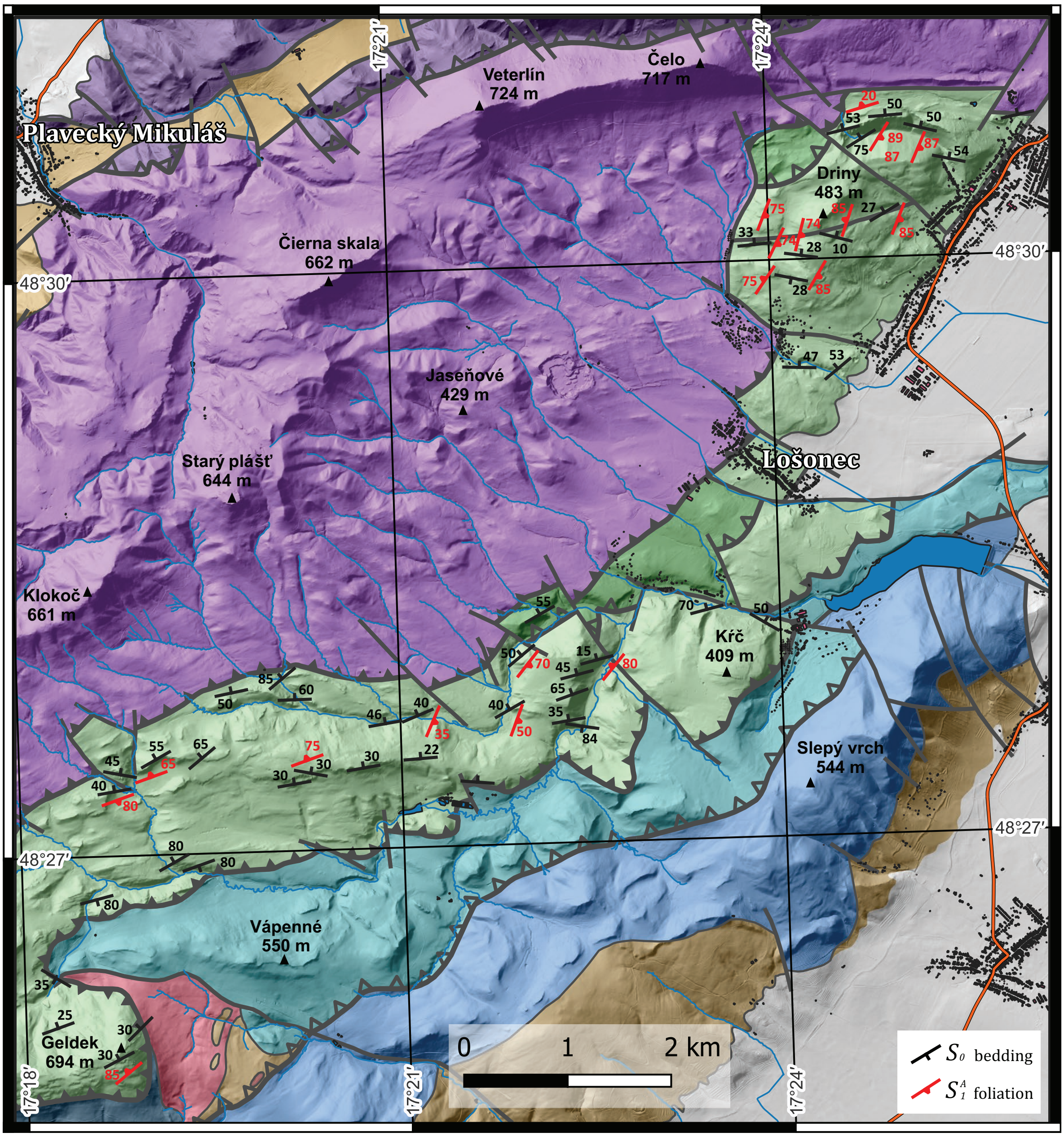

Fig. 5. Tectonic map showing the orientation of bedding planes S_0 and the Alpine fabric S_1^A in the northeastern part of the Fatric Unit. For the legend, see Fig. 2. Modified after Polák et al. (2011).

an asymmetric arrangement of tectonic planar structures (S_1^A) formed under sub-simple to simple shear conditions.

This horizontal compressive stress led to the evolution of Alpine thrusts and reverse faults, resulting in the shortening of the crust, where the hanging wall was displaced upward relative to the footwall. The sense of shear within such zones can be interpreted primarily through the presence of asymmetric and intrafolial folds, parallelogram-shaped structures, and stretching lineations observed in deformed rocks (e.g., Ramsay 1980; Lister & Snoke 1984; Passchier & Trouw 2005; Pelech & Hók 2017). Kinematic indicators, such as these asymmetric structures, provide evidence of shear direction associated with the Eo-Alpine tectonic phase because younger sediments were not incorporated to these fold structures (e.g., Marko et al. 1990; Schittenhelm 2017).

The main criteria to determine the shear movement were *S–C* fabric with a combination of the intersection and stretching lineations. These data also refers to the Alpine thrusting of the Fatric Unit onto the Tatric Unit with the principal vector of tectonic transport an average azimuth of 305° (NW direction). This top-to-the-northwest direction of the Alpine tectonic transport was determined by stretching or slickenside

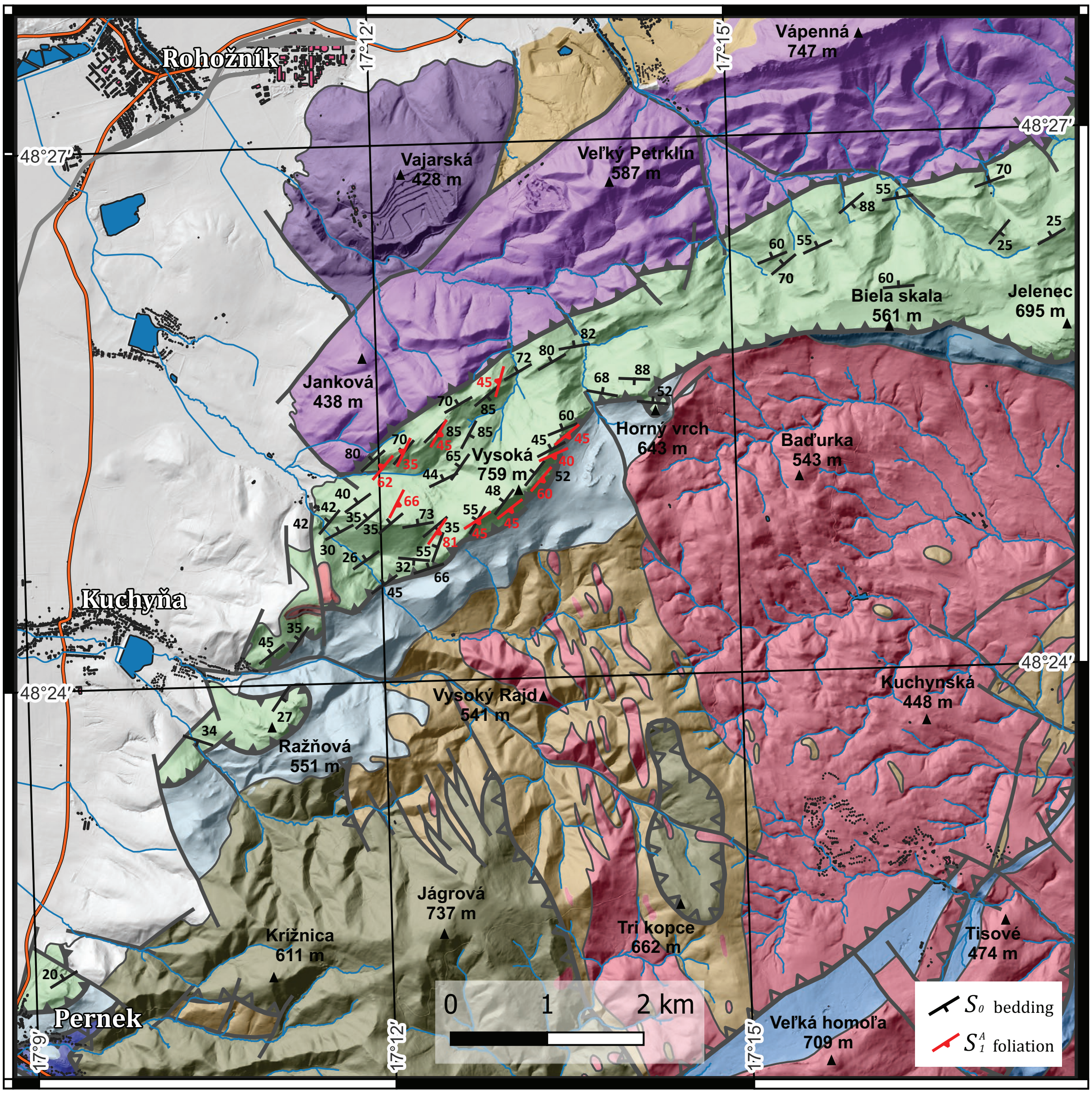

Fig. 6. Tectonic map showing the orientation of bedding planes S_0 and the Alpine fabric S_1^A in the southwestern part of the Fatric Unit. For the legend, see Fig. 2. Modified after Polák et al. (2011).

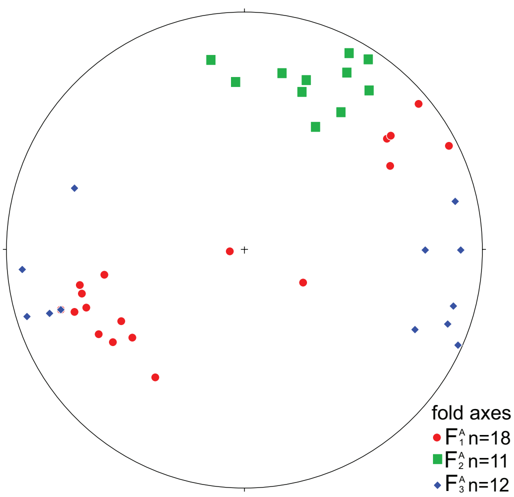

Fig. 7. Measured Alpine fold axes of the Fatric Unit (Lambert projection, lower hemisphere).

lineations with NW–SE trends (L_{1t}^A), fold axes with NE–SW trends (F_1^A) and also by large-scale recumbent folding affecting the sedimentary sequences. The emplacement of the Fatric Unit (Vysoká and Zliechov nappes) onto the Tatric Unit occurred approximately 90 Ma ago (cf. Plašienka et al. 1997; Plašienka 1999, 2003, 2018, 2019; Putiš et al. 2009; Prokešová et al. 2012). This is further supported by the thrust surface of the Tatric crystalline complex over the Borinka Unit, where the timing of thrusting has been constrained to the Late Cretaceous (~80–75 Ma) based on K–Ar dating of Alpine

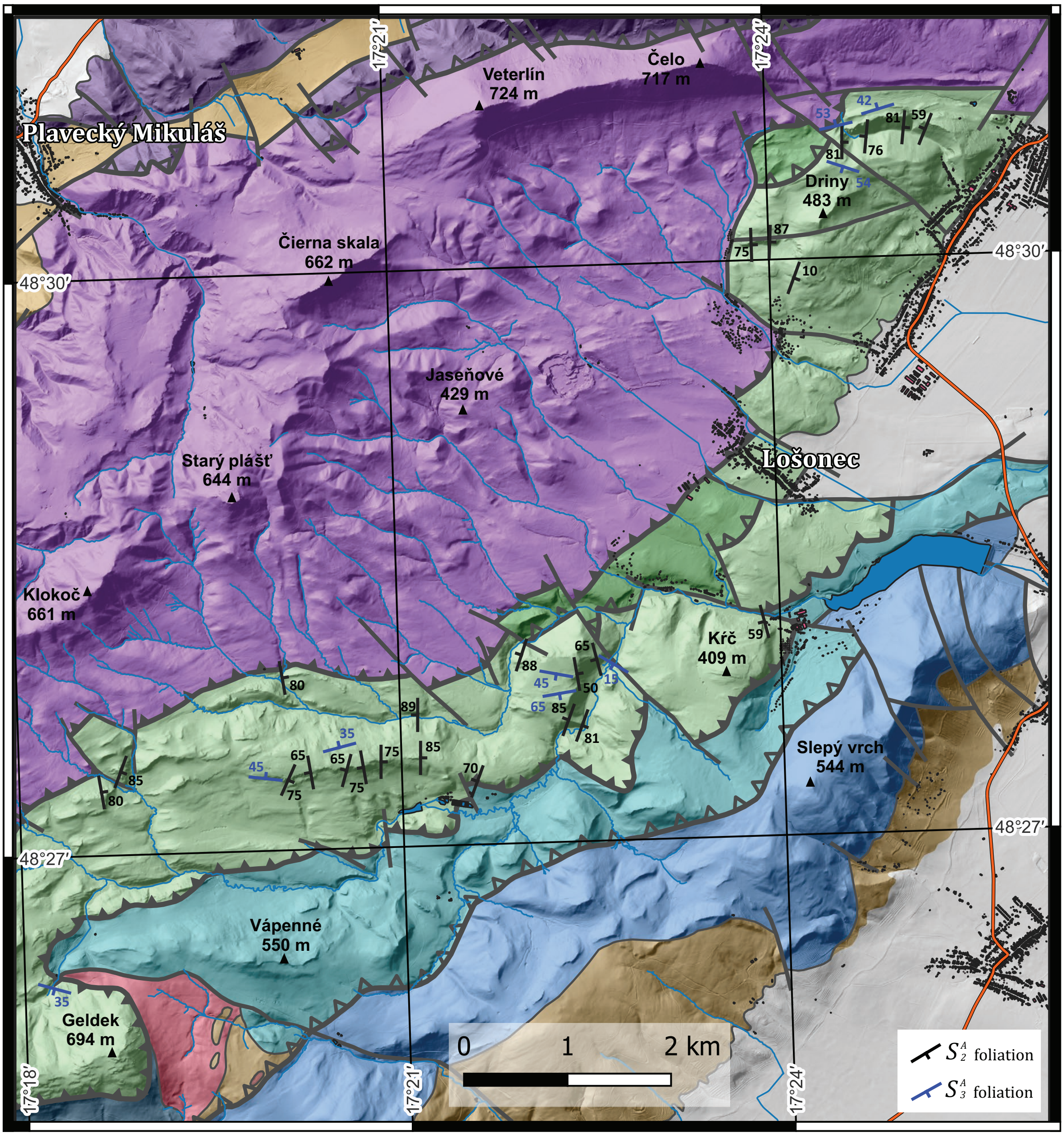

Fig. 8. Tectonic map showing the orientation of the Alpine fabric S_2^A and S_3^A in the northeastern part of the Fatric Unit. For the legend, see Fig. 2. Modified after Polák et al. (2011).

sericitic blastomylonites within the granitoids (Kantor et al. 1987; Putiš et al. 2009). These geochronological data are consistent with the lithostratigraphy of the Fatric Unit, where the youngest known deposits (synorogenic flysch of the Poruba Formation) are of Cenomanian age (approximately 95 Ma) (Jablonský 1988).

A substantial reorganization of the palaeostress field took place during the Late Cretaceous to Early Eocene (D_2^A). The principal shortening axis shifted from a northwest–southeast to a west–east (W–E) orientation. The observed deformation (D_2^A) was identified in the Mesozoic rocks of the Vysoká Nappe; however, it is no longer present in the Eocene–Oligocene of the Malé Karpaty Group (Marko et al. 1995; Schittenhelm 2017). Therefore, it is considered to be of an older origin. The final stage of this deformation (D_2^A) is characterised by an extension, and it is expressed by the development of extensional structures, predominantly joints filled with calcite. These planes were favourably oriented and acted as zones of weakness, later filled with fibrous or blocky calcite and on some places with extensional en-echelon pattern. The orientation of the calcite veins varies, and this phenomenon will be object of further research. During the field research, it was not

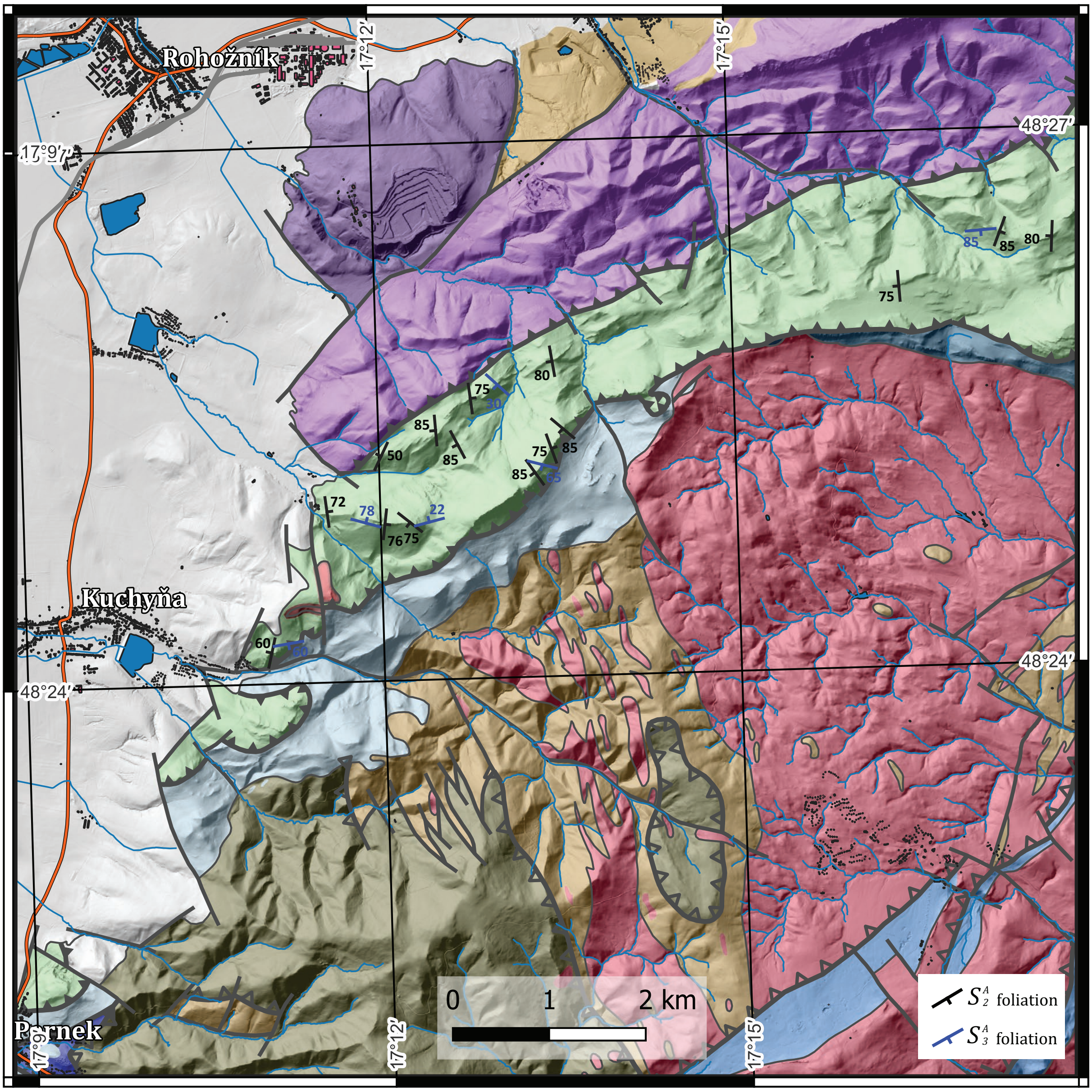

Fig. 9. Tectonic map showing the orientation of the Alpine fabric S_2^A and S_3^A in the southwestern part of the Fatric Unit. For the legend, see Fig. 2. Modified after Polák et al. (2011).

possible to confirm unambiguously whether these were older calcite veins or extensive structures of Early to Middle Miocene age (cf. Marko et al. 1991, 1995; Fodor 1995).

During the Late Oligocene to Early Miocene period, the tectonic regime gradually changed to a compressional setting, with the maximum shortening oriented in a north–south direction (D_3^A). This led to south-vergent reworking of the originally north-vergent Fatric tectonic structure in the Malé Karpaty region (cf. Marko et al. 1991, 1995). The general structure of the Fatric sedimentary sequences was rotated and tilted, with bedding dipping towards the north-northwest. Rheologically weaker rock formations underwent re-folding (F_3^A), accompanied by the development of backthrusts with top-to-the-south kinematics. This deformation event is dated based on observations of deformation affecting Oligocene and Lower Miocene rocks. While the Oligocene sediments were affected by the same south-vergent deformation, the Karpatian sedimentary sequence unconformably overlie this structural framework (e.g., Nováková et al. 2017; Tomašových et al. 2024). The relatively steep dip of the nappe body also reflects the influence of the south-vergent tectonic structure and is attributed to the soft docking of the ALPACA Mega-Unit and the European Platform (e.g., Kováč et al. 1989; Marko et al. 1991; Pešková et al. 2012; Shittenhelm 2017). This process led to thrusting within the External Western Carpathians and the occurrence of reverse faulting in the hinterland. It is likely that this deformation is associated with the development of a fan structure in the broader region surrounding the Pieniny Klippen Belt (e.g., Marko et al. 1991; Pešková et al. 2012).

Conclusions

The Fatric Unit is primarily composed of Triassic to Cretaceous sedimentary sequences, which exhibit varying rheological properties. Despite these differences, all formations are characterised by well-preserved and well-developed bedding (S_0), which served as a reliable primary fabric. This bedding was utilised as a key structural marker for identifying and analysing Alpine deformation during this study.

The structural analysis of the Fatric Unit reveals a complex tectonic history marked by multiple deformation phases associated with the Alpine orogeny. Three principal deformation stages (D_1^A) to (D_3^A) were identified, each reflecting distinct stress regimes and tectonic processes. The earliest deformation phase (D_1^A) is linked to Eo-Alpine compressional tectonics, resulting in northwest-directed thrusting and large-scale recumbent folding. Subsequent reorganization of the paleostress field during the Late Cretaceous to Early Eocene (D_2^A) introduced a W–E oriented shortening phase, followed by extensional processes expressed through calcite-filled joints. The final compressional phase (D_3^A) is refered to the Late Oligocene–Early Miocene, involved south-vergent backthrusting that overprinted earlier structures and contributed to the overall fan-shaped architecture of the region. This structural evolution reflects the complex interplay of compressionanl and extensional tectonic regimes during the Alpine orogeny, culminating in the present-day configuration of the Western Carpathians.

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Electronic supplementary material is available online:
Supplementary Table S1 at https://geologicacarpathica.com/data/files/supplements/GC-76-6-Lacny_TableS1.xlsx