Cretaceous collision and thrusting of the Veporic Unit onto Tatric Unit in the Nízke Tatry Mts. revealed from structural analysis

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Abstract: The Nízke Tatry Mts. is a significant mountain range in the middle part of the Central Western Carpathians which is divided into two important sub-units, the eastern part is composed of the Veporic crystalline basement (Kráľovohoľské Tatry), which is thrust onto the Tatric crystalline basement (Ďumbierske Tatry) located in the western part during the Eo-Alpine (Cretaceous) tectogenesis. Both basements are characterised by well-developed Variscan pervasive planar fabric, which originate from the syn-metamorphic crystallisation of rock-forming minerals and their parallel alignment. This Variscan foliation is an important marker for understanding the Alpine deformation, which was accompanied by low-grade metamorphism, mylonitisation, and cataclasis, especially in the microscale, originating during the simple shear deformation mechanism with the evolution of spaced, crenulation and mylonitic foliations. On a map scale, the Alpine structure is indicated by individual thrust shear zones, that are composed of mylonites with ENE – WSW strike and predominantly intermediate SE dip. The internal structures of these shear zones have pronounced asymmetry characterised by asymmetrically deformed objects, such as quartz lenses and asymmetry of macro-folds, porphyroblasts, shear bands stretching, and mineral lineations referring to the top-to-the-NNW transport (average azimuth of 343 degrees) of the Veporic Unit onto the Tatric Unit along the Čertovica thrust during the Eo-Alpine tectogenesis.

Key words: Western Carpathians, Variscan structure, Alpine structure, fabric, folds, thrust, kinematics

1. INTRODUCTION

The Western Carpathians are a part of the European Alpine orogenic belt, which continues to the Eastern Alps in the west and the Eastern Carpathians in the east. The mountains are divided into the External, Central, and Internal Western Carpathians (e.g., Andrusov et al., 1973; Froitzheim et al., 2008; Plašienka, 2018). Some authors also used a simplified division model into the External and Internal Western Carpathians (e.g., Mišík et al., 1985; Hók et al., 2014, 2019).

The External Western Carpathians, extending to the north, are formed by the Cenozoic accretionary prism (flysch belt), and the narrow zone of the Pieniny Klippen Belt. The Internal Western Carpathians, spreading to the south, are composed of atypical tectonic blocks, which have a Dinaride affinity. The Central Western Carpathians consist of a nappe stack of thick-skinned crustal-scale basement imbricates (Tatric, Veporic, and Gemeric) which had been incorporated into the Eo-Alpine collisional wedge associated with the décollement of Mesozoic sedimentary sequences forming superficial nappe system (e.g., Andrusov et al., 1973; Plašienka, 2018; Vojtko et al., 2023). The post-Variscan Uppermost Carboniferous to Upper Cretaceous formations originally formed basins separating individual crustal segments, which were inverted and passively transported northward in the form of three large-scale nappes (Fig. 1).

The study area is located in the western part of the Kráľovohoľské Tatry Mts. and covers the Veporic and Tatric tectonic units. The tectonic boundary of both tectonic units coincides with the Čertovica shear zone, which can be observed directly on the surface in the study area. During the Eo-Alpine time, the Veporic Unit collided with the Tatric Unit and was thrust on it. The wide area along the Čertovica shear zone has an imbricated structure with several partial thrusts especially in the Veporic Unit in the hanging wall position (Fig. 2).

The main objective of this study was a detailed analysis of the deformation structures and their precise spatial orientation and pattern. Often contradictory interpretations appear in previous frames, and the evolution of deformation structures is associated with either Variscan (e.g., Siegl, 1973, 1978; Putiš, 1987, 1992; Kriváňová et al., 2023) or Alpine deformations (e.g., Putiš, 1989; Kohút et al., 2000; Plašienka, 2003; Putiš et al., 2009; Bezák & Olšavský, 2008). All this data is an important source for the reconstruction of the tectonic evolution of the study area. However, observations and interpretations of the geometry of structures in rocks should be used with care. Using a detailed analysis of kinematic indicators, we attempted to reconstruct the motion vectors of the tectonic duplexes of the Veporic Unit and its emplacement on the Tatric Unit. The wide shear zone between Tatric and Veporic basement-cover thrust sheets is characterised by the complicated structure of Upper Cretaceous imbrications.

2. GEOLOGICAL SETTING

The study area is located immediately at the contact zone between two major basement-involved thrust sheets (Fig. 2). The Tatric Unit together with the Veporic Unit to the east represents segments of the Variscan crust that had been incorporated into the structure of the Central Western Carpathian wedge during the Cretaceous, Eo-Alpine, convergence (e.g., Putiš et al., 2009; Plašienka, 2018).

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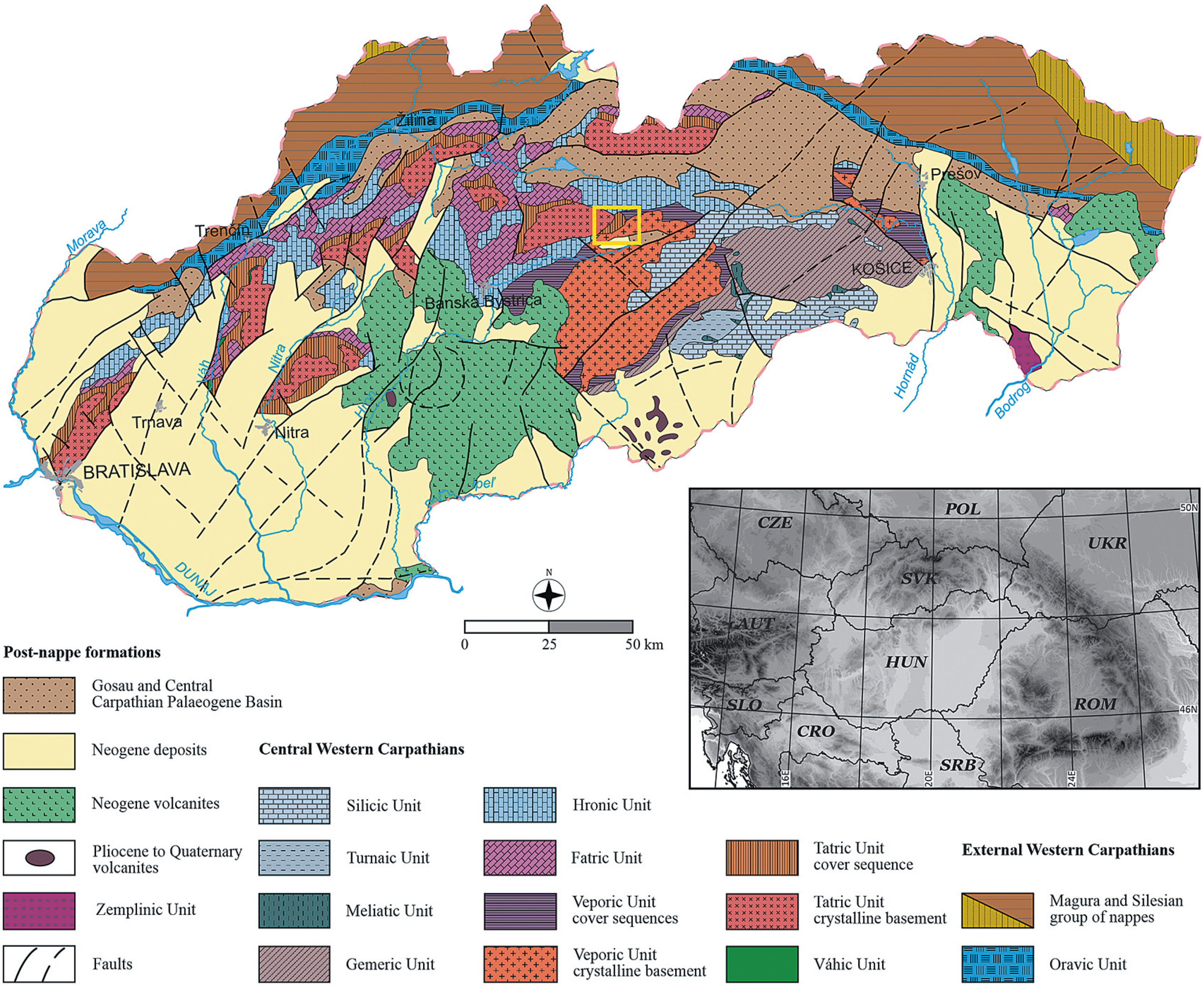


Fig. 1: Tectonic map of the Slovak part of the Western Carpathians (according to Biely et al. 1996). A yellow rectangle in the middle of the map marks the study area.

The Tatric Unit occupies the footwall position and is composed of the Lower Carboniferous I-type granodi S_2^V orite to tonalite with a Mesozoic cover sequence marked by low- to very low-grade Alpine metamorphism. The estimated metamorphic condition did not reach 300°C during the Eo-Alpine metamorphosis which is indicated by the Variscan $^{40}Ar/^{39}Ar$ ages (Maluski et al., 1993) and Alpine zircon fission track ages (Danišík et al., 2011). However, there is some indication of the Upper Jurassic's earliest Lower Cretaceous thermal signal (Danišík et al., 2011). The granitoids (Ďumbier and Prašivá types) are of the Variscan age, as established using several geochronological methods: zircon SIMS U–Th–Pb dating 356 ± 2 Ma (Broska et al., 2013); zircon SHRIMP U–Th–Pb 340 ± 3 Ma (Kohút & Larionov, 2021), respectively 353.4 ± 2.2 Ma and 352 ± 3.0 Ma (Maraszewska et al., 2022).

On the contrary, the southern part of the Tatric basement comprises a massive complex of intensely high-grade metamorphosed Lower Paleozoic rocks and syn-kinematic Upper Paleozoic granitoid, assigned to the Jarabá Complex (Kamenický in Mahel' et al., 1968). The rocks can be designated as garnet–sillimanite-muscovite–biotite gneiss that belongs to the sillimanite zone (amphibolite facies) with an estimated temperature of 550 – 690 °C, and a pressure of 4 – 4.7 kbar (e.g., Krist et al. 1992; Petrík et al. 2006).

The crystalline basement of the Veporic Unit is also composed of Paleozoic volcano-sedimentary rocks mainly characterised by medium-grade Variscan metamorphic overprint (Vrána, 1964; Méres & Hovorka, 1991; Kováčik et al., 1996; Putiš et al., 1997; Jeřábek et al., 2008). These metamorphosed rocks belong to the so-called Hron Complex (Klinec, 1965, 1966, 1976) or upper (gneiss-migmatitic) and middle (gneiss-mica schist) Variscan units (Bezák et al., 1997, 2004) and are located beneath the Mississippian (~370 – 350 Ma) granitoid rocks (Kráľova hoľa Complex; e.g., Siman et al., 1996; Michalko et al., 1998; Broska et al., 2013). The contact between them has been previously associated with Variscan thrusting (Klinec, 1966, 1976; Bezák, 1994; Bezák et al., 1997).

In the study area, the Hron Complex is composed of white mica – biotite ± garnet paragneiss and mica schist with common amphibolite bodies conformable with surrounded paragneisses, i.e. Variscan metamorphic foliation (S_2^V) (cf. Kriváňová et al., 2023). The Hron Complex has undergone a

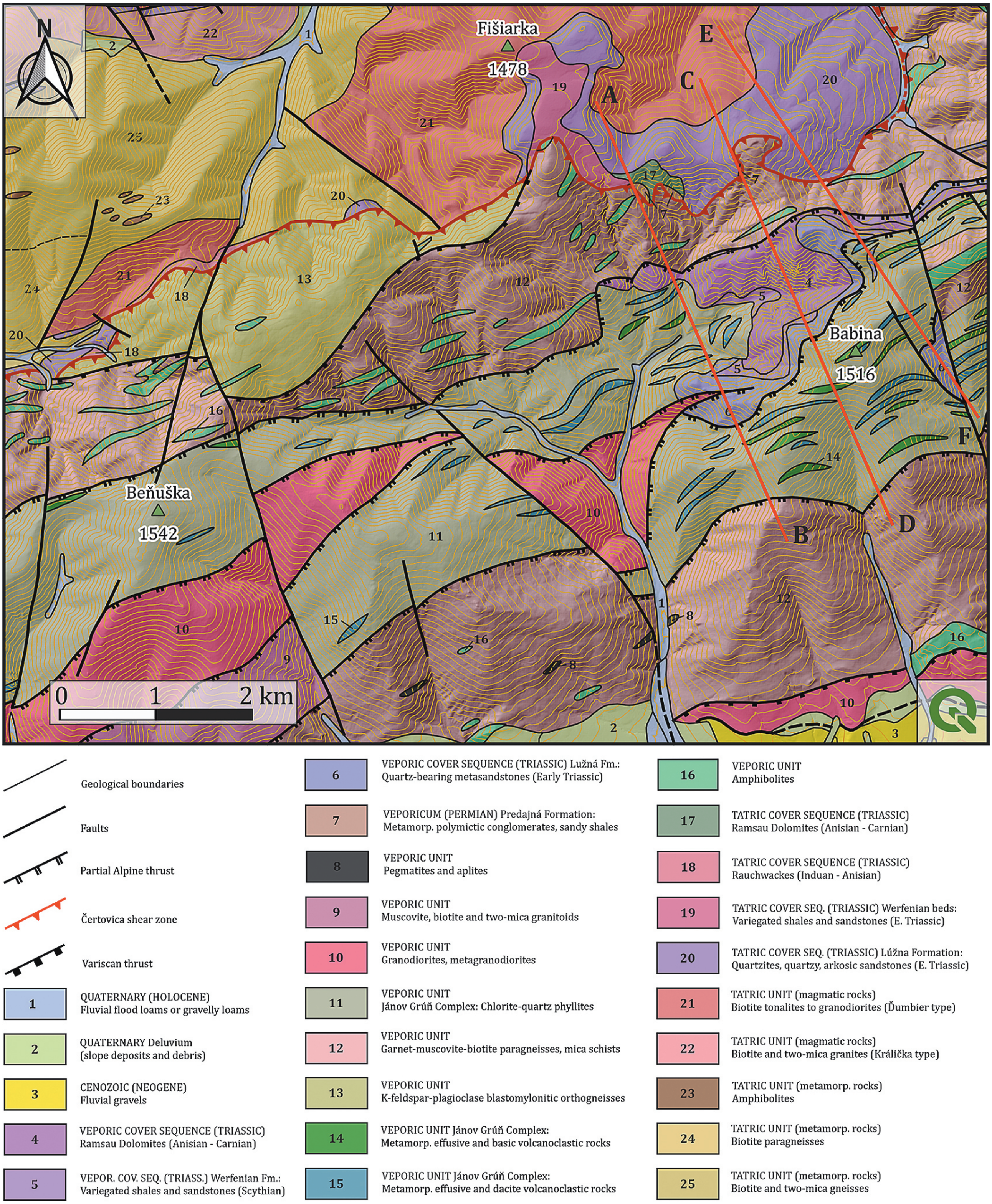


Fig. 2. Geological map of the study area north of the village of Bacúch (according to Biely et al., 1992) with geological cross-sections through the Tatric and Veporic crystalline complexes and cover sequences.

medium- to medium-/low-grade progressive metamorphosis with a maximum in the staurolite-andalusite zone (580 – 590 °C, 0.5 – 0.6 GPa). However, the garnet-biotite zone in particular is common. The retrograde metamorphosis is characterised by the replacement of staurolite by chloritoid (Putiš, 1981, 1987) and it is of the Variscan age as indicated by the K/Ar ages 290 ± 6 Ma on muscovite (cf. Cambel et al., 1986). The protolith age of the entire complex is unknown, but it is assumed to be Early Paleozoic.

The upper partial nappe of the Hron Complex is occupied by metamorphosed felsic rocks, mylonitic granites, and phyllite upper Silurian to Devonian age and traditionally are denominated as the Jánov Grúň Complex (Klinec et al., 1975; Planderová & Miko, 1977; Miko, 1981). The rocks underwent only low-grade regional metamorphism under greenschist facies. Along with the Jánov Grúň Complex, strongly deformed mylonite granites of the Sparistá type (Miko, 1981; Miko et al., 1982) also outcrop. The estimated age of the Sparistá granite is approximately 370 Ma (Late Devonian; Cambel et al., 1977) but Permian age is also reported (Bezák et al., 2008). The metamorphic conditions are characterised by 350 – 600°C and 0.4 – 1.0 GPa, which fall to the garnet–biotite zone at the boundary between greenschist and epidote-amphibole facies (Kohút et al., 2000). Two metamorphic phases can be recognised in the Sparistá mylonite granite. The first phase (550 – 600°C, 0.8 – 1.2 GPa) is older than 110 Ma and the second (350 – 400°C, 0.6 GPa) is older than 78 Ma as it is depicted by $^{40}Ar/^{39}Ar$ dating 88 – 78 Ma (Maluski et al., 1993; Dallmeyer et al., 1996; Kováčik et al., 1996; Kohút et al., 2000).

Paleozoic to Mesozoic sediments in autochthonous position on the Vepor crystalline basement are classified into two main cover sequences. This is due to their different evolution, metamorphic grade, and deformation. The southern Veporic Unit is characterised by the Federata cover sequence (Schönnenberg, 1948) and the northern Veporic by the Veľký Bok sequence (Kettner, 1931). Both units, divided by the Pohorelá Fault (e.g., Hók & Hraško, 1990; Madarás et al., 1994; Hók & Vojtko, 2011), have uniform crystalline rock complexes but differ in lithostratigraphic evolution of these cover sequences (e.g., Vojtko et al., 2015; Michalíková & Vojtko, 2019).

3. METHODS

The orientations of primary (bedding) and secondary (tectonic) planar and linear structures were collected in the field and their relative age was denoted by indexes. All planes (surfaces) are marked as *"S"* with indexes in subscript representing the order of planar structure from the older to the younger. The index S_0 is reserved for bedding planes as a primary planar structure, and the indexes S_1 to S_n represent secondary (tectonic) planar structures. The pole presentation (normal to plane) of foliation was denoted by the *"P"* symbol. The same classification was also used in the case of linear *"L"* and fold (axes) *"F"* structures. The linear structures were also divided into parallel with tectonic transport (L_t), e.g., mineral lineation, and perpendicular to the shortening (L_c), e.g., an intersection or crenulation lineations parallel with fold axes (*F*).

The tectonic structures were divided into two groups according to which geological units were affected and of what age. The upper index on the right side represents the evolution of the deformation structure, which is linked to the orogeny. The older deformation cycle denoted as (with a superscript *"V"*), records Variscan deformation and affects the crystalline basement. The latter deformation cycle, which affects both the basements and covers, is related to the Alpine deformation denoted as D^A (with a superscript *"A"*).

For the computation of a plane intersection or a plane containing lines, even a plane bisecting two planes, correction of line-plane pairs, and so on, GeolCalc software (developed by R. Vojtko) was used. The visualization was performed by Stereonet software (developed by R. Allmendinger; cf. Allmendinger et al., 2012; Cardozo & Allmendinger, 2013).

4. STRUCTURAL RECORD

4.1. Alpine vs Variscan fabric

The observed deformation structures are only evident in the outcrops and have been used as a basis for further considerations. Structural observations were carried out on 116 sites (Figs. 3, 4). The deformational structures have been documented in the Veporic crystalline basement, Veľký Bok cover sequence, and a little also in the Tatric Unit (cf. Tab. 1).

Within the hanging-wall Veporic Unit, we identified one significantly penetrative metamorphic foliation (S_2^V) of the crystalline basement overprinted by three less intense phases of the Alpine deformation (Fig. 5a). The greenschist to amphibolite facies metamorphic foliation (S_2^V) recognised exclusively in the Paleozoic rocks of the Tatric and Veporic crystalline basements is the result of a Variscan tectonometamorphic stage (e.g., Siegl, 1973, 1981; Putiš, 1992; Kriváňová et al., 2023).

The Variscan deformation (D_2^V) is the most important pervasive deformation of the metamorphosed rocks of the Tatric and Veporic basements in the study area. This foliation (S_2^V) is significant in the country rocks and was used as a deformational marker for the Alpine deformation. The general strike of the Variscan foliation (S_2^V) is in the NE – SW direction with a dip on both sides (Fig. 5a). A Von Mises distribution of poles to Variscan foliations is 342.5 ± 6.6° which is a trend of the Variscan

Tab. 1: Synoptic table of deformational structures – foliations, lineations, and fold axis (according to Kriváňová et al., 2023).

Deformation	Planar fabric	Lineation t	Lineation c/Folds	Tectonic regime	Age
D_1^V	S_1^V (E–W)	unknown	various orientation	compression	Early Variscan or older
D_2^V	S_2^V (E–W to WSW–ENE)	L_{2t}^V (WSW–ENE)	L_{2c}^V (SW–NE) F_2^V (E–W to SW–NE)	compression	Variscan
D_3^V	S_3^V (E–W to WSW–ENE)		F_3^V (E–W to WSW–ENE)	compression	Late Variscan
D_4^V	S_4^V (E–W & N–S)			extension	Late Variscan
D_1^V	S_1^A	L_{1t}^A (NNW–SSE)	L_{1c}^A (WSW–ENE) F_1^A (WSW–ENE)	compression	Eo-Alpine
D_2^A	S_2^A	L_{2t}^A (WNW–ESE)	L_{2c}^A (NNE–SSW)	extension	Meso-Alpine

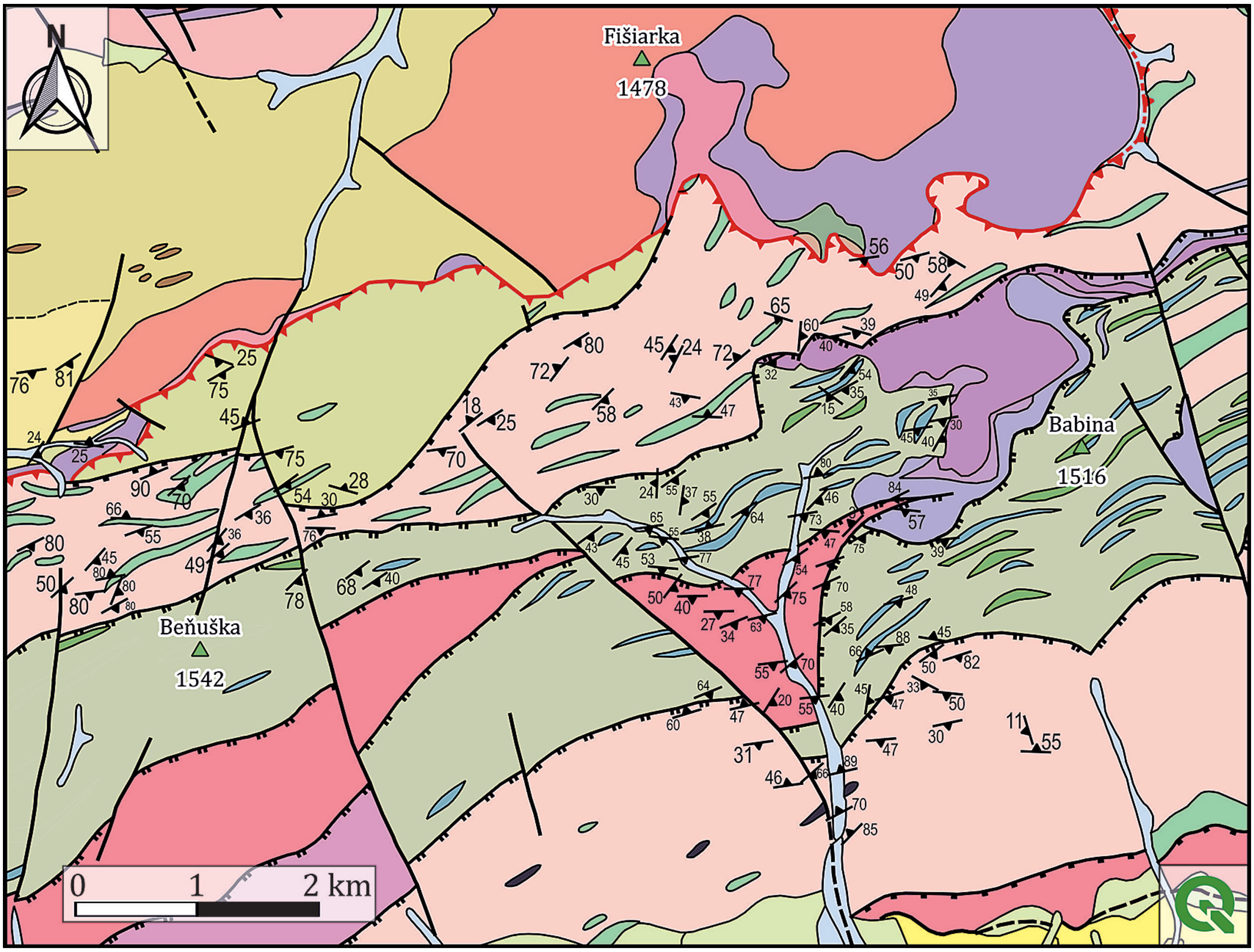


Fig. 3. Geological map of the spatial distribution of Variscan fabric with well-visible parallelisation with Alpine fabric (Fig. 4). Note: for the legend, see Fig. 2, structural marks represent the Variscan pervasive foliation.

shortening. The Variscan foliation also contains mineral and stretching lineations with a general trend in the ENE – WSW direction with a Von Mises distribution of 75.6 ± 33.8° (Fig. 5b).

The Alpine deformation (D^A) is associated with lower greenschist facies phyllonites and mylonites heterogeneously reworking Variscan fabrics (S_2^V) in the basement. The most pronounced Alpine deformation (D_1^A) can be characterised by the evolution of asymmetric folds, crenulation foliations, mylonitic fabric (S_1^A), and stretching, mineral and crenulation lineations (L_1^A). This deformation (D_1^A) was replaced by the Alpine deformation (D_2^A) related to the extensional tectonic regime.

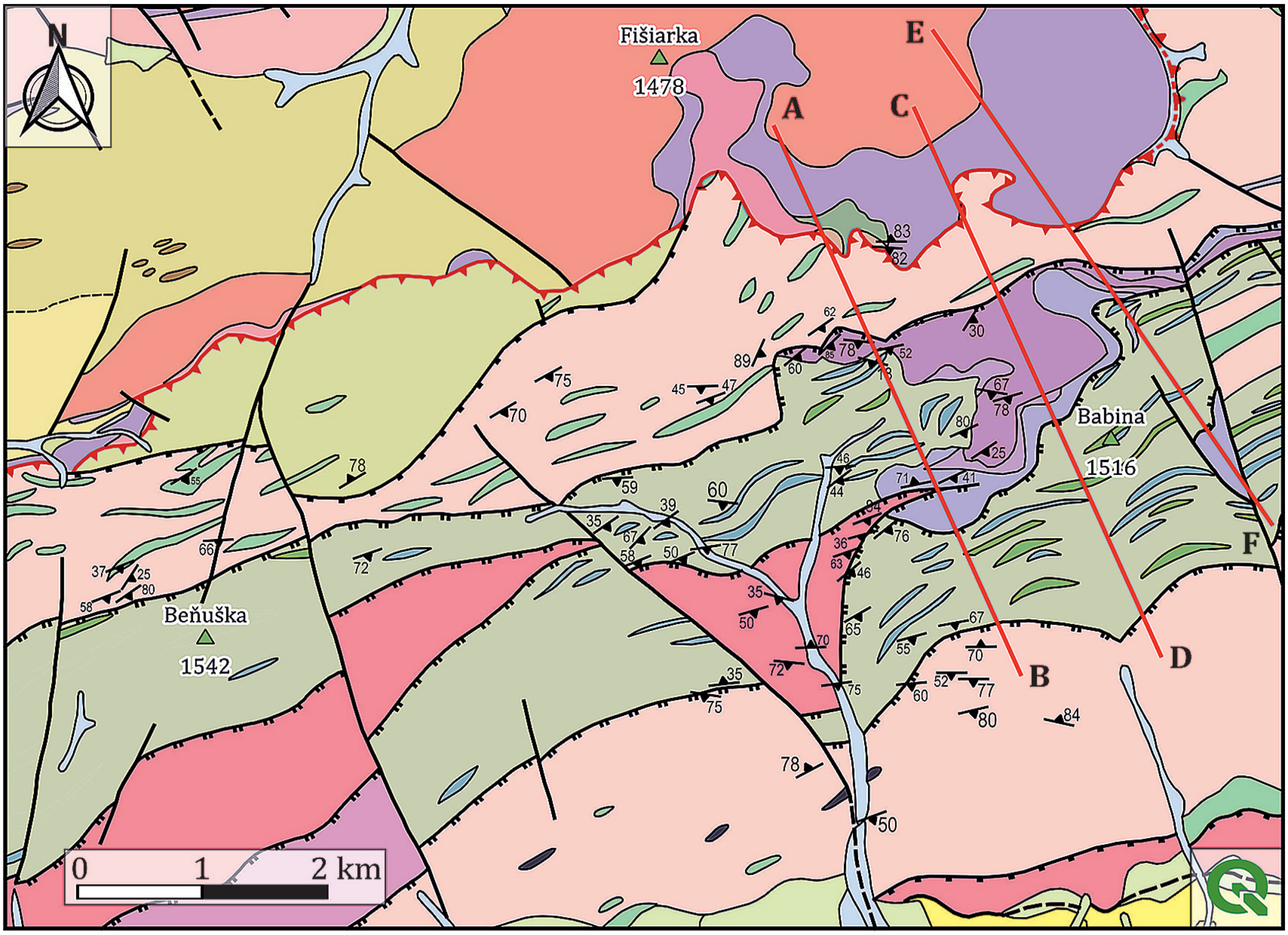
4.2. Alpine thrusting vs extension

The Alpine deformation (D_1^A) is linked to the Eo-Alpine tectonic processes during the compressional tectonic regime and low-grade metamorphism. During this deformation (D_1^A) the spaced to zonal and in some places pervasive foliation (S_1^A) was formed. The fabric of the Alpine foliation (S_1^A) depends on their orientation concerning the Variscan pervasive foliation (S_2^V).

If the Alpine foliation (S_1^A) develops sub-parallel (0 – 30°) to the Variscan foliation, a symmetrical or only slightly asymmetrical crenulation cleavage is formed in the host rocks (Figs. 6a,d, 7a). If the direction of Alpine shortening is diagonal (30 – 70°) to the Variscan pervasive foliation (S_2^V), a nicely asymmetric crenulation cleavage (S_1^A) with kinematics top-to-the-NNW is originated (Fig. 7b,c). Conversely, in the case where Alpine shortening is sub-perpendicular (70 – 90°) to foliation (S_2^V), flattening with mylonitic foliation is formed (S_1^A) and completely transposed former Variscan pervasive foliation (S_2^V) and the rock-forming minerals are reorganised to the Alpine fabric.

The Alpine crenulation cleavage (S_1^A) affected the Variscan metamorphic foliation (S_2^V). The cleavage is well-developed in fine- to middle-grained metamorphosed rocks such as phyllite or paragneiss and on the outcrop scale can be seen as discrete foliation planes. In general, it is less visible in coarse-grained rocks. The spatial distribution of the measured Alpine foliation as its poles (S_1^A) shows the NNW – SSE shortening in the direction of 334.4 ± 7.9° for the Von Mises distribution and Fisher vector distribution with the value of P_1^A 333.2/47.8°, respectively (Fig. 5c).

The orientation of Alpine fold axes and intersection lineations (L_{1c}^A) of the Alpine deformation (D_1^A) is shown in Fig. 5e. The Von Mises distribution of this data is 80.8 ± 28.1° with Fisher vector distribution in L_{1c}^A 81.5/4.5°. The L_{1c}^A fold axes and lineation parallel with the XY plane of the deformation



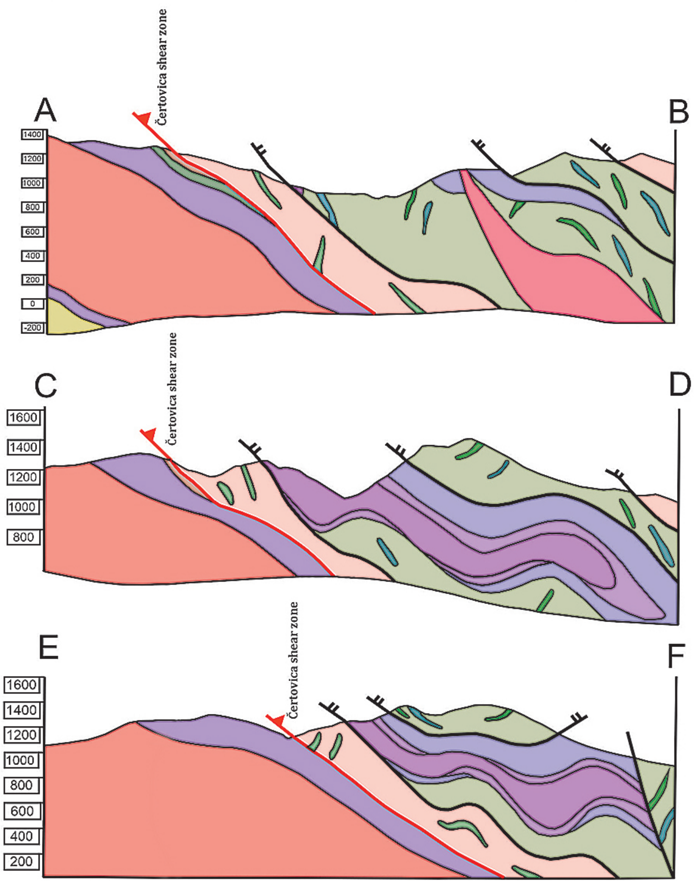


Fig. 4. Geological map of the spatial distribution of Alpine fabric and cross-sections in the study area, showing large-scale Alpine recumbent fold structure. Note: for the legend, see Fig. 2., structural marks represent the Alpine spaced to pervasive foliation.

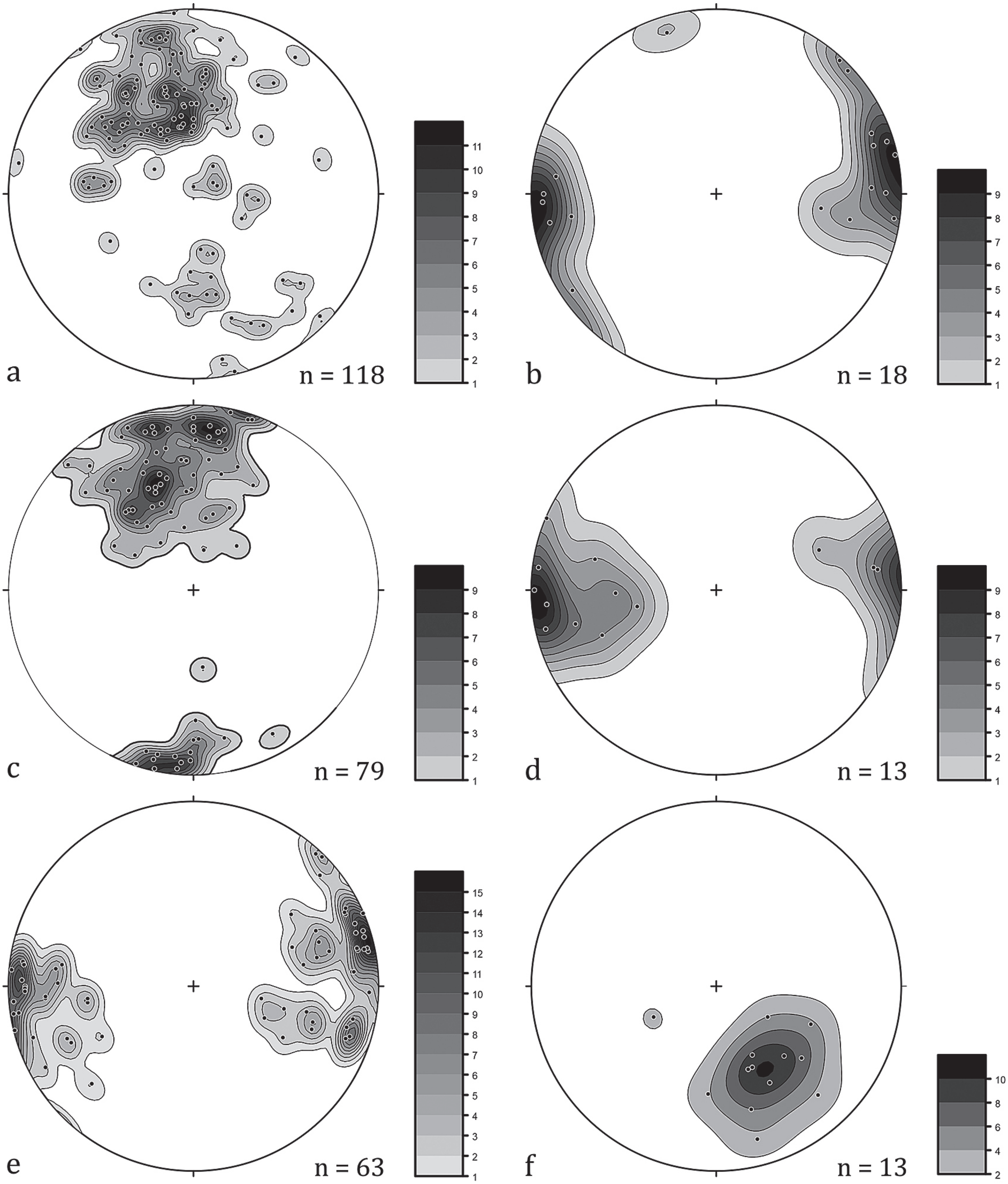


Fig. 5: **Contour plots of measured Variscan and Alpine fabric (Kamb contours in standard deviations, Kamb, 1959): a) pervasive Variscan S_2^V metamorphic foliations (poles of planes); b) Variscan mineral and stretching lineations (L_{2l}^V); c) Alpine S_1^A spaced, crenulation, and mylonitic foliation (poles of planes); d) Alpine S_2^A spaced and mylonitic foliation (poles of planes); e) Alpine fold axes, crenulation, and intersection lineation (L_{1c}^A); f) Alpine mineral and stretching lineations (L_{1l}^A).**

ellipsoid are perpendicular to the orientation of foliation, lineations of tectonic transport and maximal shortening which is in line with Alpine deformation (D_1^A). The spatial orientation and geometric relationships of the planar (S_1^A) and linear (L_{1c}^A, L_{1l}^A) structures define the transport of the Alpine thrusting/folding with the top-to-the-NNW direction.

The top-to-the-NNW thrusting is also documented by the recumbent syncline which is up to 3 km long and the maximum

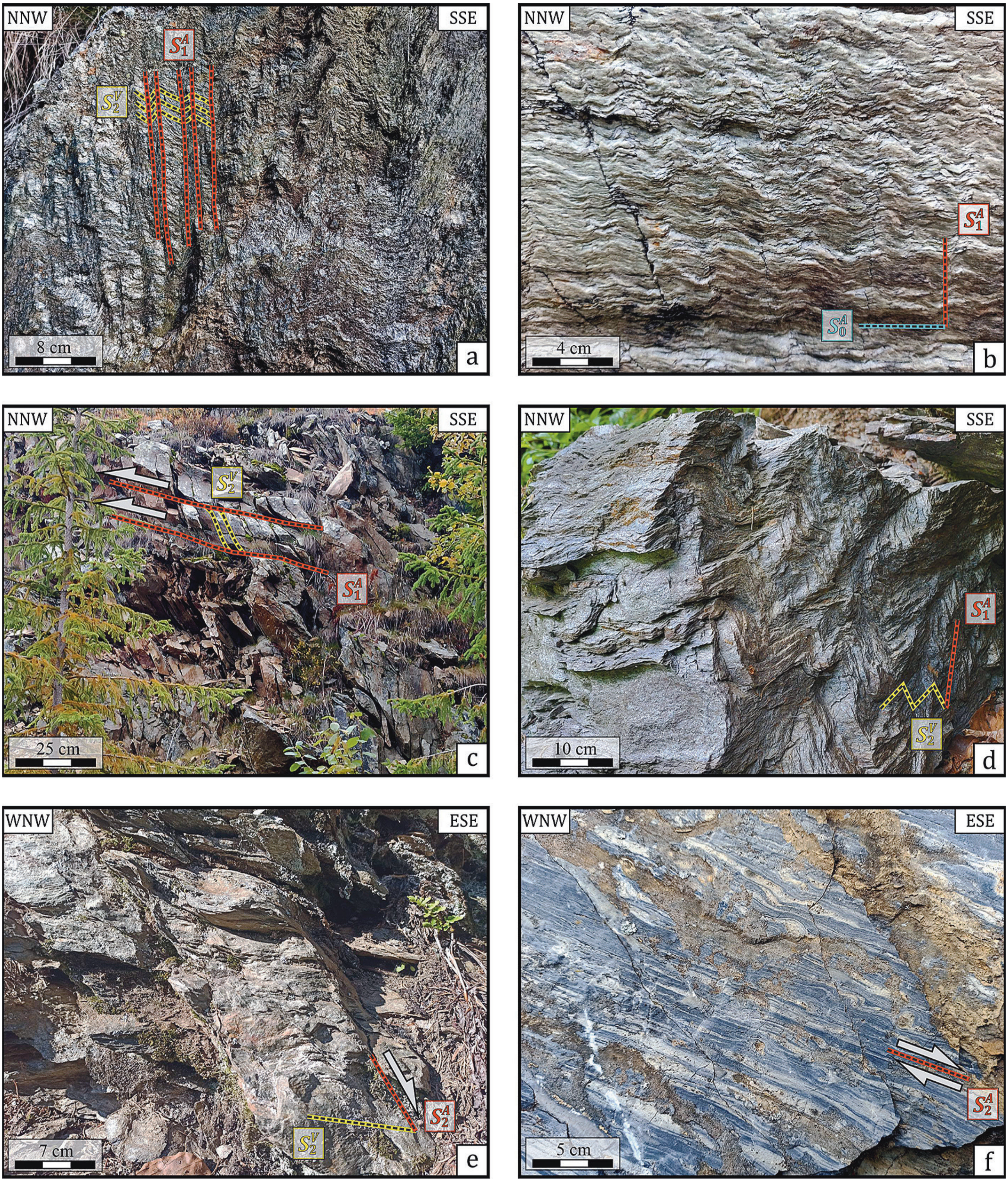


Fig. 6. Field photographs of the Variscan and Alpine fabrics: (a) symmetric Alpine crenulation cleavage *(S_1^A)* with folded Variscan pervasive metamorphic foliation *(S_2^V)* in paragneiss (Veporic Unit; NT177 site); (b) nicely developed symmetric Alpine crenulation cleavage *(S_1^A)* in Lower Triassic quartzites (Early Triassic, Veporic cover sequence; NT238 site); (c) the Varsican foliation *(S_2^V)* forms in the orthogneiss (Veporic Unit; NT190 site) close to the narrow shear zones *(S_1^A)* and it is deflected and parallelised to the mylonitic foliation (subhorizontal). In the shear zone, the orthogneiss has been almost completely transformed into a mylonite (top-to-the-NNW tectonic transport); (d) High amplitude 'V-shaped' kink fold with the Alpine axial plane cleavage *(S_1^A)*. Pervasive foliation is related to the Variscan fabric *(S_2^V)* in paragneiss (Veporic Unit; NT254 site); (e) cross-section of the mylonitic paragneiss (Veporic Unit; NT215 site) perpendicular to *S* planes and parallel with stretching lineation with well-developed *C* planes with macroscopic shear band cleavage and asymmetric bending of the foliation (top-to-the-E transport); (f) ductile deformation in the marbles with kinematic indicators which refers to tectonic transport top-to-the-E (Triassic, Veporic cover sequence; NT285 site).

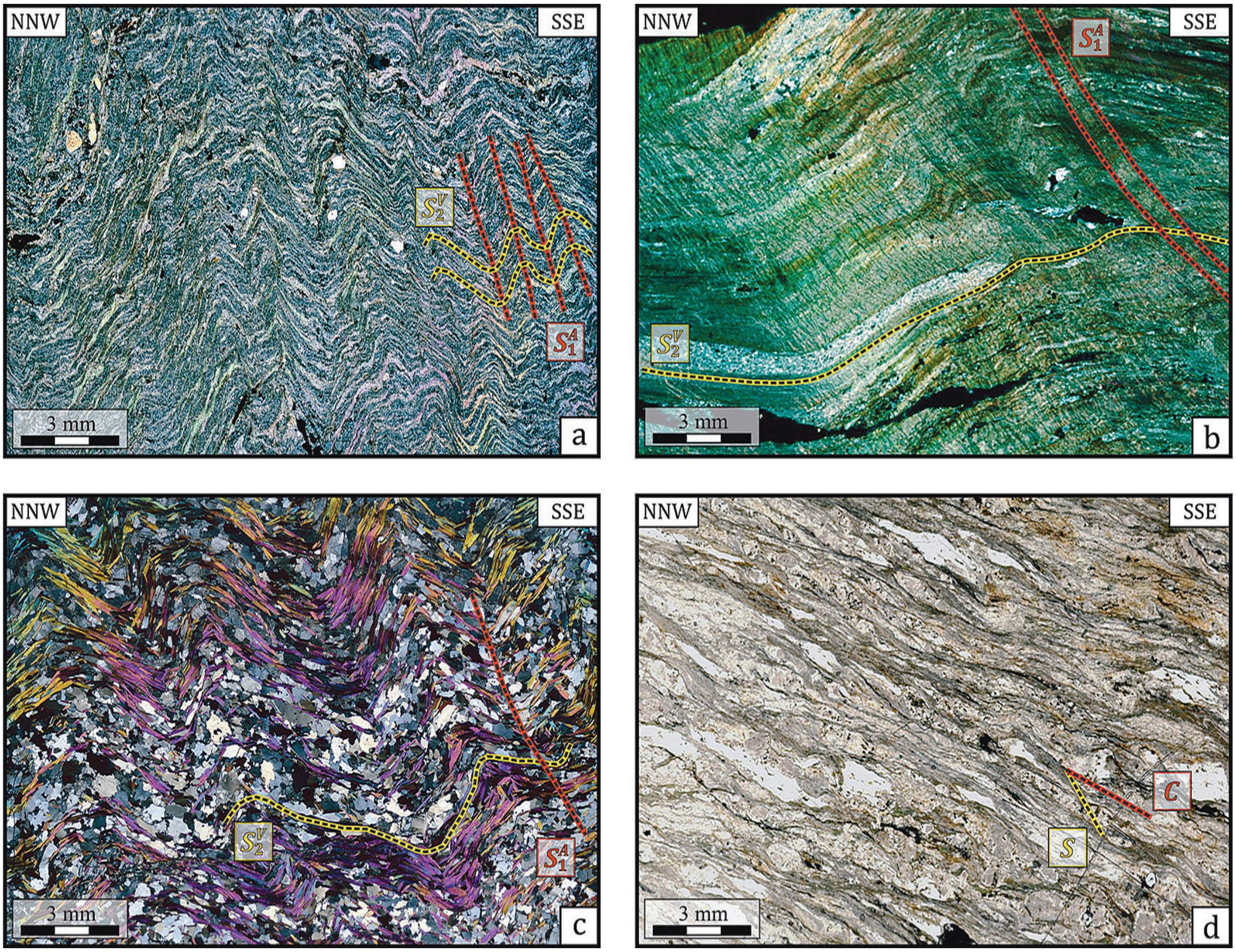


Fig. 7. **Micrographs of main Alpine planar fabric: (a) well-developed overprinting symmetric crenulation cleavage *(S_1^A)* is characterised by phyllosilicate-rich *(M)* domains, in which phyllosilicates define the overall cleavage, separated by quartz and feldspar-rich *(QF)* domains (NT203 site; XPL image); (b) partly asymmetric crenulation cleavage *(S_1^A)* in a slate relationship of the *C* and *S* planes in shear band fabric, *S* planes are asymmetrically curved near the *C* planes referring to top-to-the-NNW tectonic transport (NT273 site; PPL image); (c) the steeply inclined set on photo transpose an early Variscan metamorphic foliation *(S_2^V)* defined by the alignment of biotite and muscovite flakes, and flattened quartz grains to the Alpine crenulation cleavage *(S_1^A)*. Asymmetry of crenulation cleavage refers to top-to-the-NNW tectonic transport (NT172 site; XPL image); (d) sheared gneiss with the evolution of mylonitic fabric with *S–C* fabric. The drag folds refer to top-to-the-NNW tectonic transport (NT294 site; PPL image). Note: Section parallel to the aggregate lineation and normal to the foliation, PPL – plane-polarised light, XPL – crossed polarised light, all samples – Veporic crystalline basement.**

thickness of Mesozoic strata is up to 400 m (Fig. 7). The syncline is filled with a typically overturned sequence of Lower Triassic meta-quartzites and Middle- to Upper-Triassic carbonates. The recumbent fold has an unusual structure because its overturned limb has completely preserved sedimentary succession, whereas the normal limbs are strongly reduced and on the sole of thrust sheared (Fig. 7).

The Alpine deformation (D_2^A) is younger and was controlled by an extensional tectonic regime with a principal minimum stress axis in an E – W direction. The planar structures are represented by space, not pervasive, mylonitic and shear band foliations (S_2^A) which are in discrete zones (Fig. 6e). The poles (P_2^A) to the Alpine spaced foliations (S_2^A) attain Von Mises distribution 270.8 ± 17.8° and Fisher vector distribution of 271.4/33.9°, respectively (Fig. 5d). Determining the sense of shear was possible in the cases where geometrical relationships of the *S* and *C′* planes in paragneiss and orthogneiss mylonites were clear (Fig. 6e). Based on these kinematic indicators as well as the asymmetry of structures on a microscale perpendicular to *S* planes and parallel with stretching lineation with well-developed *C′* planes, the overlying blocks of the shear zones moved the top-to-the-E simple shear. The extensional shear band with well-visible drag folds of the Variscan foliation (S_2^V) are deflected and parallelised to the S_2^A mylonitic foliation (Fig. 6e). Rarely, the metamorphosed rocks have been significantly transformed into a mylonite fabric.

The carbonate rocks contain flow foliation and asymmetric intrafolial (L_{2c}^A) folds in ductile shear zones (Fig. 6f). It also indicates extensional translation with the top-to-the-E shearing. Folds and flow foliation are the most spectacular deformational structures in the Triassic carbonate rocks of the Veľký Bok cover sequence, despite of they are restricted to the ductile shear zone related to an extensional simple shear regime.

5. INTERPRETATION AND DISCUSSION

Based on the origin and genetic aspects of contemporaneously and sequentially developing fabric, the deformational pattern preserved in protolith rocks represents independent, through mutually related deformation phases/regimes. Subsequent deformation during the Alpine Orogeny produced regional-scale cleavage, polyphase folds, thrust-nappe structures, and low- to very low-grade metamorphism. Based on deformation and metamorphism differences between Paleozoic and Mesozoic host rocks, we suggest that the observed deformational structures that influenced the Variscan metamorphic foliation (S_2^V) were associated mainly with the Alpine Orogeny. However, the possibility of a very late Variscan deformation cannot be excluded.

The Variscan pervasive metamorphic foliation formed during the high- to medium-grade metamorphism (Krist et al., 1992) was a suitable planar marker for the study of younger, predominantly Alpine deformational phases in crystalline rocks of the Veporic and Tatric units. In most cases, the Variscan fabric is still sufficiently visible despite its overprinting by the planar and linear structures related to the Alpine deformation. However, in some places, mainly in the shear zones of the Alpine nappe or partial nappes décollements, the Variscan structure is more or less transposed into the Alpine fabric. The Variscan fabric is completely overprinted only in the Alpine shear zone's central portions. In the Veporic Unit, the spatial distribution of the measured Variscan pervasive foliations (S_2^V) progressively coincides with the Alpine disjunctive foliations (S_1^A). However, they are easily distinguishable in the field (Fig. 6a–e).

Besides this, field research has confirmed the position of the Lower Triassic quartzites and Middle- to Upper Triassic carbonates in the tectonic windows or half-windows beneath and below the Variscan Veporic crystalline basement (Fig. 2) in the cores of folds (Fig. 4 -cross-sections). In addition to the significant shortening in the contact zone between the Veporic and Tatric units, this observation refers to the large Alpine partial nappes in the northern part of the Veporic Unit. These arguments are supported by the Mesozoic deposits incorporated into this structure. This Alpine nappe stack has also been observed by several authors in the past (Biely et al., 1992, 1997; Plašienka, 2003; Bezák & Olšavský, 2008).

In the study area, the horizontal compressive stress caused the evolution of Alpine thrusts and reverse faults which caused the shortening of the crust where the hangingwall moves up relative to the footwall. The ductile shear sense from such zones can be deciphered mainly from asymmetric and intrafolial folds, *S–C* tectonites, sigmoids, parallelograms, and lenticular clast structures in deformed rocks (e.g., Ramsay, 1980; Lister & Snoke, 1984; Mawer, 1992; Passchier & Trouw, 2005; Pelech & Hók, 2017). The kinematics indicators as asymmetric structures developed within the zones indicate shear direction during the Eo-Alpine tectonics.

The most reliable kinematic indicators are those formed by foliation pairs within the mylonites. There are two main types of these, *S–C* fabric (D_1^A) and shear-band (*S–C'*) foliation (D_2^A) with completely different geometry and orientations (Fig. 6c,e), and it is useful to distinguish the two as they represent different stages in a progressive deformation (cf. Lister & Snoke, 1984; Mawer, 1992). The main criteria to determine the shear movement were *S–C* fabric, the orientation of fold axes with a combination of the intersection lineation, stretching, and mineral lineations (cf. Fig. 5c,e,f). All Alpine structures have point distribution, whereas the Variscan foliation refers more to the girdle distribution in the NW – SE direction. Thus, the Alpine thrusting was determined by structural analysis in many places and the principal vector of tectonic transport is an average azimuth of 343° (NNW direction). This top-to-the-north direction of the Alpine tectonic transport was determined by stretching lineations with NNW – SSE trends (L_{1c}^A), small-scale shear sense criteria NNW-wards, fold axes with ENE – WSW trends (L_{1c}^A) and also by large-scale recumbent folding affecting both the basement and cover sequences.

In the study area, the thrust faults typically dip at low- to moderate angles, from 10° to 45°. However, because thrust faults cut through lithological sections as either ramps or flats, in some places their orientations can vary considerably. The zones of partial thrusting are represented by the mylonitic foliation, which is commonly fine, planar, and laterally continuous, and usually forms a parallel to anastomosing pattern around ellipsoidal parallelograms of less-deformed rock (low-strain domains) at all scales. Sometimes the transition from host rocks through progressively higher Alpine foliated and finer-grained mylonite can be traced in the study area. The Alpine overprint was also observed on magnetic fabrics of the basement and cover formations (Hrouda et al., 2002).

As was written above, the transport direction is top-to-the-NNW, but the question is the time of this process. In this case, using the lithostratigraphy of Veľký Bok cover sequence and published geochronological data is possible. The youngest known sediments of the Veľký Bok cover sequence are Early Cenomanian and belong to the synorogenous flysch (e.g., Bujnovský & Lukáčik, 1985; Biely et al., 1997). These sediments indicate mid-Cretaceous shortening (100–90 Ma), affecting the Veporic – Tatric junction area. Besides this, $^{40}Ar/^{39}Ar$ ages of newly formed white micas constrain the main Alpine tectono-metamorphic phase to occur during the Late Cretaceous (86–78 Ma; Dallmeyer et al., 1996; Kohút et al., 2000).

The attenuated basement of the Fatric domain was fully underthrusted beneath the Veporic nappe stack, its cover was detached and thrust northward as the Fatric (Krížna) cover nappe system and together with the Veporic Unit overrode the Tatric Unit (e.g., Plašienka, 2003; Putiš et al., 2009). The northward movement of the Veporic Unit was also indicated in previous works (Putiš, 1987, 1989; Plašienka et al., 2003; Putiš et al., 2009) but evidence of the top-to-the-west tectonic transport has also been documented in some areas of the northern Veporic Unit (e.g., Hók et al., 2013). However, a more detailed structural analysis was never carried out.

The syn-collisional exhumation of the northern part of the Veporic hanging wall indicates ages of approximately 80 Ma (Putiš et al., 2009), similar also to the southern part of the Veporic Unit (Vojtko et al., 2016, 2017). Exhumation was controlled, in the upper crust, by an extensional tectonic regime with the orientation of the extensional palaeostress axis (σ_3) in the E – W direction. At the same time, compression continued in the lower parts of the crust and the Fatric and Tatric basements were underthrusted beneath the Veporic Unit. The present-day distribution of the partial nappe boundaries is oriented diagonally, at an acute angle to the measured orientation of the Alpine shortening (D_1^A) at the outcrops. This is probably due to this extensional tectonic regime (D_2^A).

6. CONCLUSIONS

The Veporic crystalline basement is mainly composed of para- and orthogneisses, mica schists, and amphibolites, which were predominantly affected by high- to medium-grade Variscan metamorphism (M_2^V) and then by a generally low-grade Alpine overprint (M_1^V). The Variscan deformation (D_2^V) is characterised by pervasive metamorphic foliation (S_2^V) which is well-developed in the entire crystalline basement of the study. This Variscan fabric (S_2^V) was a suitable marker for determining the Alpine deformation.

The Alpine deformation (D_1^A) was accompanied by retrograde lower greenschist facies metamorphosis (M_1^A). Therefore, the complete transposition of to the fabric originated only very locally, making it possible to study the relationships between the deformations. The evolution of Alpine tectonic fabric (S_1^A) is more significantly localised to shear zones and evolved during the Cretaceous orogeny (Eo-Alpine deformation).

The spatial distribution of the measured Alpine mylonitic foliation and crenulation cleavage (S_1^A), mineral and stretching lineations (L_{1t}^A) shows the NNW – SSE shortening. The foliations (S_1^A) have generally NE – SW striking and dip shallowly or moderately to the SE. The deformation (D_1^A) is accompanied by crenulation lineation, fold axes, and intersection lineations (L_{1c}^A) showing the NNW – SSE shortening. The folds (D_1^A) are often asymmetric. From these observations, we can unambiguously determine that the shortening was carried out during the simple shear tectonic regime with the top-to-the-NNW tectonic transport which determines the kinematics of the Alpine thrusting from 105 to 90 Ma.

The Alpine deformation (D_2^A) is represented by the exhumation of the Tatric Unit from beneath the Veporic Unit. The en-block exhumation of the already formed internal structure of the Veporic Unit occurred most probably between 80 and 55 Ma.

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