GEOLOGICA CARPATHICA, 2024, 75, 5, 315–327 https://doi.org/10.31577/GeolCarp.2024.18

Polyphase deformation of the Tatric Unit in the southwest part of the Malé Karpaty Mts. (Slovakia)

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(Manuscript received September 17, 2024; accepted in revised form November 22, 2024; Associate Editor: Igor Broska)

Abstract: The study area is located in the Devínske Karpaty Mts., which represents the southwestern part of the Malé Karpaty Mts. It is formed by the Tatric crystalline basement and its Permian-to-Cretaceous sedimentary cover, which is thrust over the Jurassic sediments of the Borinka Unit. The basement consists of Lower Paleozoic metamorphosed rocks of the Pezinok and Pernek groups with granite intrusions of the Lower Carboniferous. The analysis of deformation structures allowed us to identify Variscan and Alpine deformations within the Tatric Unit. The Variscan deformation (D^V) is accompanied by middle-grade metamorphism and is characterised by penetrative metamorphic foliations (S_2^V), which are intensely folded. The deformation is pre-Carboniferous because it does not affect granite intrusions. The Alpine deformations (D^A) are marked by structural evolution under low-grade metamorphism with the evolution of phyllitic, crenulation, and mylonitic foliations (S_1^A and S_2^A). The Eo-Alpine (Cretaceous) shortening is evidenced by asymmetric folds with an ENE–WSW orientation of fold axes (F_2^A) and line intersections (L_{2c}^A) with pronounced top-to-NW tectonic transport over the Borinka Unit.

Keywords: Western Carpathians, structural analysis, Variscan deformation, Alpine deformation

Introduction

The Western Carpathians represent a part of the Alpine–Carpathian orogenic belt and are traditionally interpreted as a result of Cretaceous (Eo-Alpine) to Cenozoic (Neo-Alpine) crustal shortening of the Variscan basement associated with thin-skinned nappe stacks of Mesozoic sedimentary sequences (Andrusov et al. 1973; Plašienka et al. 1997; Hók et al. 2014; Plašienka 2018).

The Malé Karpaty Mts. are the westernmost so-called core mountains of the Internal Western Carpathians (Fig. 1a; Maheľ 1986; Hók et al. 2014, 2019) or Central Western Carpathians (e.g., Plašienka 2018) and geomorphologically divided into (from southwest to northeast) the Devínske Karpaty, Pezinské Karpaty, Brezovské Karpaty, and Čachtické Karpaty Mts. (cf. Mazúr & Lukniš 1978). They are characterised by the allochthonous position of the Tatric crystalline basement on the Borinka Unit (Koutek & Zoubek 1936; Plašienka et al. 1991; Bielik et al. 1992; Hók et al. 2022), the Permian to Cretaceous cover successions (predominantly discontinuous and reduced) with a hiatus during the Late Triassic, and the presence of the Fatric and Hronic cover nappes only in the northern part of the mountain range (Fig. 1b; Maheľ 1986; Polák et al. 2011). The crystalline basement is formed by the Lower Paleozoic metamorphosed volcano-sedimentary formations of the Pezinok and Pernek groups (Ivan & Méres 2006) intruded by the Lower Carboniferous granitoid rocks (e.g., Cambel & Vilinovič 1987; Kohút et al. 2009; Putiš et al. 2009a; Uher et al. 2011; Polák et al. 2012).

The main objective of the contribution is to decipher and separate the Variscan and Alpine deformations and define the sense of displacement of rock complexes in the westernmost region of the Western Carpathian internides.

Geological setting

The study area comprises the Tatric crystalline basement composed of the Lower Paleozoic metamorphosed rocks and Lower Carboniferous granitoids (Kohút et al. 2009; Putiš et al. 2009a; Uher et al. 2011). The Tatric crystalline basement is overlain by Permian to Lower Cretaceous autochthonous sediments (Devín cover). The entire structure was thrust above the Borinka Unit, which is part of the Infratatric (Plašienka 2018) or Lower Australpine sequences (Hók et al. 2022).

The largest part of the studied area is composed of different varieties of granitoid rocks of the Bratislava Massif. These rocks are predominantly located in the central and eastern parts of the area. Towards the northwest, metamorphic rocks of the Pezinok and Pernek groups appear. During the Variscan orogenic cycle, granitoid rocks intruded into the Pezinok and Pernek groups with signs of thermal metamorphosis (Cambel

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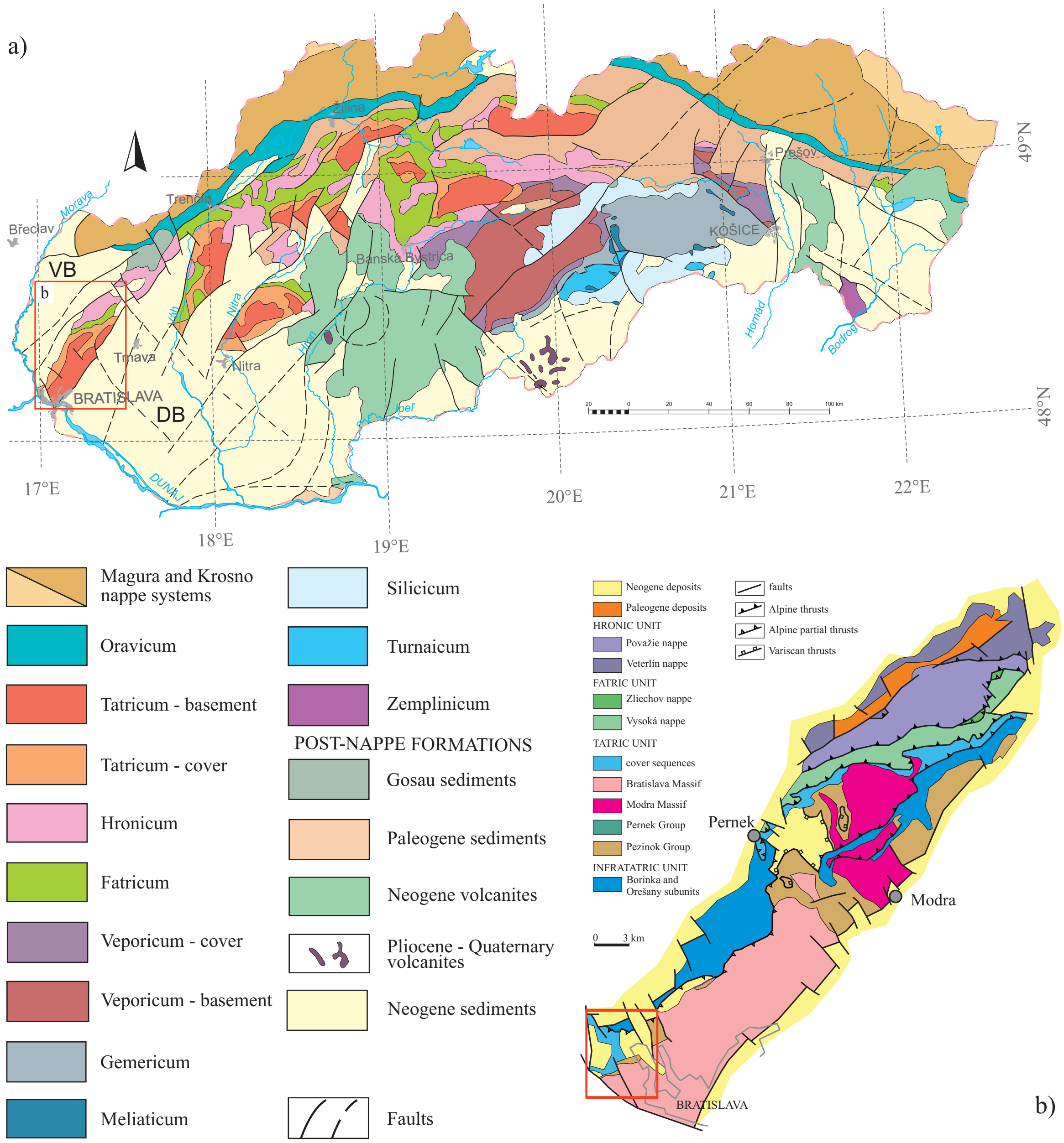


Fig. 1. Tectonic map of the study area: **a** — Map of the Slovak part of the Western Carpathians. The Malé Karpaty Mts. are marked by a red rectangle (according to Biely et al. 1996). **b** — Tectonic map of the Malé Karpaty Mts. with the marked study area in the Devínske Karpaty Mts. (according to Polák et al. 2011, modified). Note: VB – Vienna Basin, DB – Danube Basin.

& Vilinovič 1987). The Bratislava Massif is composed predominantly of middle-grained muscovite–biotite granodiorite and granite, middle- to coarse-grained muscovite–biotite porphyric granites, pegmatite and aplite dykes, and scarcely of biotite–amphibole diorites (Polák et al. 2012; Fig. 2).

The rocks of the Pernek Group represent an advanced stage of riftogenesis with an incomplete and metamorphosed ophiolite sequence that formed the upper part of the oceanic crust, containing metamorphosed mafic rocks that were originally fine-grained basalts, gabbros, dolerites, and black shales (Ivan & Merés 2006). The Pezinok Group is significant due to the occurrence of flysch sequences and progressively-graduating, fine-grained metasediments, occasionally with carbonates (not presented in the study area). The protolith of the Pezinok Group was composed of clay shale, sandstones, and black fine-grained schists with organic admixture (Putiš et al. 2004; Fig. 2). The Pernek Group was thrust onto the Pezinok Group during the Variscan orogenic cycle (Ivan & Méres 2006), which was also a partial objective of this work.

Jurassic to Cretaceous sediments of the Devín cover, together with the Upper Permian and Lower Triassic siliciclastic rocks, and Middle Triassic carbonates constitute

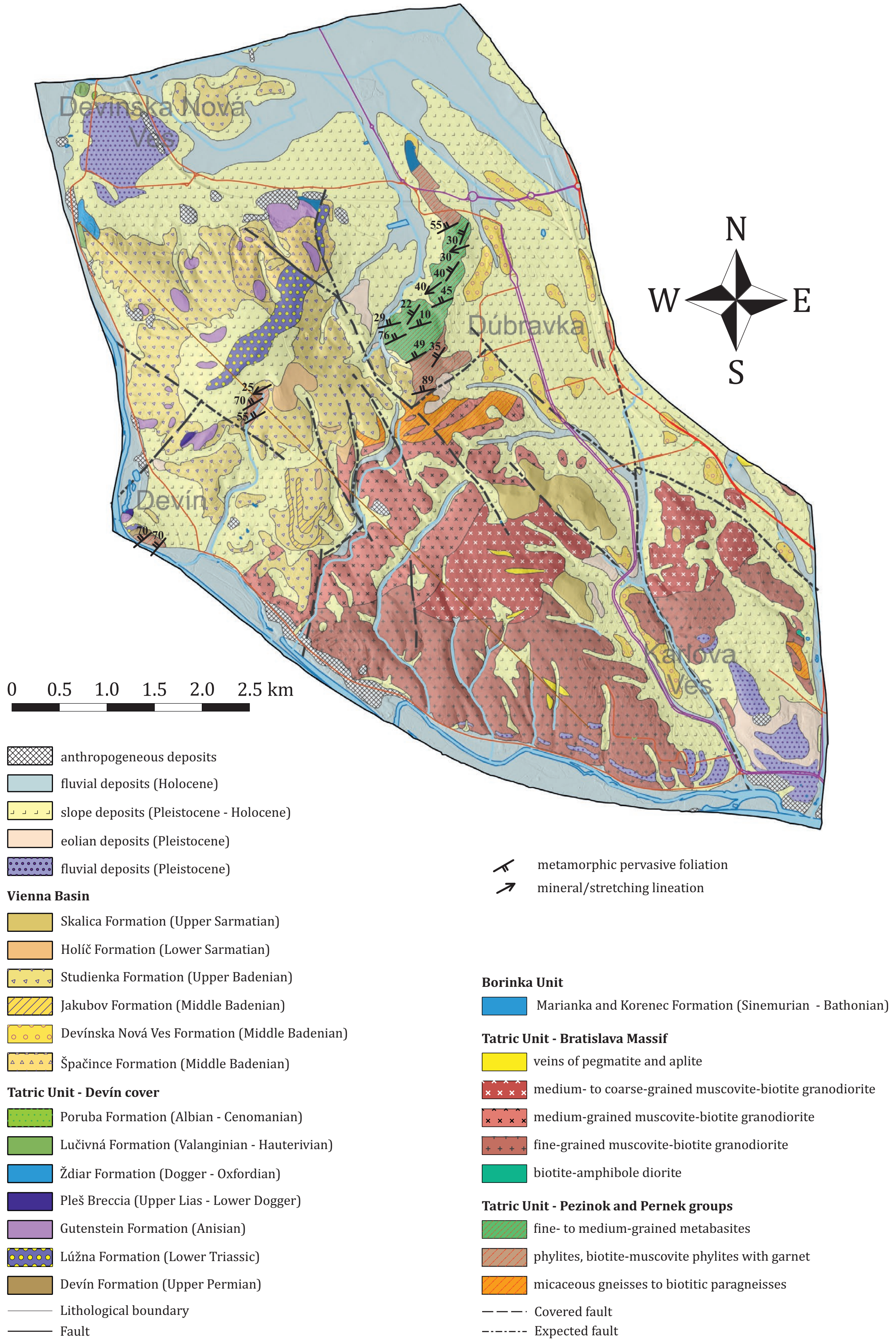


Fig. 2. Geological map of the study area according to Polák et al. (2011), simplified. Structural marks represent the Variscan pervasive foliation and lineation.

the sedimentary cover of the pre-Alpine basement (cf. Plašienka 1987, 1990, 1999; Plašienka & Putiš 1987; Polák et al. 2012). The Eo-Alpine structure of the Devínske Karpaty Mts. is covered by Neogene sediments of the Vienna and Danube basins (Fig. 2). The Paleogene sediments are unknown in the study area (e.g., Králiková et al. 2016; Kováč et al. 2016).

Methods and data

The rock complexes were studied on the mesoscale, and the spatial orientationof foliations, fold planes, fold axes, stretching, and mineral lineations were analysed. In geology, planar structures are generally referred to as *S*-surfaces. Numerical indexing by relative age was usually used in the following order: where S_0 is the primary surface, generally foliation or magmatic layering and S_1, S_2, ..., S_n are indices for secondary (tectonic) foliations in the order of their designated superposition from oldest to youngest.

As with foliations, lineations are referred to as *L*-structures in the rocks. When lineations of different generations are present in the same rock, they are assigned numerical suffixes according to their relative ages: L_0 is the primary lineation and L_1, L_2, ..., L_n are secondary (tectonic) lineations in the order determined by their superposition. Fold axes are marked by F_1, F_2, ..., F_n symbols. A similar approach is followed to index the associated deformation (D_1, D_2, ... D_n) and metamorphic (M_1, M_2, ... M_n) stages that generated the tectonic structures. The analysed mesoscopic, macroscopic, and microscopic tectonic structures can be divided into two groups. The earlier deformation cycle was denoted as D^V and records Variscan deformation. The latter deformation cycle is related to the Alpine deformation denoted as D^A.

All outcrop scale structural data were processed by the Stereonet version 11 software (Allmendinger et al. 2012; Cardozo & Allmendinger 2013). Oriented thin-section samples for the microscale study were collected from the selected sites. The photomicrographs were captured by the Plustek Opticfilm 8200i scanner operating with SilverFast 8 software.

The digital terrain model (DTM) used in this study was derived from Airborne laser scanning products (LiDAR) of the Digital Model of Relief 5.0 (DMR 5.0) and Digital Model of Surface 1.0 (DMP 1.0), provided by the Geodetic and Cartographic Institute Bratislava ("Source of products LLS: ÚGKK SR – The Geodesy, Cartography and Cadastre Authority of the Slovak Republic" https://zbgis.skgeodesy.sk/mapka/sk/teren?). All spatial data was handled using the GeoPackage in the Quantum GIS software 3.34 (QGIS.org 2023).

Obtained structural data

Structural measurements were carried out in Mesozoic sediments of the cover sequence as well as in the crystalline basement to distinguish between Alpine and Variscan structures.

Tatric cover sequences

Primary structures are well-preserved in Mesozoic sediments of the Devín cover sequence, but less so in the Borinka Unit and hardly occur in the crystalline basement due to Alpine metamorphosis and deformation (Figs. 3, 4a). They are represented by bedding planes (S_0^A), rare ripple marks (L_{0t}^A) and cross-bedding. The orientation of the bedding planes indicates fold deformation that had originated during the NW–SE shortening (Fig. 4a).

The original bedding (S_0^A) is accentuated by compression in the vertical direction (flattening) under the pure shear tectonic regime with the evolution of newly-formed S_1^A planar structures and generally parallel with S_0^A. The foliation (S_1^A) is represented by the compaction or stylolitic foliation, which is particularly well-observed in limestones and siltstones (Fig. 4a).

The folds (F_1^A) are predominantly open-to-closed, with amplitudes of tens to the first hundred meters. The fold axial planes, representing fold axial cleavages (S_2^A), are oriented in the NE–SW direction and occurred due to the NW–SE oriented shortening (Fig. 4b).

Structurally-younger spaced cleavage (S_3^A) was observed predominantly in Mesozoic sediments of the Devín cover. The orientation of the cleavage (S_3^A) is characterised by the NW–SE strike and refers to an NE–SW shortening (Fig. 4b). Intersection lineation (S_{3i}^A) is oriented in an NW–SE direction with a subhorizontal inclination.

Tatric crystalline basement

The metamorphosed rocks of the Pernek and Pezinok groups contain the best-preserved planar and linear tectonic structures. Foliation (S_1^V) is folded and preserved in the form of isoclinal and rootless folds (F_1^V), which resulted from intense deformation during the Variscan orogenic cycle (D_2^V; Fig. 5a). The example of this deformation is shown in Figs. 6a, 7a, b, where the foliation (S_1^V) has been folded to isoclinal folds and almost completely transposed into the metamorphic foliation (S_2^V). This is the oldest observed foliation in the metamorphic rocks of the Tatric crystalline basement, and it is not present in granitoid rocks or cover sequences.

The S_2^V fabric is the most distinct structure in the metamorphic rocks of the Pezinok and Pernek groups. The phyllites and paragneisses assume a distinct planar structure, with sharply-defined QF cleavage domains (composed mainly of quartz) from microlithons of the M strips in these rocks (cf. Figs. 6a, b, 7). Quartz is dynamically recrystallised and composed of fine-grained aggregates of crystals in the rock between phyllosilicate microlithons (Fig. 7). The planar structure (S_2^V) is most dips at intermediate angles to the northwest (Fig. 5a). Distinct crenulation cleavage (S_2^A) disrupts it with a relatively flat inclination to the SE (Figs. 6a, b, 7c–f).

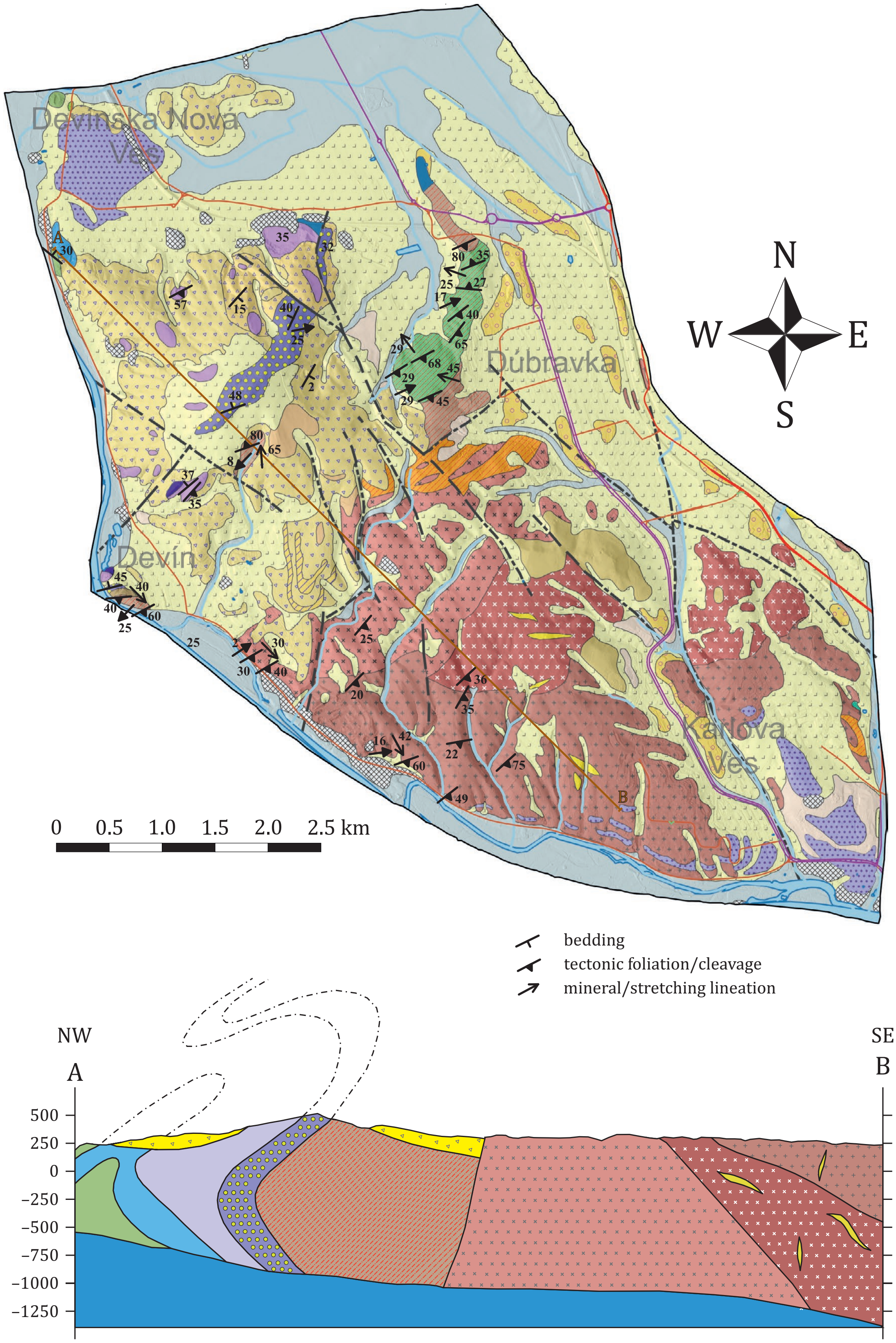


Fig. 3. Geological map and the cross-section of the study area according to Polák et al. (2011), simplified. Structural marks represent the Alpine spaced, crenulation, mylonitic foliations, and lineations. Note: for the legend, see Fig. 2.

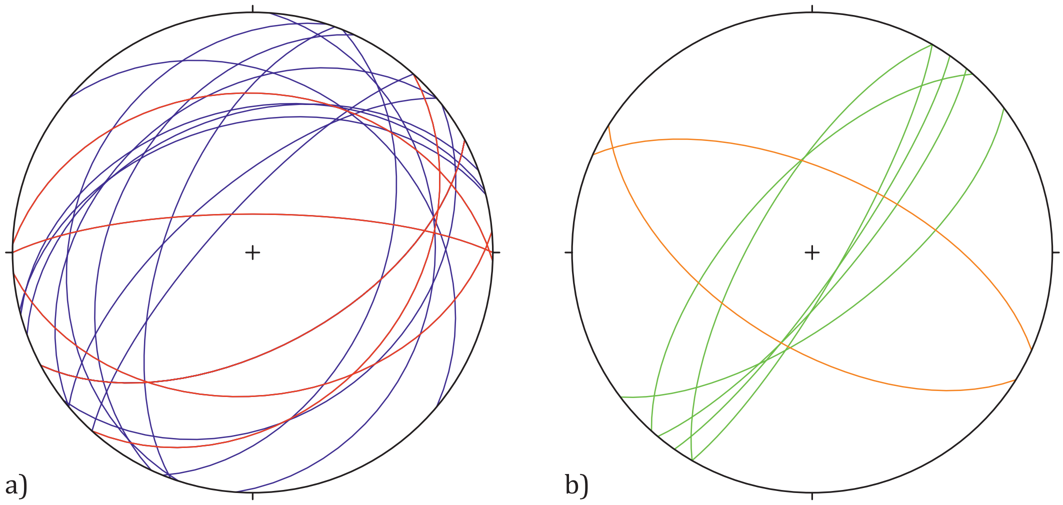


Fig. 4. Stereograms of structures measured in the Devín cover succession (lower hemisphere, Lambert projection): **a** — A great circle plot of primary planar structures (bedding planes S_0^A – blue) and tectonic foliation (S_1^A – red); **b** — A great circle plot of spaced cleavages of S_2^A in green, S_3^A in orange colours.

Stretching or mineral lineations could be observed on the less-folded domains of S_2^V foliation surfaces and have an ENE–WSW trend.

The crenulation cleavage (S_2^A) can be well-observed on outcrops in phyllites of the Pernek Group (Fig. 6a, b). The cleavage (S_2^A) is developed in metamorphic rocks pervasively. The crenulation folds (F_2^A) are asymmetric with a maximum wavelength of 1.5 cm and amplitude of up to 4 mm and resemble *S*-folds indicating top-to-the-NW tectonic displacement (Fig. 7c–f). Crenulation lineations (L_{2c}^A) are sub-horizontally oriented with a NE–SW trend and mostly inclined to the SW.

The muscovite–biotite granodiorites are undeformed to a certain degree (Figs. 8a, 9a). However, in some outcrops, the granitoids were strongly deformed with a well-developed mylonitic foliation (e.g., Fig. 6c). The early phase of mylonitisation (Figs. 6e, 9c, d) is manifested by porphyroblastic fabric. Interestingly, the fine-grained deformed material around the hypidiomorphic feldspar grains is visible to the naked eye (Fig. 8b). The intermediate phase of the mylonitic fabric in granitoids is presented (see Fig. 8c, d). The higher stage of mylonitic structures is visually homogeneous with strong pervasive mylonitic foliation (Figs. 8d, 9e, f). Macroscopically, it is not possible to see the grains, and it is completely smooth, altered, and sericitised on this sample. Mylonitised granite contains small grains of pink to red garnets, mostly up to 1 mm (Fig. 9e, f).

The S_2^A spaced to mylonitic foliation is inclined at a moderate angle, generally to the southeast (Fig. 6c–e). Spaced foliation in granitoid rocks locally assumes a mylonitic character with *S*–*C* structures (Fig. 6c–e). Mineral/stretching lineations are present on the mylonitic foliation, indicating transport to the NW.

In granitoid rocks, the spatial characteristics of pegmatite and aplite veins were observed and measured. For the most part, thin veins from 3 to 40 cm were apparent. Altogether, 6 veins were found. The veins had a general orientation from the southeast to the east with a relatively gentle inclination. Only two pegmatite veins had steep inclinations.

Interpretation of chronology of deformation

Variscan deformation

As was interpreted by earlier authors, the Variscan rocks were formed in the continental slope (turbidites – the Pezinok Group) and ocean floor (basalts, gabbro – the Pernek Group) environments of the Rheic Ocean until the Late Devonian, when the ocean was closed (e.g., Németh 2005, 2021; Putiš et al. 2009b; Németh et al. 2016; Hraško et al. 2024). Subsequently, within the Variscan orogeny, these rocks were metamorphosed in greenschist to amphibolite facies (Ivan & Méres 2006) and intruded by granitoids of the Early Carboniferous age, which caused thermal metamorphosis (Cambel & Vilinovič 1987; Gaweda & Kohút 2007; Polák et al. 2012).

The metamorphosed volcano-sedimentary rocks of the Pernek and Pezinok groups underwent intense Variscan deformation (cf. Figs. 5a, 6a, 7a, b), because we have not been able to unambiguously identify the original primary planar structure (S_0^V bedding) at any of the localities in the study area.

Intensely-isoclinal folded planar structures (S_1^V) are considered to be the oldest structures, which had been completely transposed by the Variscan deformation (D_2^V) into the metamorphic foliation (S_2^V; Figs. 5a, 6a, b, 7a, b). The isoclinal folds are, in some places, replaced by rootless folds, where only the hinge parts of the folds could be observed, which had completely interrupted limbs in the inflexion zones.

The most striking manifestation of the Variscan deformation in the metamorphosed rocks of the Tatric Unit is the intense and pervasive S_2^V metamorphic foliation, which had certainly

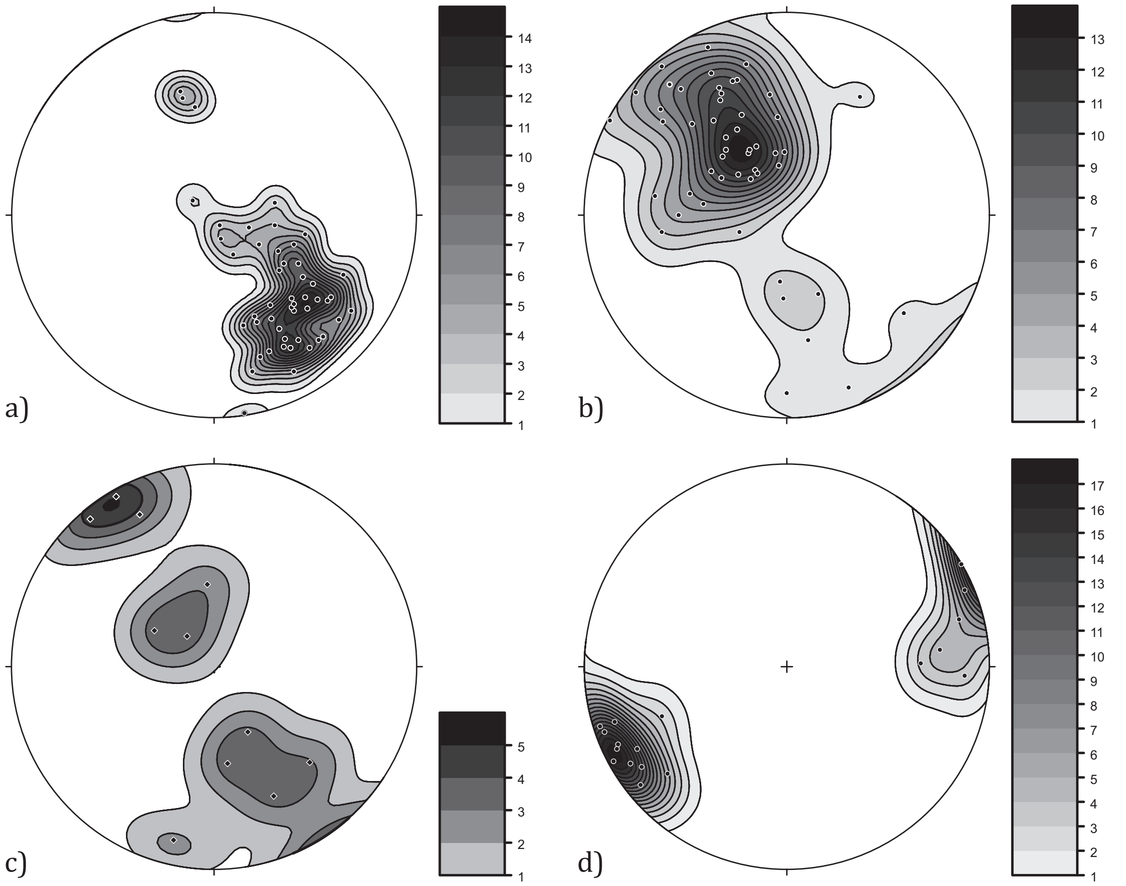


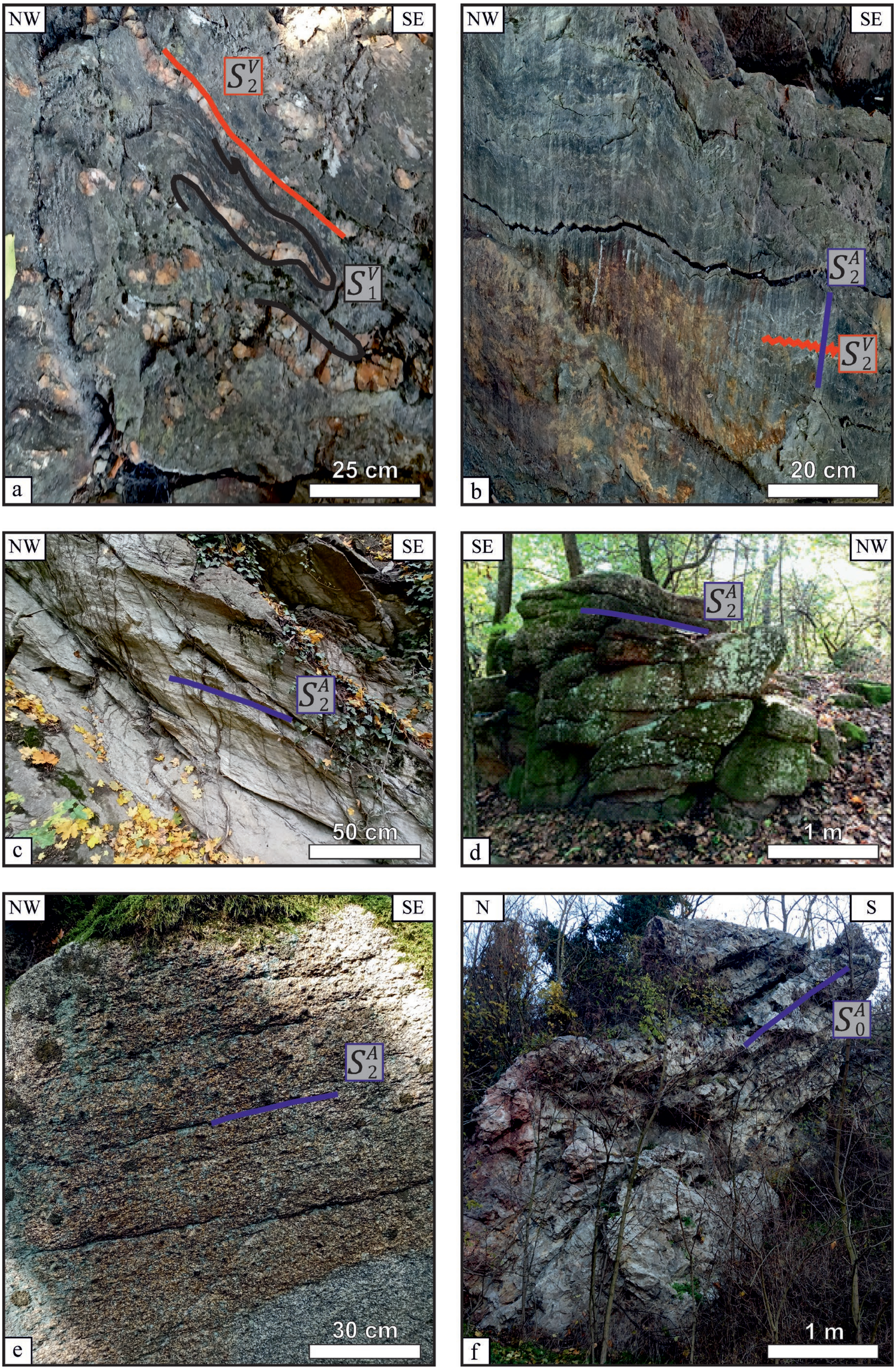
Fig. 5. Stereograms of planar and linear structures (contour plots), measured in the Tatric crystalline basement (lower hemisphere, Lambert projection): **a** — Variscan S_2^V pervasive foliation (Pernek and Pezinok groups) indicated by poles of planes; **b** — Alpine S_2^A mylonitic foliations (Pernek and Pezinok groups) indicated by poles of planes; **c** — Alpine L_{2t}^A stretching lineations in S_2^A mylonitic foliation (Pernek and Pezinok groups); **d** — Alpine L_{2c}^A crenulation lineations and F_2^A fold axes (Pernek and Pezinok groups).

formed during the main phase of Variscan folding (D_2^V). Based on the geochronological dating of the granitoid intrusions of the Bratislava massif, whose age has been determined at 355±18 Ma on monazite (Finger et al. 2003), 355±5 Ma on SHRIMP U–Th–Pb zircon (Kohút et al. 2009), and 353 ±2.3 Ma (Uher et al. 2011), we can conclude that the deformation occurred before this period because the granitoid rocks do not contain D_2^V Variscan deformation (cf. Figs. 6c–e, 8, 9). These structures were preserved only in the Variscian metamorphosed rocks of the Pernek and Pezinok groups (Figs. 6a, b, 7). The Early to Middle Devonian age has been documented from marbles and hornfels by sporadic finds of goniatites and tentaculites (Chlupáč in Buday et al. 1962). Altogether, the inferred age of the rocks is in the stratigraphic range from Silurian to Middle Devonian (cf. Polák et al. 2011, 2012). On the basis of these arguments, we can consider this main phase of the Variscan deformation (D_2^V) to be Middle to Late Devonian in age. The contact metamorphism is deduced from mineral association, although it has been reported in the Pezinské Karpaty area by several studies (e.g., Korikovskij et al. 1984; Cambel & Vilinovič 1987; Cambel et al. 1989; Vojtko et al. 2011; Polák et al. 2012).

The pervasive foliation developed during a compressional tectonic regime with a shortening orientation in the NW–SE direction. We assume that the stacking of the Variscan nappes was controlled by top-to-the-SE tectonic transport, as reported from other areas of the Tatric crystalline basement (e.g., Putiš 1992; Bezák 1994; Bezák et al. 1997).

Alpine deformation

During the Alpine evolution of the Tatric Unit, it was possible to identify three low-temperature deformation stages that did not reach a pervasive character in the study area. Sedimentary rocks of the Devín cover and the Borinka Unit contain preserved primary beddings (S_0^A) folded during northwest–southeast shortening. Primary planar structures are affected by flattening during the D_1^A deformation phase, which is characterised by stylolitic cleavage (S_1^A) subparallel to bedding (S_0^A). The flattening is documented by the folding of originally vertical calcite veins. All earlier structures are partly overprinted by the Alpine (Cretaceous) foliations (S_2^A), which belong to the D_2^A deformation phase (Fig. 5b) with kinematic criteria indicating top-to-the-NW direction of movement.



NW
SE
S_2^V
S_1^V
25 cm
a
NW
SE
S_2^A
S_2^V
20 cm
b
NW
SE
S_2^A
50 cm
c
SE
NW
S_2^A
1 m
d
NW
SE
S_2^A
30 cm
e
N
S
S_0^A
1 m
f

Fig. 6. Field photographs: **a** — The oldest known foliation S_1^V represented by tight to isoclinal folds almost completely transposed to S_2^V (phyllites of the Pernek Group); **b** — Alpine S_2^A crenulation cleavage affecting Variscan S_2^V sub-horizontal pervasive metamorphic foliation (phyllites of the Pernek Group); **c** — Mylonite derived from the granitic rock with mylonitic foliation of S_2^A fabric, shear asymmetry indicates top-to-the-NW displacement; **d** — Anastomosing spaced cleavage (S_2^A) in the granite of Bratislava Massif; **e** — Early stage of S_2^A mylonitic foliation in granite (Bratislava Massif); **f** — Bedding in quartzites on the base of Tatric cover succession.

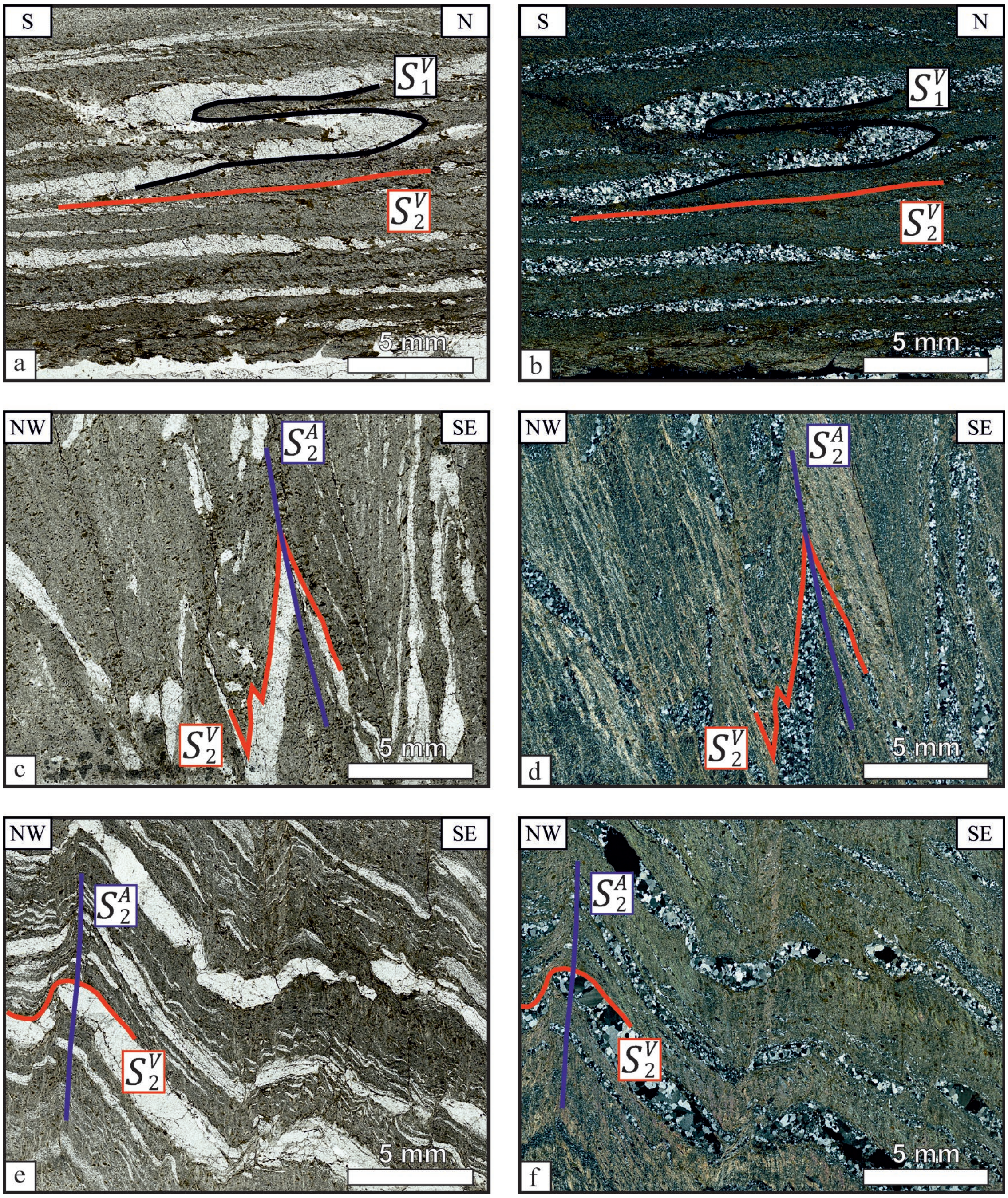


Fig. 7. Photomicrographs of metamorphic rocks of the Pernek Group of the Tatric crystalline basement with lepidoblastic chlorite and mica layers, as well as granoblastic quartz layers' fabric. This fabric is due to the parallel orientation during the recrystallisation of sericite and chlorite with a flaky habit. White layers in PPL images are composed predominantly of recrystallised granoblastic quartz: PPL (**a**) and XPL (**b**) – isoclinal microfold with preserved foliation (S_1^V) and the parallelism with the pervasive foliation (S_2^V); PPL (**c**) and XPL (**d**) – symmetric Alpine kink band folds (F_2^A) in strongly anisotropic thin-layered rock with well-developed foliation (S_2^V) ; PPL (**e**) and XPL (**f**) – asymmetric Alpine folding (F_2^A) with the evolution of the Alpine crenulation cleavage (S_2^A) affecting the Variscan pervasive foliation (S_2^V). Note: PPL – plane polarised light, XPL – cross polarised light.

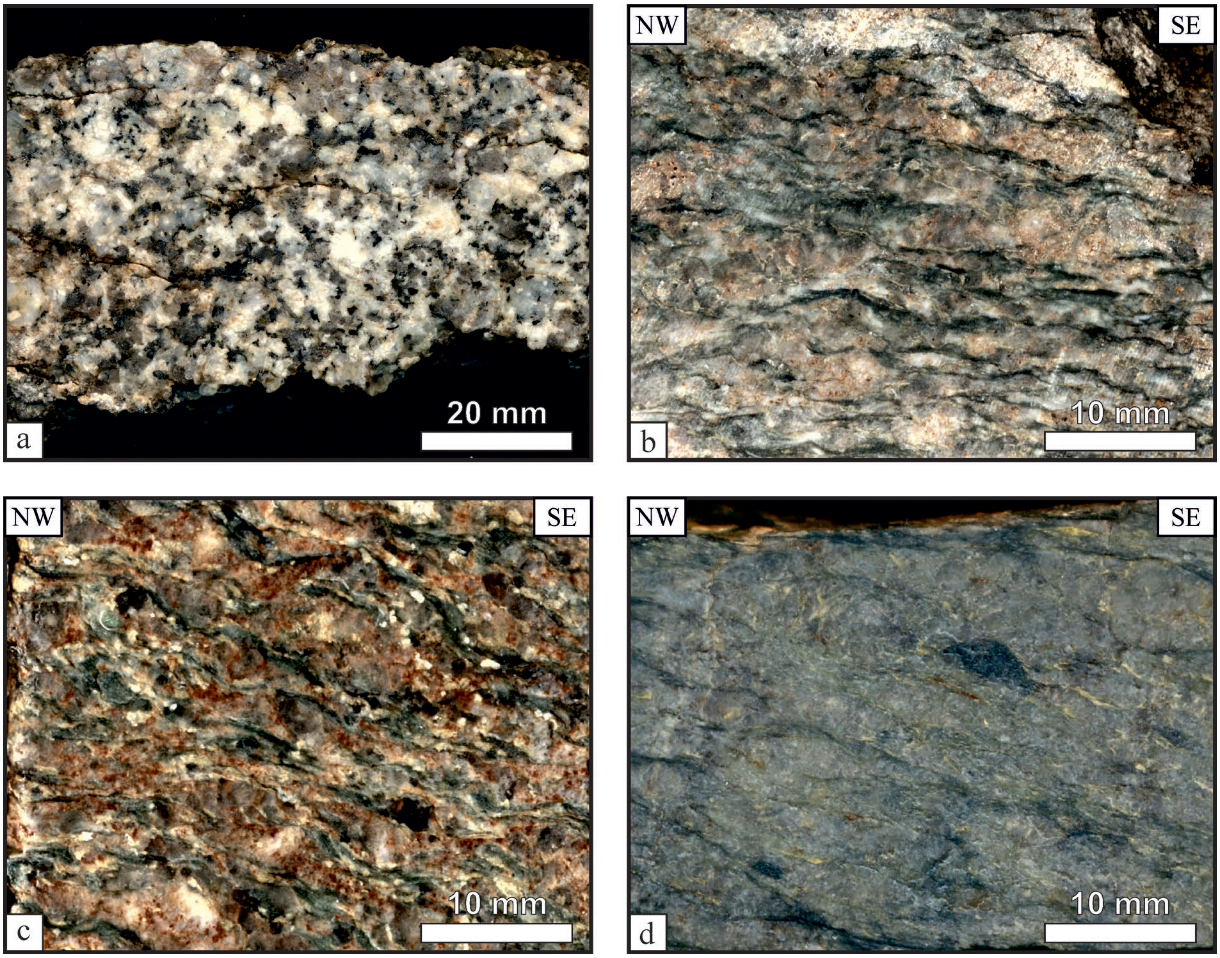


Fig. 8. Macrophotographs of the Alpine deformation in granite rocks of the Bratislava Massif: **a** — Undeformed granite rock with well-preserved, rock-forming minerals; **b** — Slightly-deformed granite rock, biotite began to be replaced by chlorite with evolution of *S*–*C* fabric; **c** — Deformed rock with *S*–*C* fabric; **d** — Strongly-deformed granites with mylonitic foliation.

The Alpine cleavage (S_2^A) is recorded in granitoid and metamorphosed rocks of the Tatric crystalline basement (cf. Figs. 6c–e, 8b–d, 9c–f) and sediments of the Devín cover and the Borinka Unit. The emplacement of the overlying Fatric and Hronic units on the Tatric Unit occurred around 90 Ma (cf. Plašienka et al. 1997; Plašienka 1999, 2018; Putiš et al. 2009a). This spaced to mylonitic in some places even penetrative cleavage as a cleavage of the fold axial plane (Figs. 6b, 7c–f). The Alpine cleavage (S_2^A) originated during the thrusting of the Bratislava nappe onto the Borinka Unit. The age of the thrusting of about 75 Ma is documented by radiometric data obtained by the K–Ar method from the Alpine sericite blastomylonite granitoids of the Prepadlé shear zone (Kantor et al. 1987; Putiš et al. 2009a).

Significant mylonitisation of granitoids is related to the thrusting of the Bratislava nappe. Low-temperature mylonite granite to mylonite with a well-developed *S*–*C* fabric has been documented at this locality (Figs. 6c–e, 8b–d, 9c–f). Mylonites have pervasive transport lineations, thereby indicating westward movement of the hanging wall.

The youngest Alpine structures are represented by spaced cleavage surfaces (S_3^A). The strike of cleavage has a NW–SE direction and subvertical dip, and this was observed in all rocks of the Tatric Unit. It shows the NE–SW shortening and is best observed in limestones of the Devín cover succession and granitoid rocks of the Tatric Unit. The age of deformation is younger than the Late Cretaceous. However, precise dating of this deformation is still unknown.

Conclusion

The study area is located on the southwestern edge of the Malé Karpaty Mts. and is mainly composed of the Tatric Unit and Borinka Unit. The Tatric Unit is mainly built up by the Variscan crystalline basement and its Permian-Mesozoic cover succession. The extent of the largest area is represented by various granitoid rocks located in the central and eastern parts of the territory, which later intruded into the metamorphosed volcano-sedimentary rocks of the Pernek and Pezinok groups.

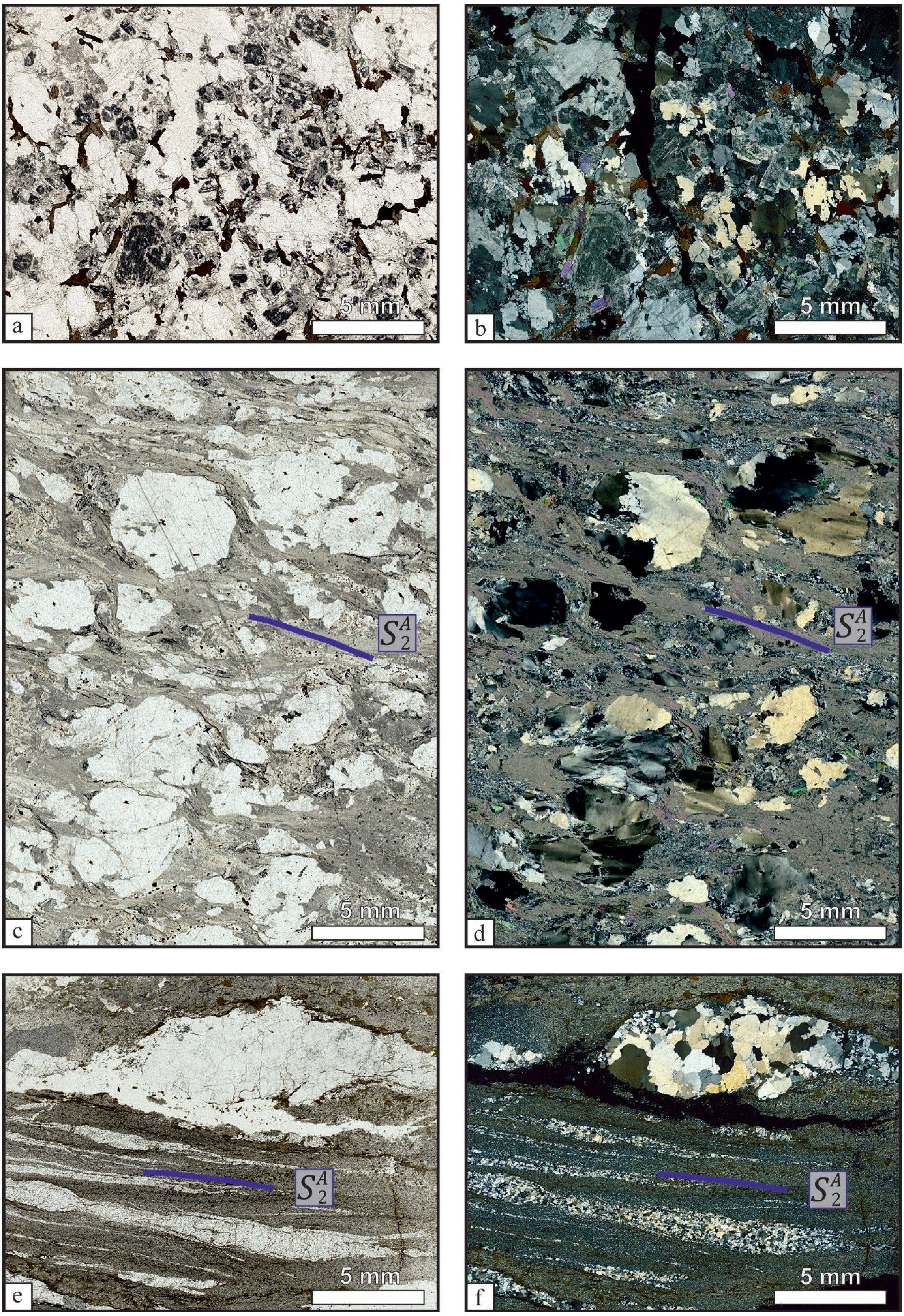


Fig. 9. Photomicrographs of the Bratislava granitoid rocks of the Tatric Unit at the Mokrý jarok, Fialková dolina, and Gronáre localities: **a** — Undeformed granite (PPL); **b** — Undeformed granite (XPL); **c** — Low deformed granite (PPL); **d** — Low deformed granite (XPL); **e** — Strongly deformed, mylonitic rock (PPL); **f** — Strongly-deformed, mylonitic rock (XPL). Note: PPL – plane polarised light, XPL – crossed polarised light.

Towards the structural hanging wall, Permian coarse-clastic sediments and Triassic carbonates of the Devín cover lie on top of the metamorphosed rocks. Jurassic and Cretaceous sediments of the succession are also preserved on the western edge of the study area. In the northernmost part of the area, Jurassic carbonates belonging to the Borinka Unit are cropped out from beneath the Tatric crystalline basement.

The oldest deformation phase is the Variscan deformation (D_1^V), which is preserved only in the form of isoclinal or rootless folds and is represented by the S_1^V planar structures. The parallelism of S_1^V foliation concerning the pervasive metamorphic foliation, which we refer to as (S_2^V), was caused by the transposition of the former planar structure. The pervasive foliation (S_2^V) represents flattening in the main phase of Variscan folding, and these structures are preserved only in metamorphosed crystalline rocks (Pernek and Pezinok groups) and do not occur in the granitoid rocks and cover sequences.

The original bedding (S_0^A) is preserved in the sedimentary rocks of the Devín and Borinka units. However, the latter is often highlighted by a flattening and low metamorphosis within the D_1^A deformation. The main Alpine deformation phase (D_2^A) is characterised by significant mylonitisation of granitoids, which is a well-developed *S–C* fabric in metasediments indicating top-to-the-NW hanging wall tectonic transport. All previously observed structures are intersected by tectonic foliation (S_3^A) belonging to the D_3^A deformation phase.

Acknowledgements: This work was supported by the Slovak Research and Development Agency under contracts Nos. APVV-21-0281 "Alpine geodynamical evolution of the Western Carpathian inner zones", APVV-20-0120 "Calibration of the authigenic ^{10}Be/^{9}Be dating method for geochronological models of the latest Cenozoic of the Carpathian–Pannonian region" and by Comenius University Grant UK/3229/2024: Structural and low-thermal evolution of the Malé Karpaty crystalline basement (Central Western Carpathians, Tatricum).

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