*Mineralia Slovaca, Web ISSN 1338-3523, ISSN 0369-2086*
*53, 2 (2021), 81 – 90, © Authors 2021. CC BY 4.0*

# Lithotectonic units of the Western Carpathians: Suggestion of simple methodology for lithotectonic units defining, applicable for orogenic belts world-wide

ZOLTÁN NÉMETH

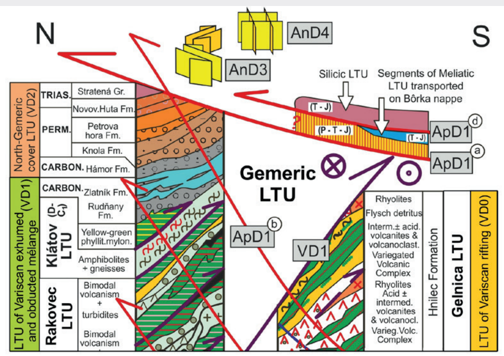
State Geological Institute of Dionýz Štúr, Mlynská dolina 1, SK-817 04 Bratislava, Slovak Republic;
zoltan.nemeth@geology.sk

**Abstract:** New methodology of **XD labelling** for defining of lithotectonic units, tested in the Western Carpathians at a general scale of 1 : 2 000 000, as well as in the innermost W. Carpathians (Gemericum and adjacent units) at the detail scale of 1 : 50 000, has a uniform applicability for orogenic belts world-wide. Lithotectonic classification is based on orogenic (Wilson) cycles, being indicated in **XD** designation by the prefix **X** (paper suggests the prefixes for the orogenic cycles known within Europe), as well as an affiliation of individual lithological unit to particular orogenic phases **D** of these cycles: **D0** – divergent process of riftogenesis, **D1** – convergent processes of subduction, obduction, closure of this elongated oceanic space by collision, **D2** – post-collisional thermal / deformation processes, unroofing and metamorphic core complex evolution; **D3** – intraplate consolidation (strike-slips, transpression, transtension, rotation of blocks, etc.) and **D4** – regional extension (pure shear-type regional faults, Basin and Range-type tectonics). Possible is even more detail classification applying the subphases – e.g. **D1a**, **D1b**, etc. Using extended set of prefixes for orogenic cycles besides Europe, makes proposed methodology universal.

The W. Carpathians, as a segment of Alpine-Himalayan orogenic belt, developed in Phanerozoic during multiple orogenic (Wilson) cycles of Intra-Pangea type. The Variscan (**V**; Paleozoic), Paleo-Alpine (**Ap**; Mesozoic) and Neo-Alpine (**An**; dominantly Cenozoic) orogenic cycles in this territory were proved by exact geological data, including revealed three suture zones (**V**; **Ap**; **An**) after elongated basins with oceanic crust in their axial zones and three generations of high-pressure rocks of subduction metamorphism (**V**; **Ap; An**). Two generations of dismembered ophiolite suites remains (**V; Ap**) and two proved metamorphic core complexes related to post-collisional evolution of Variscan and Paleo-Alpine orogenic cycles (**V; Ap**) complete the geodynamic interpretation of W. Carpathians. The youngest – Neo-Alpine (Cenozoic) orogenic cycle (**An**) has besides interpreted suture zone and accretionary prism also well-defined related volcano-sedimentary sequences.

**Key words:** lithotectonic units, orogenic cycle, Wilson cycle, Western Carpathians

**Graphical abstract**




**Highlights**

- Proposed is a new methodology of the XD labelling of the lithotectonic units, applicable in Phanerozoic and Proterozoic terranes world-wide
- New methodology was tested on lithotectonic units of the Western Carpathians, being produced by three orogenic cycles.

## Introduction

The Earth`s crust can be characterized by two types of the first-order objects: besides extended oceanic spaces of present Pacific, Atlantic, Indian, Southern and Arctic oceans, the continents are bearing geologically significant mountain ranges, produced by earlier orogenic processes. The Earth`s geodynamics during the Phanerozoic era principally deals with the super-continent Pangea, developed after the closure of Iapetus ocean by gradual collision and amalgamation of lithospheric plates (continents) of Laurussia, Gondwana and Siberia, being primarily derived from earlier supercontinent of Rodinia. Phanerozoic evolution encompasses multiple disintegrating (divergent) processes, producing within the Pangea the elongated basins of Tethys, mainly trending equatorial. Multiple divergent processes were alternated with convergent and collisional ones, producing a system of parallel geosutures and orogenic belts.

The products of multiple alternating divergent and convergent processes, having main compressional and extensional axes perpendicular to the course of orogenic

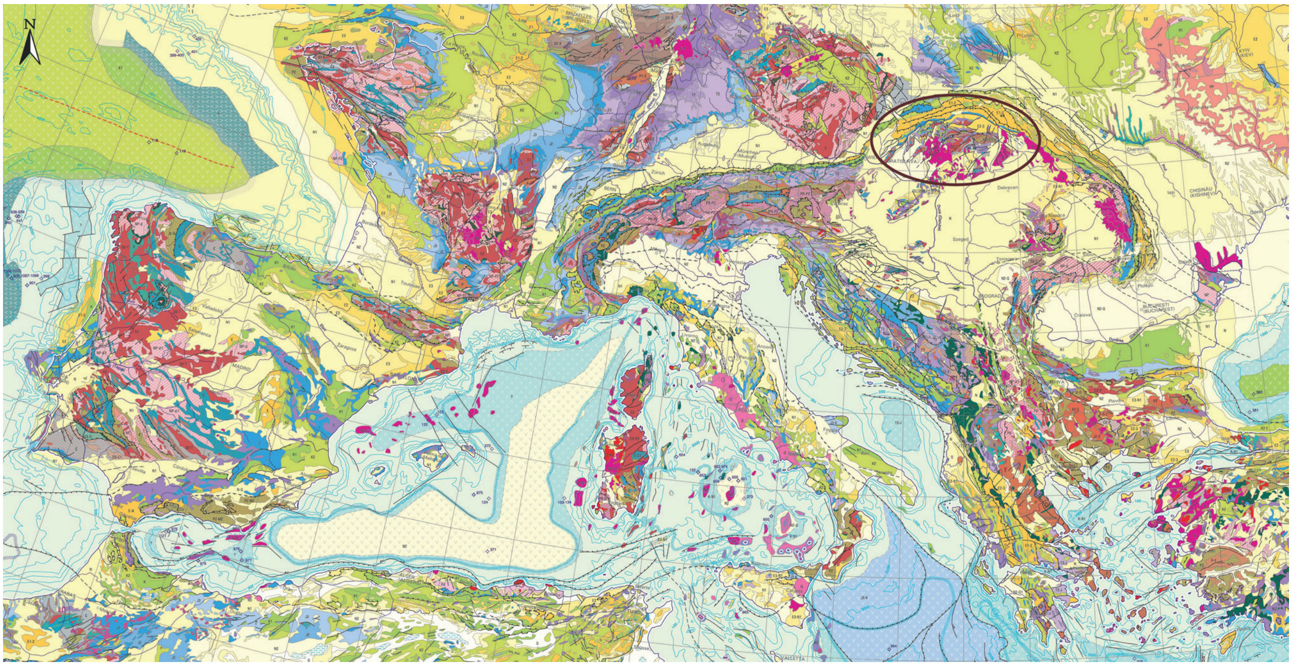


**Fig. 1.** Position of the Western Carpathians (brown ellipse) in the frame of Alpine-Carpathian orogenic belt. Presented segment of geological map is from the IGME 5000 – Asch, K. (ed., 2005). The 1 : 5 Million International Geological Map of Europe and Adjacent Areas. BGR (Hannover).

belts, are exemplarily well decipherable in the Western Carpathians – the northernmost segment of the Alpine-Carpathian orogenic belt (Fig. 1). The Western Carpathian belt is arched to the north and is characteristic with relatively high degree of symmetry in both arms. Owing to this, the suture zones after multiple disintegration and collisional joining within the Pangea terrane are well observable here (e.g. Plašienka et al., 1997; Németh et al., 2016; cf. Domeier et al., 2012). Evolution of these basins, designated by us as Proto- and Paleo-Tethys (products of Variscan riftogenesis; marked as **V**), Neo-Tethys (product of Paleo-Alpine riftogenesis; **Ap**) and Proto-Atlantic (Vahic) zone (product of Neo-Alpine processes; **An**) was partially overlapping in their divergent vs. convergent phases, which magnifies the complexity of the Intra-Pangea geodynamic processes (Németh et al., 2017a; Németh, 2018).

Based on INSPIRE (Infrastructure for Spatial Information in Europe) classification, summing up a number of geological definitions, **the lithotectonic unit is "a geologic unit defined on basis of structural or deformation features, mutual relations, origin or historical evolution. Contained material may be igneous, sedimentary, or metamorphic".**

Applying the definition above, the territory of Western Carpathians (Fig. 1) was used as a test region for defining the lithotectonic units (LTUs) at two differing scales: 1 : 2 000 000 – whole W. Carpathians in Slovak territory (Fig. 3) and 1 : 50 000 – the innermost part of W. Carpathians – Gemericum and adjacent units (Fig. 4). LTUs defined at both scales are briefly described and their role in geological evolution at Variscan and Alpine orogeneses of W. Carpathians is documented.

## Applied methodology

The defining of lithotectonic units in the Western Carpathians is based on long-time research by the author, taking into account also results of several generations of geologists, principally contributing to the recent interpretation of the multiphase orogenic evolution of W. Carpathians.

Presented methodology of defining lithotectonic units (LTUs), based on plate tectonic principles, distinguishes **LTUs as lithological sequences with special type of lithological, facies and/or tectonometamorphic parameters, differing from neighbouring sequences/LTUs.** These differences are caused by tectonic positioning of different LTUs originating or bearing overprint during different orogenic phases or subphases of particular orogenic cycle. Within the concept of plate tectonics, the orogenic cycles/phases are precisely defined, having universal validity for Phanerozoic era, as well as Proterozoic.

Based on practice from the Western Carpathians, we recommend the uniform **XD labelling** of individual phases of orogenic (Wilson) cycle (Fig. 2). Using the letter D follows a universal practice of geologists world-wide to designate the deformation phases by this letter, though the sequences of events marked by them mostly differ. This paper intends to introduce a uniform system. The letter D (instead of other possible letters) has a supreme priority, because it is immediately understandable, what it represents: In each orogenic phase the involved sedimentary processes and tectono-metamorphic overprints of rock sequences are accompanied with some degree of deformation, so the letter D interlaps all these processes the most appropriately.

Symbols **D0-4** indicate particular orogenic phase within an orogenic cycle (Fig. 2): and **X prefixes** designate the orogenic cycles: **Sv – Svecofennian, Go – Gothian, Sn – Sveconorwegian, Ti – Timanide, Cd – Cadomian, Cl – Caledonian, V – Variscan, Ur – Uralian, A – Alpine** (in the case of W. Carpathians: Ap – Paleo-Alpine of Mesozoic evolution and An – Neo-Alpine – partly Mesozoic and Cenozoic evolution; both representing complete orogenic cycles), **He – Hellenic orogeny**. By this way suggested methodology is applicable for the orogenic processes/belts throughout the whole Europe, and when adding additional prefixes it is applicable also for the rest of the world. The main benefit of the proposed XD labelling methodology for defining real lithotectonic units is a readily accessible and simple understandable information provided by the index alone about the whole evolution path of particular LTU.

**XD0** – Divergent process of riftogenesis, starting the orogenic cycle, being characterized with characteristic volcanosedimentary sequences produced by the rifting within the continental crust, origin of graben / halfgraben structures, addition of volcanic material (extrusive, effusive) of acid / intermediate and later dominating basic composition, tied to gradual development of oceanic crust in the axial zone of elongated riftogeneous basin. The embryonal phase of divergence leads to evolution of mature basin with the mid-oceanic ridge type spreading. Generated rock sequences form later (post-collisional) ophiolites of dismembered type.

The divergent phase **XD0** index has added an **X** prefix indicating particular orogenic cycle, e.g. VD0 or ApD0 in the case of W. Carpathians. Because the XD0 orogenic phase is characteristic also with the metamorphism of mid-oceanic ridge-type, we indicate metamorphic overprint with similar **MX labelling**: **X** indicates orogenic cycle with added number, indicating its particular phase (Fig. 2). Special labelling of metamorphic overprint within XD0-2 phases (Fig. 2) is involved due to the fact that it is not acting in all orogenic phases – not like sedimentation and volcanism, being generally present in all.

The divergent VD0 process of riftogenesis is within the Western Carpathians well documented for several LTUs. The VD0 evolution of Gemeric LTU was documented in details by Grecula (1982; and following research outputs).

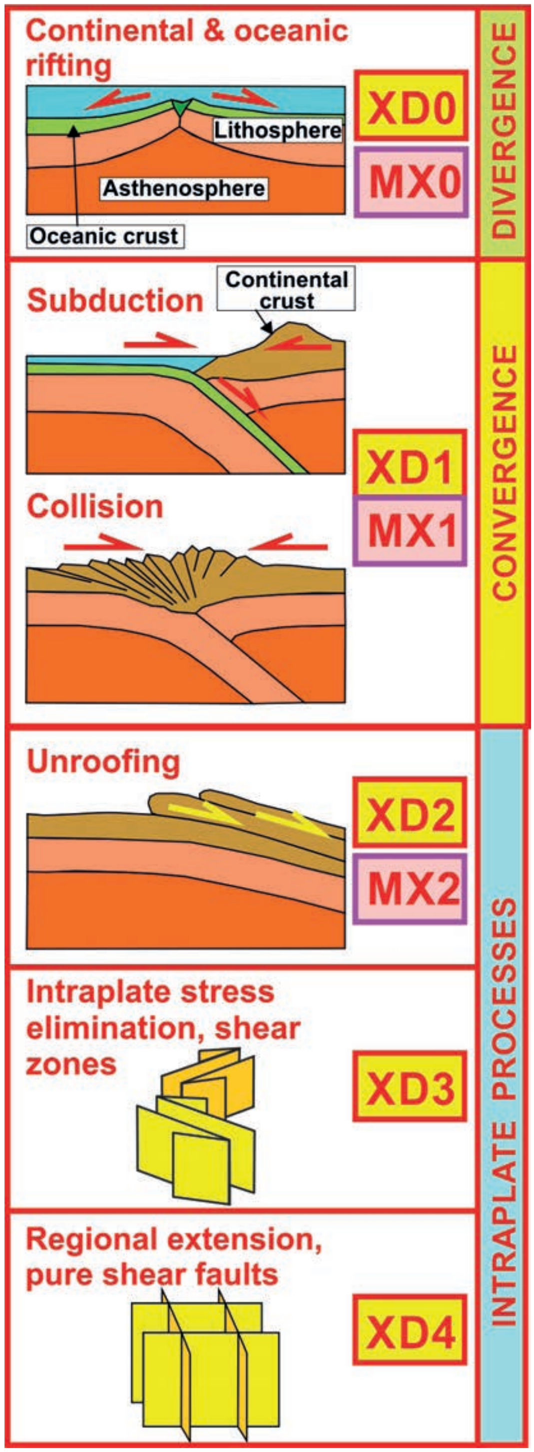



**Fig. 2.** Orogenic (Wilson) cycle with designation of individual orogenic phases (XD0-4), representing the ground for the XD labelling methodology. The variable X will be substituted by the prefix, indicating the name of orogenic cycle. Orogenic phases XD0, XD1 and XD2 are accompanied with characteristic metamorphic overprint of rock sequences. The designation of metamorphic overprint related to particular orogenic phase uses corresponding designation of MX0-2 type. For the list of prefixes of orogenic cycles present in European territory and further explanation see the relevant text.

**XD1** – Within the Intra-Pangea type convergent phase – the subduction immersion / reduction of the space is greater than the simultaneous enlargement of the space by still simultaneously acting rifting. This special case leads, after the immersion also of the mid-oceanic ridge zone beneath the active continental margin, to subduction of the second half of the basin and to collision of both converging lithospheric plates/microplates. The convergent kinematics forms accretionary prism with tectonic mélange type lithology, thrusting, obduction, partial exhumation of former sequences from the subduction slab, possibly also with parts of lower crust and the mantle (exhumed rigid rocks as a rule have a spherical shape, produced by their floating upwards in the ductile rock environment). Convergent processes culminate with collision. When sufficient data allow, the lithotectonic units undergoing the XD1 overprint can have defined even more details, e.g.: **XD1a** – subduction, **DX1b** – continental arc origin, **XD1c** – back-arc basin formation, **XD1d** – exhumation, **XD1e** – obduction, etc. Metamorphic overprint – usually of higher-pressure type – related to this orogenic phase, is labelled as **MX1**, where X indicates the orogenic cycle.

Within the Western Carpathians the XD1 phase, either Variscan VD1 or Paleo-Alpine ApD1 is well documented in majority of lithotectonic units (Fig. 3). In following chapter we will exemplify this multiple convergent process in the region of Gemeric LTU (Fig. 4).

**XD2** – Post-collisional evolution, related to overheating of collisionally thickened continental crust, causes higher temperature recrystallization up to local anatexis and origin of S-type granites, metallogenetic processes with formed ore veins and metasomatic mineralizations, extensional tectonics and the unroofing of previously overthrust sequences. Metamorphic overprint by overheating related to this orogenic phase is labelled as **MX2**, where X indicates the orogenic cycle.

In the Western Carpathians our previous research has confirmed that both – the Variscan and Paleo-Alpine collisions thickened continental crust, and with the contribution of linear-course mantle convectional heat (hot line; c.f. Németh et al., 2016) the orogen parallel metamorphic core complexes have developed twice – in Permian (the late Variscan metamorphic core complex) and Late Cretaceous (Paleo-Alpine metamorphic core complex). These orogen parallel metamorphic core complexes are accompanied with relevant metallogeny as well as unroofing kinematics (Hók et al., 1993; Kováč et al., 1994; Madarás et al., 1996; Plašienka, 1999; Janák et al., 2001; Németh et al., 2004; Dallmeyer et al., 2005; Jeřábek et al., 2007; Fig. 4).

**XD3** – Adaptation of post-collisional stresses: Development of the systems of regional shear-zones, transpression, transtension, blocks rotation, etc. Parallel systems of shear zones produce new systems of regional synthetic and antithetic shears. They tend to join and regional faults / lineaments parallel as well as perpendicular to orogenic belt originate (Németh et al., 2017b). Their origin marks a new orogenic phase marked XD4.

Within the Western Carpathians the AnD3 processes – penetration or rock sequences by shear zones, usually causing partial offset of counterpart rock blocks, are recorded in all pre-AnD4 lithotectonic units (Fig. 3).

**XD4** – indication of possible beginning of a new orogenic cycle with a new sequence of orogenic phases D0-4.

The kinematics of the origin of AnD4 pure shear faults / lineaments having preferably meridional and equatorial trends by joining of synthetic and antithetic mega-shears of AnD3 NW-SE and NE-SW trending systems of regional shear zones, was revealed in the W. Carpathians relatively recently (Németh et al., 2017b).

Methodology for defining the LTUs for particular region can consist of two approaches:

(A) **Direct method** of defining LTUs is applicable, if geological evolution of the region is sufficiently known and already proved by exact scientific data.

(B) **Indirect method** represents a more complicated approach, based on composing of a mosaic of often fragmentary geological findings, defining the principal (above stated) lithotectonic environments: continental and oceanic rift zones, ocean-floor environment (all affiliated with the deformation phase XD0), accretionary prisms, collision terranes (XD1), metamorphic core complexes and related unroofing kinematics (XD2), subsequent intra-plate / intra-collision zone stress adaptation (XD3), and regional pre-rifting extension (XD4).

## Lithotectonic units of the Western Carpathians based on known geological evolution

Modern summary of Phanerozoic geodynamics of the whole W. Carpathians is available in monographic issues edited by Grecula et al. (1997), Rakús (1998), Vozár & co-eds. (2010), Kováč (2000) and Janočko & Elečko (eds., 2003). Presently there was issued an extended paper about Early Alpine tectonic evolution (**Ap**) of the Western Carpathian by Plašienka (2018). Territory of W. Carpathians in Slovakia is covered with a complete set of state approved general geological maps at the detail scale of 1 : 50 000 with extended explanatory notes, summing up also available knowledge and proofs of geodynamic evolution in covered regions. Owing this wealth of data, the defining of LTUs of the W. Carpathians by XD labelling at various scales becomes relatively easy.

Defining the sequence of LTUs by understandable (and easily rememberable) way predestines to do it in the order from the younger LTUs towards evolutionary older ones: The younger ones do not encompass multiple overprints by several (or many) orogenic phases. Dealing with older

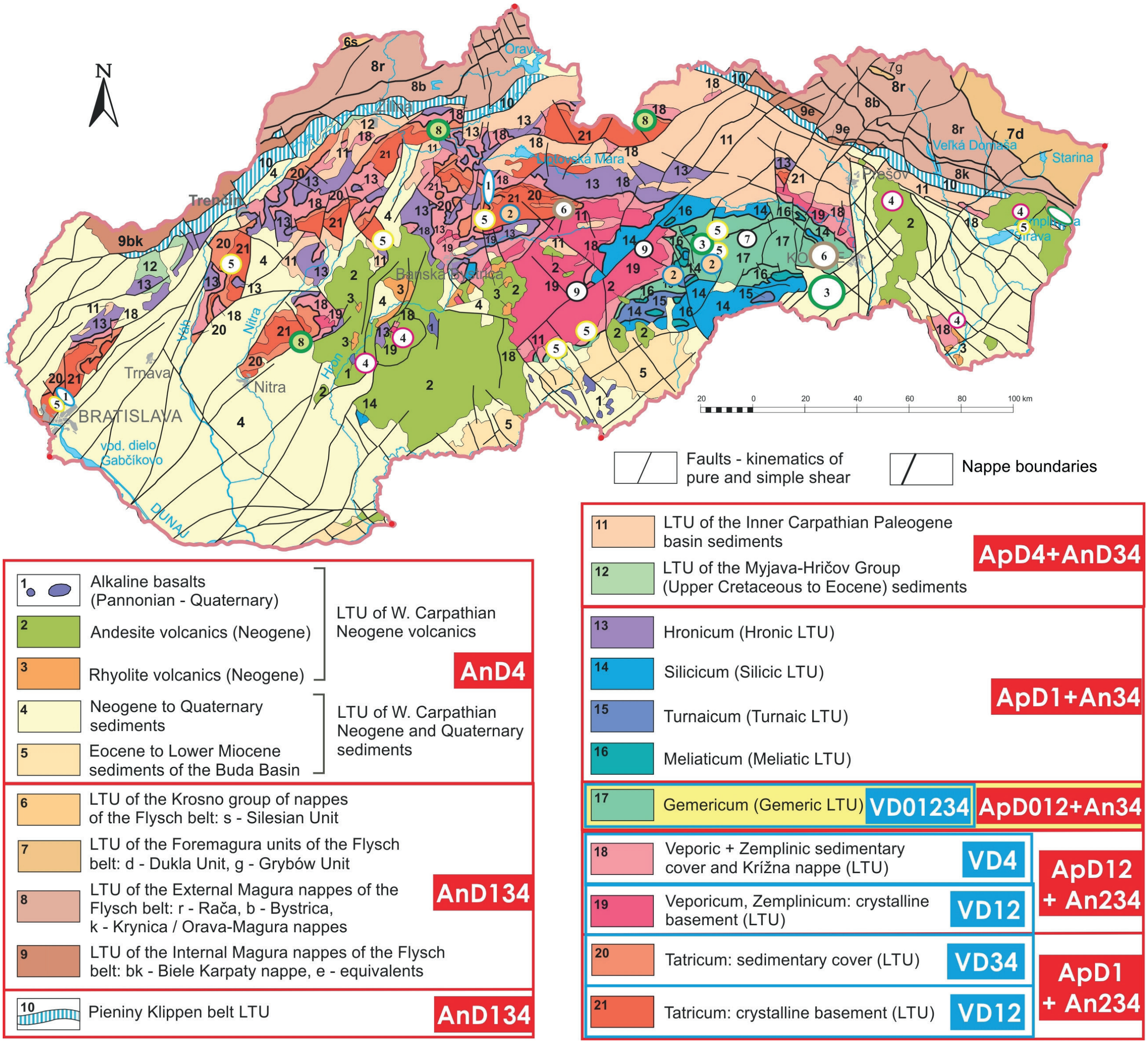



**Fig. 3.** Lithotectonic units of the Western Carpathians defined at a scale 1 : 1 000 000, applying the tectonic sketch of the Slovak part of Western Carpathians based on Geological map of Slovak Republic (Vozár & Káčer – eds., 1998). Black numbers within the tectonic sketch indicate individual lithotectonic units as stated in the table located below this sketch. Numbers in circles indicate a practical side of the LTUs concept – positioning of individual mineralization types bound to those LTUs, which underwent required geodynamic evolution for the genesis of following raw materials: 1 – antimonite ore deposits – Sb, 2 – tungsten ore deposits and occurrences – W, 3 – more significant occurrences of Co-(Ni) and Cr minerals, 4 – base metal ore deposits (+ Ga, Ge, In, Te, Bi), 5 – more significant occurrences of Ta, Nb + REE + Li ± Rb minerals ± fluorite, 6 – B minerals (tourmaline ± borates), 7 – $SiO_2$ deposits (quartz and other raw materials providing $SiO_2$), 8 – phosphates (mainly apatite), 9 – graphite occurrences. Position of mineral deposits and occurrences taken after Lexa et al. (2004) and numerous research reports, being simplified by Bačová in Bačo et al. (2007).

ones we have to take to our consideration the fact that older tectonometamorphic overprints may be overshadowed by younger ones.

### *Lithotectonic units of Neo-Alpine evolution*

The Neo-Alpine evolution of regional extension **AnD4** has produced two LTUs: LTU of W. Carpathian Neogene volcanics and the W. Carpathian Neogene and Quaternary sediments. Evolution of both relates to the Neo-Alpine post-collisional evolution and rhyolite, andesite and alkaline basalt volcanism (Nos. 3–1 in Fig. 3) as well as simultaneous sedimentation (Nos. 5–4). For further reference see e.g. Lexa & Konečný (1998), Kováč (2000) and Janočko & Elečko (eds., 2003). The AnD4 overprint (brittle penetrative pure-shear faults / lineaments) was registered in all older LTUs.

Neo-Alpine convergence and accretionary prism formation **AnD1** encompasses following LTUs of the W. Carpathian Flysch belt: Krosno group of nappes (6), Foremagura units of the Flysch belt (7), External Matura nappes (8) and Internal Magura nappes of the Flysch belt (9).

The **Neo-Alpine** collision and extensive overprint by Neo-Alpine regional shearing **AnD134** have produced the LTU of **Pieniny Klippen belt** (10). This distinct narrow belt represents a boundary of External and Internal W. Carpathians and is bending along the whole W. Carpathians (cf. Potfaj, 1998; Márton et al., 2013; Plašienka, 2018).

*Lithotectonic units of Paleo-Alpine post-collisional evolution*

Paleo-Alpine post-collisional evolution **ApD4(+AnD34)** is characterized with extended sedimentation in the Inner (Internal) Carpathian basins, so originating Paleogene sedimentary sequences (11) represent an individual lithotectonic unit, which has originated in clearly distinguished geodynamic conditions. Corresponding evolution was revealed also in the case of the Upper Cretaceous to Eocene sediments of Myjava-Hričov Group (12).

The Paleo-Alpine post-collisional thermal processes and unroofing in the South-Veporic zone **ApD2** are described in more details in following sub-chapter about Gemeric LTU.

*Lithotectonic units of Paleo-Alpine collisional evolution ApD1 – superficial nappes*

Lithotectonic units of **Hronicum** (13), **Silicicum** (14), **Turnaicum (Tornaicum)** (15) **and Meliaticum (Bôrka nappe)** (16) represent superficial nappes displaced northward after the Paleo-Alpine Lower Cretaceous collision. Each of these units has its own (volcano)-sedimentary evolution, related on primary position of their sedimentary area within the zonality of post-Variscan evolution. Long-time research has allocated the homeland of Hronic LTU to Pohorelá suture (line) present in Veporicum. The Silicic, Turnaic (Tornaic) & Meliatic LTUs were derived from the zone located south of Gemericum. After their displacement these units underwent faulting by Neo-Alpine deformation phases An34. (For further information see e.g. Plašienka et al., 1997; Kováč & Havrila, 1998; Mock et al., 1998; Mello et al., 1998.)

*Lithotectonic units of Paleo-Alpine collisional evolution ApD1 – basement units*

The W. Carpathian basement LTUs – Gemericum (Gemeric LTU, No. 17 in Fig. 3), Veporicum (Veporic LTU, including related Zemplinic LTU and sedimentary cover of both units, as well as Fatricum – Fatric LTU – the Krížna nappe; 18), Tatricum (Tatric LTU) – basement (21) and its cover (20) were individualized as basement nappes during the Lower Cretaceous Paleo-Alpine collisional event (ApD1). The tectonometamorphic evolution of these units is very complex, concerning their subsequent Upper Cretaceous–Cenozoic evolution (ApD2 + AnD34), but also earlier – pre-collisional evolution – Paleo-Alpine divergent phase (ApD0) as well as the phases of Variscan (Hercynian) orogenic cycle. We will now focus only to more detail litho-tectono-metamorphic evolution of Gemeric LTU, explained within individual orogenic phases of Variscan and Paleo-Alpine orogenic cycles. To characterize such evolution for all W. Carpathian basement LTUs would require a space of monographic issue and is besides the range of this article. Nevertheless, needed more detail information about these LTUs is available in monographs referred at the beginning of this chapter.

**Detailed description of Gemeric lithotectonic unit** (Fig. 4) as an etalon region with revealed 9 multi-orogenic evolutionary phases **– VD01234 + Ap012 + An34**.

**VD0** divergence is documented well by the research of Grecula and co-workers published within 1982–2011. The facial development of sequences of the continental rifting, including shift from acidic, to intermediate towards basalt volcanism is encompassed in **Gelnica LTU**. The field profiling, including geophysics and soil metallometry as well as subsequent detail mapping have revealed two variegated volcanic horizons within sedimentary succession. Dominant basalt volcanic activity indicates formation of oceanic type crust (**Rakovec and Klátov LTUs**) in elongated Intra-Pangea type basin, named as Paleo-Tethys (Grecula, 1982). The metamorphosed rock sequences of former oceanic crust formed post-collisional dismembered ophiolite suite (cf. Radvanec et al., 2007).

**VD1** closure of the basin by convergence (subduction slab dipping north), south-vergent obduction and collision (Németh, 2002) led to thickening of continental crust in collision zone. The post-collisional evolution with ingress of heat along the collisional belt led to origin of Variscan metamorphic core complex and double sided unroofing (Németh in Radvanec et al., 2007).

The **ApD0** extensional activity and opening basin in so-called North-Gemeric zone has stopped in Triassic, but synchronous extensional activity in South-Gemeric zone became more vivid and led to opening of Meliata orogen parallel basin with Triassic-Jurassic crust of oceanic type.

The **ApD1** convergence and collisional closing of this basin, owing to subduction with dip of subduction slab southward led in the space of W. Carpathians to origin of accretion prism encompassing the sequences of the northern – passive margin of the Meliata basin, but also high-pressure, or even ultra-high-pressure exhumed rocks from the subduction channel. These were north-vergently thrust and transported over Gemeric LTU in so-called Bôrka nappe, reaching even the North-Gemeric zone (cf. Ivan & Méres, 2009; Putiš et al., 2011, 2019; Németh et al., 2012 and numerous other works). Final stage of collision represented the thrusting of basement nappes of Gemeric, Veporic and Tatric LTUs.

**ApD2** encompassed the thermal consequences of originated Paleo-Alpine metamorphic core complex and south-vergent unroofing of Gemeric LTU from Veporic LTU, because the axis of overheating was located beneath the southern zones of Veporic LTU. This unroofing was documented by numerous authors by structural, microstructural and petrological results. North of collided Western Carpathian terrane opened new elongated Vahic / Proto-Atlantic basin in Late Cretaceous with Couches Rouges type sediments. The closure of this basin led to the formation of the Eocene wedge of the Inner Western Carpathians (Putiš et al., 2021 and references therein).

Further evolution is localized dominantly to External (Outer) W. Carpathians and the territory of Gemeric

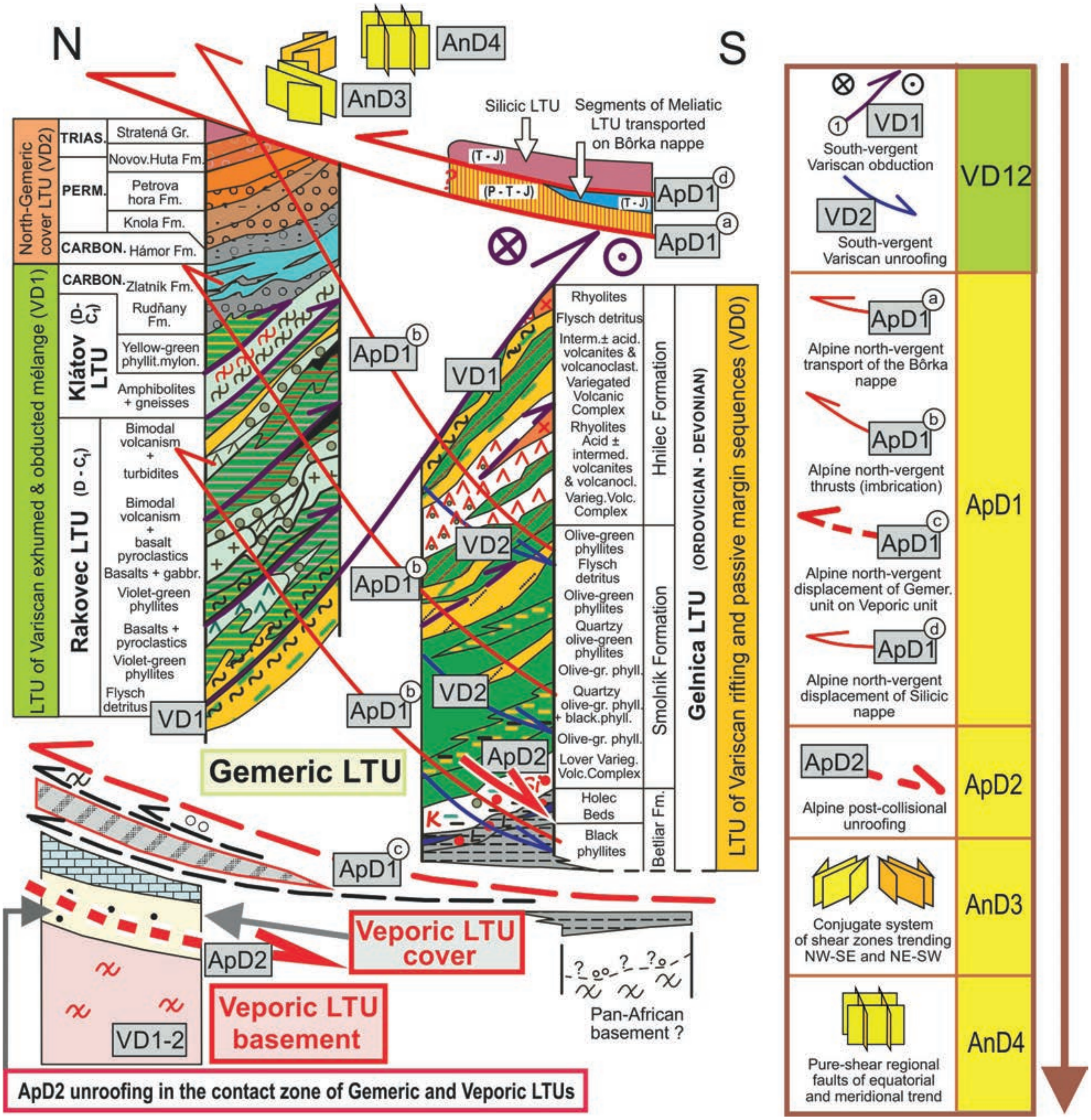



**Fig. 4.** Visualization of lithotectonic relations in the southern part of W. Carpathians, presenting Variscan and Alpine evolution of Gemeric, South-Veporic, Silicic and Meliatic LTUs. Based on geodynamic reconstruction by Németh (2005 and following works).

LTU affected by the compression field of **AnD3**, causing extensive shearing (cf. pioneering work by Grecula et al., 1990) and extension during **AnD4** producing vivid Neogene volcanism (besides the Gemeric LTU) as well as origin of pure-shear regional discontinuities.

## Conclusion

Presented methodology of XD labelling allows exact defining and classification of real regional LTUs at different scales, but provides also a clear information about reason of distinguishing of particular lithotectonic unit and expresses its more-or-less complete sedimentary and tectono-metamorphic evolution path. Proposed methodology enables clear cataloguing of scientific and geological survey information within individual lithotectonic units, where to sections devoted to individual orogenic phases is possible continuously add new findings and results. Moreover, the cataloque of orogenic phases within orogenic cycles of studied regions may indicate by a glance if some knowledge is still missing and can direct further scientific research.

Despite the territory of recent Western Carpathians represents relatively small part of Europe, three revealed and proved orogenic (Wilson) cycles, acting in this territory during Phanerozoic era, allow us to propose our findings and interpretations at least for the correlation within the Alpine-Carpathian orogenic belt.

The distinguished lithotectonic units of the W. Carpathians allow to understand the peculiarities of evolution of this territory, including metallogenic processes and spatial distribution of their products. LTUs defined in the Western Carpathians can contribute to parallelization of geological / lithotectonic units in neighbouring regions of the Alpine-Carpathian range. By this way they may also facilitate the parallelization of geological and tectono-metamorphic evolution and related products along this belt.

## Acknowledgement

Author expresses his thanks to the Ministry of Environment of the Slovak Republic for funding numerous regional geological and metallogenetic projects, providing high value geological data. Appreciated are also research possibilities on the EC Horizon 2020 and Horizon Europe, as well as UNESCO/IUGS IGCP platforms. Author is grateful to Professors Dušan Plašienka and Marián Putiš for inspiring comments and suggestions to primary manuscript. This paper is a contribution of the State Geological Institute of Dionýz Štúr of Slovakia to the EuroGeoSurveys Coordination & Support Action project Geological Service for Europe (GSEU).

## References

Asch, K. (ed.), 2005: The 1 : 5 Million International Geological Map of Europe and Adjacent Areas. *Hannover, BGR.*

Bačo, P., Bačová, Z., Németh, Z., Radvanec, M. & Repčiak, M., 2013: Kritické nerastné suroviny (Critical Raw Materials). Final report. *Manuscript. Bratislava, SGIDŠ archive,, 1–123 (in Slovak).*

Dallmeyer, R. D., Németh, Z. & Putiš, M., 2005: Regional tectonothermal events in Gemericum and adjacent units (Western Carpathians, Slovakia): Contribution by the $^{40}Ar/^{39}Ar$ dating. *Slovak Geol. Mag., 11, 2–3, 155–163.*

Domeier, M., Van der Woo, R. & Torsvik, T. H., 2012: Paleomagnetism and Pangea: The road to reconciliation. *Tectonophysics, 514–517, 14–43.*

Faryad, A. W., 1997: Petrological model for blueschist facies metamorphism in the Pieniny Klippen Belt. In: Grecula, P., Hovorka, D. & Putiš, M. (eds.): Geological evolution of the Western Carpathians. *Bratislava, Miner. Slov. – Monogr., 155–162.*

Grecula, P., 1982: Gemerikum – segment riftogénneho bazénu Paleotetýdy. *Bratislava, Alfa, 1–263.*

Grecula, P., Návesňák, D., Bartalský, B., Gazdačko, Ľ., Németh, Z., Ištván, J. & Vrbatovič, P., 1990: Shear zones and arc structure of Gemericum, the Western Carpathians. *Miner. Slov., 22, 97–110.*

Grecula, P., Hovorka, D. & Putiš, M. (eds.), 1997: Geological evolution of the Western Carpathians. *Bratislava, Miner. Slov. – Monogr., 1–370.*

Hók, J., Kováč, P. & Madarás, J., 1993: Extensional tectonic of the western part of the contact area between Veporicum and Gemericum, Western Carpathians. *Miner. Slov., 25, 172–176.*

Hók, J., Pelech, O., Teťák, F., Németh, Z. & Nagy, A., 2019: Outline of the geology of Slovakia (W. Carpathians). *Miner. Slov., 51, 1, 31–60.*

INSPIRE (on-line) lithotectonic unit definition (22 November 2021): http://inspire.ec.europa.eu/codelist/GeologicUnitTypeValue/lithotectonicUnit.

Ivan, P. & Méres, Š., 2009: Enkláva metamorfitu fácie modrých bridlíc v dobšinskom serpentinitovom lome – dôkaz spojitosti ultrabázického telesa s hačavskou formáciou príkrovu Bôrky. *Miner. Slov., 41, 4, 407–418.*

Janák, M., Plašienka, D., Frey, M., Cosca, M., Schmidt, S. Th., Lupták, B. & Méres, Š., 2001: Cretaceous evolution of a metamorphic core complex, the Veporit unit, Western Carpathians (Slovakia): P-T conditions and in situ $^{40}Ar$ / $^{39}Sr$ UV laser probe dating of metapelites. *J. metamorphic Geol., 19, 197–216.*

Janočko, J. & Elečko, M. (eds.), 2003: Tectono-sedimentary evolution of Western Carpathian Tertiary basins. *Miner. Slov., 35, 3–4, 161–290.*

Jeřábek, P., Stünitz, H., Heilbronner, R., Lexa, O. & Schulmann, K., 2007: Microstructural-deformation record of an orogen parallel extension in the Vepor Unit, West Carpathians. *J. Struct. Geol., 29, 1722–1743.*

Kováč, M., 2000: Geodynamický, paleogeografický a štruktúrny vývoj karpatsko-panónskeho regiónu v miocéne. *Bratislava, Veda, 1–202.*

Kováč, M., Kráľ, J., Márton, E., Plašienka, D. & Uher, P., 1994: Alpine uplif history of the Central Western Carpathians: Geochronological, paleomagnetic, sedimentary and structural data. *Geol. Carpath., 45, 83–96.*

Kováč, P. & Havrila, M., 1998: Inner structure of Hronicum. *Slovak Geol. Mag., 4, 4, 275–280.*

Lexa, J. & Konečný, V., 1998: Geodynamic aspects of the Neogene to Quaternary volcanism. In: Rakús, M. (ed.): Geodynamic development of the Western Carpathians. *Bratislava, GS SR, Vyd. D. Štúra, 219–240.*

Lexa, J. (ed.), Bačo, P., Chovan, M., Petro, M., Rojkovič, I. & Tréger, M., 2004: Metallogenetic map of Slovakia. *Bratislava, Ministry of Environment of Slovak Republic.*

Madarás, J., Hók, J., Siman, P., Bezák, V., Ledru, P. & Lexa, O., 1996: Extension tectonics and exhumation of crystalline basement of the Veporicum unit (Central Western Carpathians). *Slovak Geol. Mag., 3–4, 179–183.*

Márton, E., Grabowski, J., Plašienka, D., Túnyi, I., Krobicki, M., Haas, J. & Pethe, M., 2013: New paleomagnetic results from the Upper Cretaceous red marls of the Pieniny Klippen Belt, Western Carpathians: Evidence for general CCW rotation and implications for the origin of the structural arc formation. *Tectonophysics, 592, 1–13.*

Mello, J., Reichwalder, P. & Vozárová, A., 1998: Bôrka Nappe: high-pressure relic from the subduction-accretion prism of the Meliata ocean (Inner Western Carpathians, Slovakia). *Slovak Geol. Mag., 4, 4, 261–273.*

Mock, R., Sýkora, M., Aubrecht, R., Ožvoldová, L., Kronome, B., Reichwalder, P. & Jablonský, J., 1998: Petrology and stratigraphy of the Meliaticum near the Meliata and Jaklovce villages, Slovakia. *Slovak Geol. Mag., 4, 4, 223–260.*

Németh, Z., 2002: Variscan suture zone in Gemericum: Contribution to reconstruction of geodynamic evolution and metallogenetic events of Inner Western Carpathians. *Slovak Geol. Mag., 8, 3–4, 247–257.*

Németh, Z., 2005: Paleopiezometry: Tool for determination of differential stresses for principal ductile shear zones of Gemericum, Western Carpathians. *Slovak Geol. Mag., 11, 2–3, 185–193.*

Németh, Z., 2018: Geodynamic background of the origin of Variscan and Paleo-Alpine metamorphic core complexes in the Western Carpathians and their metallogenetic importance. *XXI Int. Congress of the CBGA, Salzburg, Austria, September 10–13, 2018, Abstracts, p. 211.*

Németh, Z., Prochaska, W., Radvanec, M., Kováčik, M., Madarás, J., Koděra, P. & Hraško, Ľ., 2004: Magnesite and talc origin in the sequence of geodynamic events in Veporicum, Inner Western Carpathians, Slovakia. *Acta Petrol. Sinica, 20, 4, 837–854.*

Németh, Z., Radvanec, M., Kobulský, J., Gazdačko, Ľ., Putiš, M. & Zákršmidová, B., 2012: Allochthonous position of the Meliaticum in the North-Gemeric zone (Inner Western Carpathians) as demonstrated by paleopiezometric data. *Miner. Slov., 44, 1, 57–64.*

Németh, Z., Putiš, M. & Hraško, Ľ., 2016: The relation of metallogeny to geodynamic processes – the natural prerequisite for the origin of mineral deposits of public importance (MDoPI): The case study in the Western Carpathians, Slovakia. *Miner. Slov., 48, 119–135.*

Németh, Z., Putiš, M. & Hraško, Ľ., 2017a: Important periods with the genesis of vein and stratabound mineralization in the Western Carpathians as a consequence of polystadial orogenic evolution. *Proc. Open Geol. Congress, Vysoké Tatry 2017, p. 46.*

Németh, Z., Bačová, N. & Repčiak, M., 2017b: Tektonika východnej časti Levickej žriedlovej štruktúry. *Mente et Malleo, 2, 1, 50.*

Plašienka, D., 1993: Structural pattern and partitioning of deformation in the Veporic Foederata cover unit (Central Western Carpathians). In: Rakús, M. & Vozár, J. (eds): Geodynamic model and deep structure of the Western Carpathians. *Conf., Symp., Sem. Bratislava, D. Štúr Inst. Geol., 269–277.*

Plašienka, D., 1995: Passive and active margin history of the northern Tatricum (Western Carpathians, Slovakia). *Geol. Rdsch., 84, 748–760.*

Plašienka, D., 2018: Continuity and episodicity in the Early Alpine tectonic evolution of the Western Carpathians: How large-scale processes are expressed by the orogenic architecture and rock record data. *Tectonics, 37, 2029–2079.*

Plašienka, D., Grecula, P., Putiš, M., Kováč, M. & Hovorka, D., 1997: Evolution and structure of the Western Carpathians: an overview. In: Grecula, P., Hovorka, D. & Putiš, M. (eds): Geological evolution of the Western Carpathians. *Bratislava, Miner. Slov., Monogr., 1–24i.*

Plašienka, D., Méres, Š., Ivan, P., Sýkora, M., Soták, J., Lačný, A., Aubrecht, R., Bellová, S. & Potočný, T., 2019: Meliatic blueschists and their detritus in Cretaceous sediments: New data constraining tectonic evolution of the West Carpathians. *Swiss J. Geosci., 112, 55–81.*

Plašienka, D., Jeřábek, P., Vojtko, R., Králiková, S., Janák, M., Ivan, P., Méres, Š., Soták, J. & Milovský, R., 2016: Alpine structural and metamorphic evolution during burial and exhumation of the Veporic basement and cover complexes. *Bratislava, Comenius Univ. Press.*

Potfaj, M., 1997: Relation of the Klippen Belt and the Flysch zone in the territory of western Slovakia. In: Plašienka, D. (ed.) et al., 1997: Alpine evolution of the Western Carpathians and related areas. *Bratislava, GS SR, Vyd. D. Štúra, 119–125.*

Potfaj, M., 1998: Geodynamics of the Klippen Belt and Flysch Belt of the Western Carpathians. In: Rakús, M. (ed.): Geodynamic development of the Western Carpathians. *Bratislava, GS SR, Vyd. D. Štúra, 143–154.*

Putiš, M., Radvanec, M., Sergeev, S., Koller, F., Michálek, M., Snárska, B., Koppa, M., Šarinová, K. & Németh, Z., 2011: Metamorfovaná sukcesia silicitických bridlíc s bazaltom a diastrofickou brekciou v olistolite jurskej akrečnej prizmy meliatika pri Jaklovciach (Slovensko), datovaná na zirkóne (U-Pb SIMS SHRIMP). *Miner. Slov., 43, 1, 1–18.*

Putiš, M., Soták, J., Li, Q.-L., Ondrejka, M., Li X.-H., Hu, Z., Ling, X., Nemec, O., Németh, Z. & Ružička, P., 2019:

Origin and age determination of the Neotethys Meliata basin ophiolite fragments in the Late Jurassic-Early Cretaceous accretionary wedge mélange (Inner Western Carpathians, Slovakia). *Minerals, 9, 11, 652.*

Putiš, M., Nemec, O., Danišík, M., Jourdan, F., Soták, J., Tomek, Č., Ružička, P. & Molnárová, A., 2021: Formation of a composite Albian-Eocene orogenic wedge in the Inner Western Carpathians: P-T estimates and $^{40}Ar$ / $^{39}Ar$ geochronology from structural units. *Minerals, 11, 988.*

Radvanec, M., Németh, Z., Kráľ, J. & Pramuka, S., 2007: Variscan dismembered metaophiolite suite fragments of Paleo-Tethys in Gemeric unit, Western Carpathians. *Miner. Slov., 49, 1, 1–48.*

Radvanec, M., Konečný, P., Németh, Z. & Grecula, P., 2007: P-T-t dráha a lokálne anatektnické tavenie metapelitu s prímesou psamitického kremeňa vo variskej metamorfóze gemerika. *Miner. Slov., 39, 1, 1–44.*

Šimová, M., 1982: Eclogitoid rocks in pebbles of Cretaceous conglomerates of Klippen Belt. *Geol. Práce, Spr., 77, 55–74.*

Vojtko, R., Králiková, S., Jeřábek, P., Schuster, R., Danišík, M., Fügenschuh, B., Minár, J. & Madarás, J., 2016: Geochronological evidence for the Alpine tectono-thermal evolution of the Veporic Unit (Western Carpathians, Slovakia). *Tectonophysics, 666, 48–65.*

Vozár, J. & Káčer, Š. (eds.), 1998: Geological map of Slovak Republic 1 : 1 000 000. *Bratislava, SGIDŠ.*

Vozár, J., Ebner, F., Vozárová, A., Haas, J., †Kovács, S., Sudar, M., Bielik, M. & Péró, Cs. (eds.), 2010: Variscan and Alpine terranes of the Circum-Pannonian Region. *Bratislava, Geol. Inst. Slovak Acad. Sci., 7–233.*

Vozárová, A., 1990: Development of metamorphism in the Gemeric/Veporic contact zone (Western Carpathians). *Geol. Zbor. Geol. carpath., 41, 475–502.*

# Litotektonické jednotky Západných Karpát: návrh jednoduchej metodiky na definovanie litotektonických jednotiek, aplikovateľnej pre orogénne pásma vo svete

Navrhnutá metodika definovania litotektonických jednotiek využíva princípy platňovej tektoniky. Litotektonické jednotky (LJ) definuje podľa ich príslušnosti k jednotlivým orogénnym fázam konkrétnych orogénnych (Wilsonových) cyklov. Na označovanie takto definovaných LJ sa používa indexovanie v tvare **XD**, kde premenná **X** označuje konkrétny orogénny cyklus a **D** má priradené číslo od 0 do 4 indikujúce orogénnu fázu daného cyklu. Navrhnutá metodika formou indexovania poskytuje o LJ komplexnú informáciu – prvé číslo indexu **D** označuje orogénnu fázu, keď daná LJ vznikla, a následné čísla či pridané celé indexy XD vyjadrujú celú následnú evolučnú históriu danej LJ. Indexy pre jednotlivé orogénne fázy v rámci jedného orogénneho cyklu znázorňuje obr. 2: **D0** – divergentné procesy riftogenézy, **D1** – konvergentné procesy subdukcie, obdukcie a kolízneho uzatvorenia pretiahnutého priestoru s oceánskou kôrou v osovej časti, **D2** – pokolízne termálne a deformačné procesy, odstrešovanie a vznik metamorfného dómu, **D3** – procesy vnútroplatňovej konsolidácie (vznik regionálnych strižných zón, transpresia, transtenzia a rotácia blokov) a **D4** – regionálna extenzia, ktorá môže kontinuálne pokračovať do fázy **D0** nového orogénneho cyklu. Tieto deformačné fázy môžu mať aj detailnejšie členenie – napr. D1a, D1b, D1c v zmysle exaktne doložených subfáz konkrétnej orogénnej fázy daného orogénneho cyklu v konkrétnom regióne. V článku sú navrhnuté skratky X pre všetky hlavné orogénne cykly v európskom priestore. Podobný systém indexovania je navrhnutý aj pre metamorfnú rekryštalizáciu hornín – indexy **MX0–2**, pričom je známe, že z piatich fáz orogénneho cyklu D0–4 je metamorfné pretvorenie regionálneho významu charakteristické len pre proces riftogenézy (D0), konvergencie (predovšetkým subdukčné procesy; D1) a pokolízne termálne procesy fázy D2. Indexovanie iných, napr. sedimentačných procesov nepovažujeme za účelné, keďže sú charakteristické pre každú orogénnu fázu, a teda ich indikácia je obsiahnutá v indexe XD.

Metodika bola testovaná v podmienkach Západných Karpát ako veľmi vhodného orogénneho pásma so symetrickou oblúkovitou stavbou (obr. 1), ktoré sa vyznačuje veľmi detailným poznaním orogénnych fáz troch orogénnych cyklov (variského, **V**; paleoalpínskeho, **Ap** a neoalpínskeho, **An**), a to vďaka intenzívnemu geologickému výskumu viacerých generácií erudovaných geológov. Článok poskytuje definované LJ v generálnej mierke 1 : 2 000 000 (obr. 3), ale aj v detailnej mierke 1 : 50 000, a to pre regióny gemerika, južného veporika a susediacich jednotiek (obr. 4).

Keďže platňovo-tektonické princípy tzv. *Intra-Pangea* typu platia pre orogénne pásma na všetkých kontinentoch, navrhnutá metodika je aplikovateľná pre geologické jednotky generované od proterozoika až po súčasnosť, a to aj mimo Slovenska či európskeho priestoru.

Doručené / Received: 26. 11. 2021
Prijaté na publikovanie / Accepted: 15. 12. 2021