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Neo-Alpine uplift and subsidence zones in the Western Carpathians: Product of kinematic activity on Cenozoic AnD3 (NW-SE and NE-SW) and AnD4 (E-W – subequatorial and N-S – submeridian) regional faults

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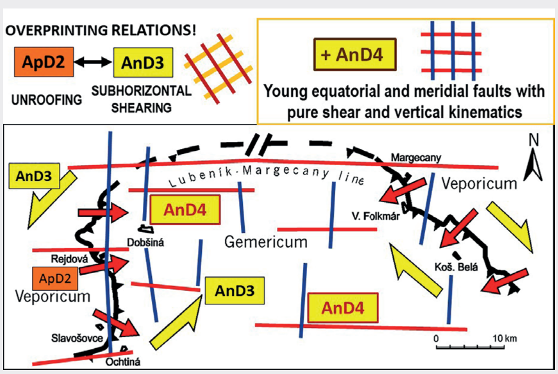
Abstract: Article presents the role of disjunctive (brittle and brittle-ductile) regional faults of two Cenozoic Neo-Alpine orogenic phases in the Western Carpathians: The AnD3 phase, producing conjugate systems of NW-SE (dominantly dextral shearing) as well as NE-SW (dominantly sinistral shearing), and younger AnD4 phase manifested with regional faults of subequatorial (E-W) and submeridian (N-S) courses (with dominantly uplift and subsidence kinematics). The disintegration of upper crust by kinematic activity on both (AnD3 and AnD4) fault systems produces the origin of block-shaped setting with lateral offsets, eventual rotation (in AnD3), as well as mutual uplifts or subsidences (in AnD4) of individual blocks. This tectonic setting represents the most striking morphological feature at the end of Cenozoic Neo-Alpine orogenic cycle, frequently overprinting or re-activating older tectonic structures.
Article provides an interpretation that parallel with the applied global stress field, the AnD4 subequatorial (E-W) and submeridian (N-S) coursing faults can originate also by merging of individual segments of synthetic (oriented N-S) and antithetic (oriented E-W) megashears between parallel AnD3 shear faults of both systems (NW-SE or NE-SW). Merging of individual segments of antithetic shears arranged naturally in one line creates a predisposition for the origin of equatorial (E-W) trending faults, while merging of synthetic segments produces meridian (N-S) trending faults, both being principal in later AnD4 phase.

Key words: XD labelling, AnD3 shear zones trending NW-SE and NE-SW, AnD4 regional faults of E-W (equatorial) and N-S (meridian) trend, overprinting relations, structural research, dilatometric research, Western Carpathians

Graphical abstract



Highlights

- Combined effect of activity on simple shear NW-SE and NE-SW trending faults (shear zones) of Cenozoic AnD3 phase and regional faults of subequatorial (E-W) and submeridian (N-S) courses of AnD4 phase produces the block-shaped disintegration of the territory of W. Carpathians with lateral offsets / uplift / subsidence of individual rock blocks, being reflected in morphology;
- There is indicated the role of equatorial and meridian trending faults in XD4 terminating phase of any orogenic cycle (expressed by the XD labelling method) for the new riftogenesis in $X^{+1}D0$ phase of new orogenic cycle.

Introduction

The youngest faults in the Western Carpathians, being the topic of this treatise, have dominant subequatorial and submeridian direction. Some cases demonstrate that they are (A) coeval with faults of conjugate NW-SE and NW-SW oriented fault systems, in other cases (B) the overprinting relations demonstrate that faults of diagonal conjugate systems are moderately older. Nevertheless, observer must still have in mind that besides geodynamic reasons for establishing / development / location of new fault(s) an important role is played also by structural predisposition – existence of older generation faults, thrust planes, old fold limbs, bed course discontinuities, etc.

To simplify the designation of relative time succession of origin of geological structures, but especially the origin

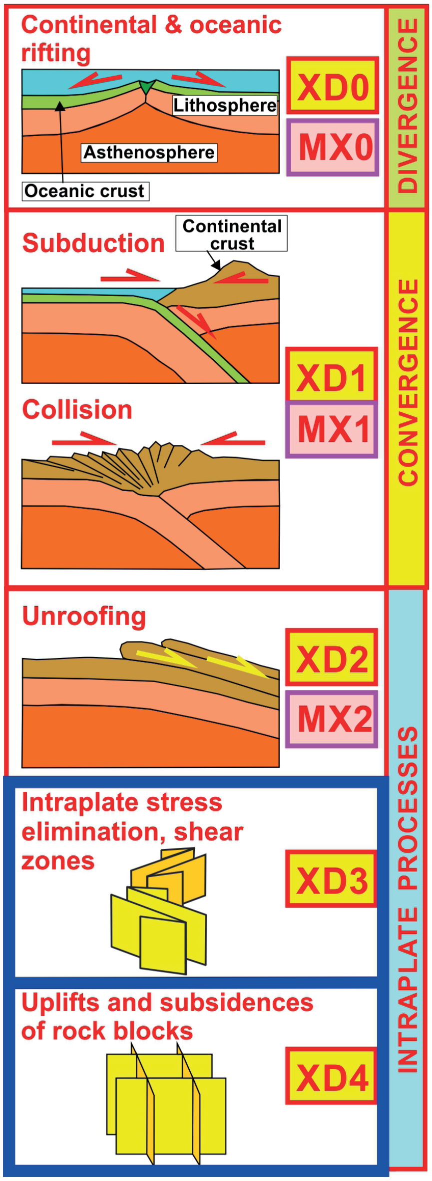


Fig. 1. The XD labeled sequence of orogenic phases within and orogenic cycle in upside down ordering. Blue rectangles highlight the youngest – Neo-Alpine AnD3 and AnD4 orogenic phases / geodynamic events with related lithotectonic units and generated structures in the Western Carpathins. Scheme is taken from Németh (2021; reproduced with permission).

of lithotectonic units, as the elements for any geological-geodynamic thoughts, a new concept of XD labelling was presently defined (Németh, 2021). This concept is based fully on plate tectonic principles of orogenic cycles and their orogenic phases (Fig. 1).

The methodology of XD labelling has universal application for present, but also past orogenic cycles world-wide. Each orogenic (Wilson) cycle – in the W. Carpathians they are dominantly Variscan (letter X is replaced by abbreviaton V), Paleo-Alpine (Ap) and Neo-Alpine (An) cycles, consisting of the same sequence of orogenic phases: XD0 – rifting (divergence), XD1 – convergence consisting of subduction (a), obduction (b), collision (c); XD2 – post-collisional overheating, active metamorphic core complex origin, uplift of collisional zone and related unroofing, XD3 – subhorizontal shearing and XD4 – subequatorial and submeridional faulting. The XD3 and XD4 phases represent the post-collisional stress adaptation / absorption within the crust. The genesis of XD3 and XD4 structures, their kinematics and products are the topic of this case study from the territory of Western Carpathians. In Fig. 1 they are highlighted by blue rectangles. The concept of XD labelling (l.c.) was defined in the Western Carpathians, representing symmetric moderately concave bended segment of the Alpine-Carpathian-Himalayan belt. Individual phases of three orogenic cycles are clearly visible here and were scientifically proved.

Within lithospheric plates, old cratonized regions, but also those regions, where the particular orogenic (Wilson) cycle is just terminated by levelling (peneplenization) of morphology, are built of fault bounded blocks, consisting of rock sequences / lithotectonic units. Owing to still acting stress field, the mutual displacement of individual blocks is represented either by lateral offsets and eventual rotation (dominantly in XD3), uplift or subsidence (dominantly in XD4) or their combination. Our present treatise aims to describe in time sequence the role of horizontal and vertical displacement along faults in the Western Carpathians as an example of polyorogenic belt within the Alpine-Carpathian-Himalayan zone. Despite, the primary driving forces for these displacements – the mantle convection currents and mantle plumes – are mentioned in this treatise only marginally, being a topic of our further publication (Németh, in print).

In polyorogenic terranes, consisting of a sequence of several orogenic (Wilson) cycles and their orogenic phases, the observer must give a special attention on ductile, brittle-ductile and brittle structural signs, indicating the evolution from higher grade to low grade tectonometamorphic overprints of relevant lithology, or generating these overprints / structures in still shallower crustal levels. Because present study deals with Neo-Alpine (Cenozoic) AnD3 and AnD4 shearing and faulting, it describes relatively "colder" structures, originating at brittle and brittle-ductile conditions and in relatively shallow crustal levels.

From the historical retrospective, the scientific dispute on the dominance of subvertical vs. subhorizontal movements in geodynamic processes has a long time tradition, in individual periods preferring either first or second alternative. The dominantly vertical kinematics was preferred by Neptunists with the main protagonist of A. G. Werner

(1749–1817) and parallel with Plutonists with A. L. Moro (1687–1764), but mainly J. Hutton (1726–1797) as the first protagonists. Vertical movements at mountain building and sedimentary basins development were principal in this first period of orogenic considerations. Nearly two centuries later, the global geodynamics started to account the subhorizontal displacements at mountain building, based on concept of continental drift, popularized by A. L. Wegener (1880–1930), though not generally accepted until the 1950s. The Wegener's concept of centrifugal forces as driving ones for the displacement of continents on the Earth's surface has failed, revealing their insufficiency for this (e.g. by P. S. Epstein, 1883–1966). The research during later period, based mainly on paleomagnetic results has contributed greatly to postulating a new concept of plate tectonics. Among tens of leading researchers, the important recognition deserves J. T. Wilson (1908–1993), contributing to concept of orogenic cycles, presently successfully explaining majority of geodynamic processes on the Earth. This short retrospective aims to highlight that the concept of each protagonist has its own justification and logic, based on that time available knowledge, observation results and data. Also the research of Western Carpathians has experienced a period with dominating vertical movements in interpretation of mountain building (orogenesis; XD4 in present day expression) and period with dominating nappe displacement kinematics (presently XD1bc). Despite, none of them has counted the role of subhorizontal displacements along shear zones (presently XD3). Hence – available parts of mosaic are building a time relevant concept, which still better describes the processes and their products in the real nature.

Used research methodology and state of present knowledge

Research consisted of (1) field geological mapping and study of affiliation of rock sequences / lithotectonic units to individual phases of orogenic cycles based on evolutionary criteria in the Western Carpathians. This article deals with the youngest – AnD3 and AnD4 phases of Cenozoic Neo-Alpine orogenic cycle, characteristic with brittle to brittle-ductile deformation, so the structural inventory of earlier Variscan and Paleo-Alpine cycles, as well as Neo-Alpine AnD12 phases are treated here only partially.

The research was accompanied with (2) structural / tectonic research, revealing the overprinting relations and displacement kinematics of individual rock sequences, rock blocks and *sensu lato* lithotectonic units. Regional scale geological mapping and tectonic research have benefitted also from (3) earlier regional geologic, tectonic and petrologic studies from the W. Carpathians published by numerous other referred researchers.

Registering overprinting relations at outcrop scale represents the most important part of structural research, aiming to clearly decipher the succession of the origin of individual structures (folds, reverse or normal faults, strike slip faults, etc.). Revealing and understanding this succession provides the principal information about geological / tectonic evolution of the region.

In this paper, the results of **recent** 3D **micro-move-ments monitoring on neotectonic AnD34 faults** using the TM-71 devices (Fig. 2; cf. Petro et al., 2004) are presented from two measuring sites – the Hodruša-Hámre (the All Saints' mine adit) and Ipeľ (Izabela adit; Fig. 8). The idea of creating a network of measuring stations on tectonic faults in Europe or in a global scale was created on the basis of the international project COST 625 *3-D monitoring of active tectonic structures* established at the beginning of 2000. Altogether 29 monitoring stations with 3D monitoring devices TM-71 were built on the territory of the Slovak Republic. They are currently under the scope of the EU TecNet project (Briestenský et al., 2018, a.o.), and 6 locations of them are managed by the State Geological Institute of Dionýz Štúr within the project Partial monitoring system of geological factors of the environment, Subsystem 02: Tectonic and seismic activity of the territory (Petro et al., 2022). Measurements have been carried out at some of these locations for more than two decades, which makes it possible to characterize dynamic phenomena on these monitored tectonic discontinuities with relatively high relevance.

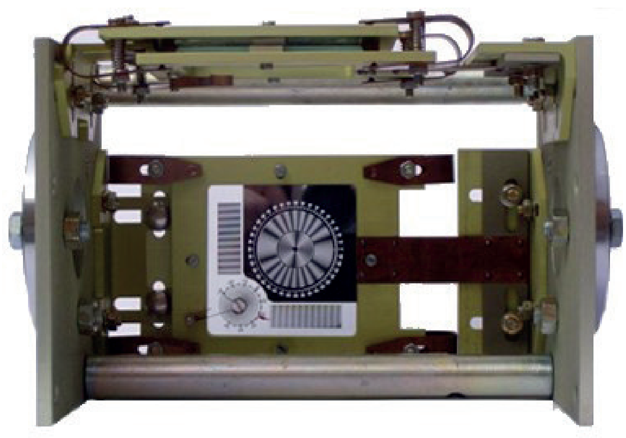


Fig. 2. Mechanical-optical dilatometer of TM-71 type.

The principle of the TM-71 dilatometer (Fig. 2) is based on optical-mechanical interference, i.e. the creation of moiré structures, visible between two glass tables with a special optical grid (Košťák, 1969). The shape of the moiré pattern has the character of a group of radially arranged stripes, the number and geometry of which corresponds to the mutual eccentric displacement of the plates with the optical gratings. The measured values are usually read manually (with the help of a digital camera), but currently, devices with an additional equipment for automatic scanning of optical grids, including a control unit and a data logger, are installed at several locations in the world.

The device can measure very slow displace-ments, i.e. ≤ 0.01 mm and rotation 0.01 gr. The measurements are carried out in two planes perpendicular to each other, so that the mutual spatial movement (3D) of both monitored blocks can be detected by calculations.

Brief description of geological and tectonic setting of the Western Carpathians

Arcued elongated orogenic belt of the Western Carpathians is a segment of Alpine-Carpathian-Himalayan zone. W. Carpathians are characteristic with dominant northern vergency of Alpine (Paleo-Alpine ApD and Neo-Alpine AnD) tectonic imbrication and nappe stacking (cf. Plašienka et al., 1997; Putiš et al., 2009, 2021, 2023), despite having incorporated also southern vergency tectonic structures of earlier Variscan (VD) evolution.

The division of the Western Carpathians to Outer, Central and Inner W. Carpathians, dominantly used in the past (e.g. Mahel', 1986), is presently simplified by division to Outer (External – EWECA)) and Inner (Internal – IWECA)) W. Carpathians (cf. Hók et al., 2019), better distinguishing units with dominant Neo-Alpine (Cenozoic) vs.

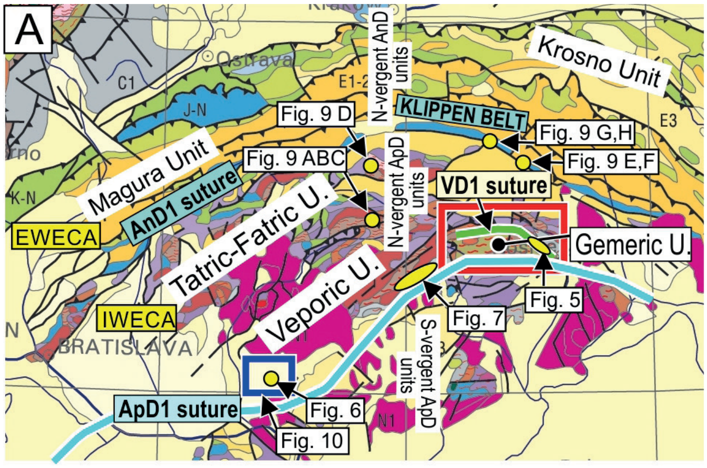


Fig. 3. General tectonic structure of Western Carpathians: A – emphasizing the role of three orogenic (Wilson) cycles producing a.o. three suture zones (Variscan – VD1 – marked light green, Paleo-Alpine – ApD1 – light blue and Neo-Alpine – AnD1 – dark blue), and B – extreme number of disjunctive structures contributing to present block setting with several levels of uplifts and subsidences. Part B highlights only the AnD34 structures – AnD3 NW-SE trending dominantly dextral faults (visualized with dark brown colour), NE-SW dominantly sinistral faults (orange colour) and the youngest AnD4 E-W trending faults (blue colour). and N-S trending faults (blue colour). AnD4 faults manifest mainly pure shear kinematics and contribute to uplifts and subsidences in combination with earlier AnD3 faults contributing by simple shear type transpression and transtension. The way how conjugate NW-SE and NE-SW faults can contribute to origin of E-W and N-S faults, in numerous cases representing joint segments of synthetic and antitethic segments of faults of conjugate system, are explained in the text and pale yellow rectangle in Fig. 7. Basemap of A: Asch (ed., 2007) – IGME 5000, magnified segment of W. Carpahtians is reproduced with permission), basemap of B: Bezák (ed., 2004) – Tectonic map of Slovak Republic (slightly modified with highlighted AnD23 faults).

dominant Paleo-Alpine / Variscan (Mesozoic / Paleozoic) evolution. The dividing line between External and Internal W. Carpathians is formed by the Klippen Belt.

Internal Western Carpathian (IWECA) belt

The Paleo-Alpine setting consists of following main lithotectonic units with northern general vergency of thrusting and nappe displacement: *Tatric-Fatric*, *Veporic* and *Gemeric units* (all three represent so-called basement nappes), *Meliatic (Bôrka nappe)*, *Turnaic (Tornaic)* and *Silicic units* (representing the superficial nappes; cf. Fig. 3A). From the space between Tatric and Veporic units the *Fatric Unit (Krížna nappe) wa*s derived and from the space between *Veporic* and *Gemeric units* it was the *Hronic Unit (Choč nappe)*.

The Tatric Unit (*Tatricum*; probable equivalent of Lower Austroalpine Unit of the Eastern Alps) – crops out in the W. Carpathian core mountains and consists of Variscan medium to high-grade metamorphic rocks (schistose gneisses with sporadic HP metamorphics and granitoids). The primary cover of Tatricum starts with Upper Paleozoic / Lower Triassic clastics, being followed by Middle Triassic carbonates. The *Tatricum* represents the lowermost unit of Internal Carpathians. In present north-vergent ApD tectonic setting the Tatric tectonic underlier is represented by *Váhicum* as equivalent of southern *Penninicum*, and tectonic flat-lying nappe overlier by *Fatricum,* containing sedimentary sequences corresponding with that of Tatric cover.

The Veporic Unit (Veporicum), similarly like Tatric Unit, comprises of Variscan crystalline basement and Upper Paleozoic / Mesozoic cover. The Alpine evolution zone between Veporic and Gemeric units is interpreted to be the homeland of *Hronic Unit (Hronicum)* consisting of Carboniferous-Permian volcanosedimentary formations.

The *Gemeric Unit (Gemericum)* as the uppermost Paleo-Alpine ApD basement nappe, has well preserved Lower Paleozoic volcano-sedimentary sequences of Variscan VD0 riftogenous phase (cf. Grecula, 1982; Radvanec et al., 2017), as well as – in Northern-Gemeric rim – well preserved VD1 suture zone, including also HP and UHP blocks subducted and exhumed from Variscan subduction zone and VD1b exhumed / obducted southward on Variscan passive margin sequences (Radvanec & Németh, 2018). The Gemeric Upper Paleozoic / Mesozoic cover sequences are bearing superficial nappes of *Meliatic Unit (Meliaticum; Bôrka nappe)*, *Turnaic and Silicic units*.

External Western Carpathian (EWECA) belt

This belt is a product of Upper Cretaceous-Cenozoic Neo-Alpine AnD evolution. External Carpathian Flysch belt consists of Cenozoic rootless nappes thrust over the North-European platform. The flysch-like Mesozoic and Paleogene formations predominate. The *Magura group of nappes (Unit)* consists mainly of Paleogene flysch formations with prevailing sandstones. These are AnD1 thrust northward over the *Krosno Unit of Flysch Belt*, built of prevailing variegated claystones.

The Klippen Belt (Oravic Unit; cf. Hók et al., 2019, p. 39 ibid.; Fig. 3A). represented in pre-Neo-Alpine evolution the Czorsztyn ridge – hypothetical continental ribbon, separated from the European Platform on the north by oceanic domain of the Northern Penninicum (Magura Ocean) and from the Internal Western Carpathians by the oceanic domain of the Southern Penninicum (Váhicum; Plašienka, 2012; Plašienka & Soták, 2015).

Above described multiple nappe and thrust setting was overprinted by AnD34 shearing and faulting, being described in more details in present treatise.

Origin and role of AnD3 and AnD4 phases in present morphology of W. Carpathians

In the Western Carpathians the existence and role of conjugate system of shear zones of generally NE-SW "Western Carpathian direction" and NW-SE "Eastern Carpathian direction" (AnD3 in our present classification) was firstly discovered by Grecula et al. (1990; Fig. 4), owing to extended regional research in the Gemeric Unit (red colour rectangle in Fig. 3A). Referred research has implemented generally N-S trending profiles in mutual distance of 1 km with application of detail geophysical profiling and soil metallometry, including detail (scale 1 : 10 000) field geological mapping, so the offsets and partial rotation of individual rock belts, but also e.g. ore veins courses, were clearly observable. Even then it was clear mainly from morphology and map view that the youngest structures, usually segmenting the course of shear zones, are represented by N-S and E-W trending (AnD4) faults.

Detail of relations of Cenozoic Neo-Alpine AnD3 and AnD4 faults, overprinting older Variscan, or even Paleo-Alpne setting are shown in Fig. 5, being focused on Eastern Gemeric course of Variscan suture zone in the area of Košická Belá and Vyšný Klátov municipalities. It is generally valid that NW-SE trending AnD3 faults are preferable developed on older VD12 and ApD12 discontinuities (former reverse and normal faults). The NE-SW trending AnD3 faults are characterized by the kinematics of transform faults, originating during the arc-bending transforming the original zonal setting. Both AnD3 systems are further cut by AnD4 submeridian and subequatorial faults.

The role of synthetic and antithetic megashears between NW-SE and NE-SW trending shear faults for the origin of N-S and E-W trending faults in the territory of W. Carpatians was confirmed by Németh (2015, 2016) performing geological mapping and structural research

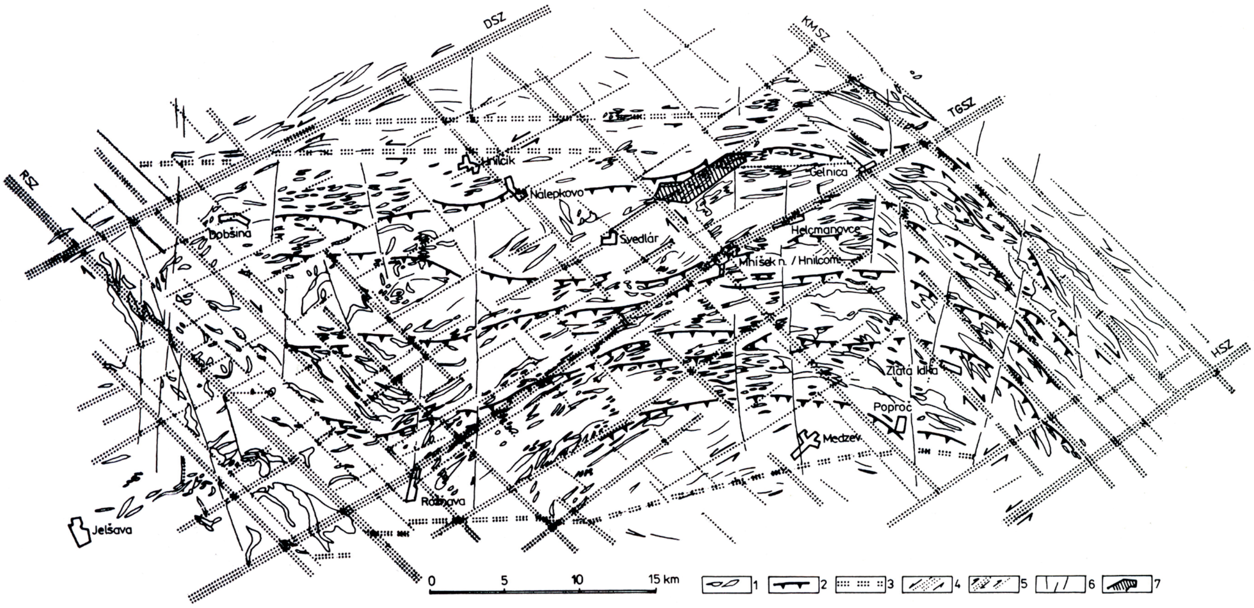
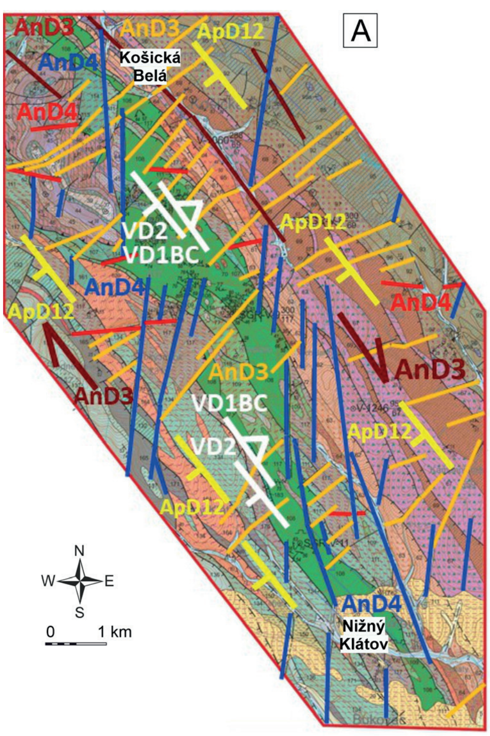


Fig. 4. Schematic visualization of shear zones of Gemericum (Grecula et al., 1990; published with permission), representing the milestone in understanding of the role of Cenozoic Alpine faulting in the territory of the Internal Western Carpathians. RSZ – the Rejdová shear zone, DSZ – the Dobšiná shear zone, KMSZ – the Košice-Margecany shear zone, TGSZ – the Transgemeric shear zone, HSZ – the Hodkovce shear zone; 1 – course of lithological units, 2 – Variscan nappes, 3 – Alpine rejuvenated Variscan(?) shear zanes, 4 – principal Alpine shear zones, 5 – shear zones of lower order, 6 – faults with a pure shear character (the youngest ones).



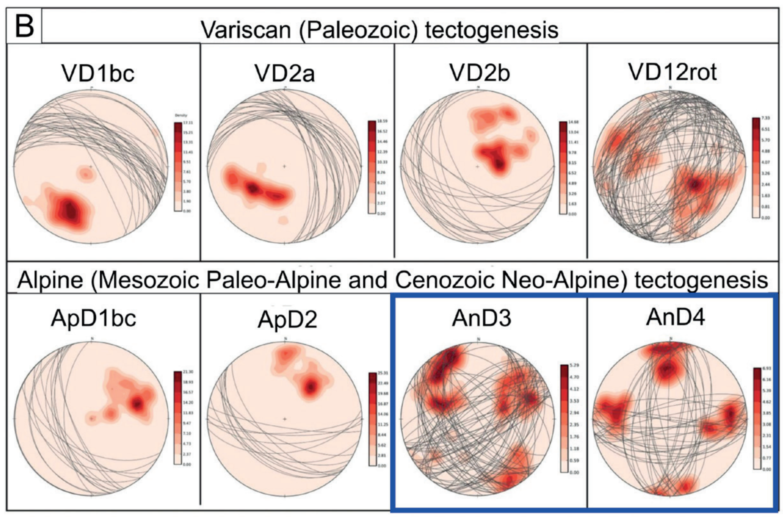


Fig. 5. General tectonic situation in eastern part of Variscan Rakovec suture between villages of Nižný Klátov and Košická Belá. with position and role of Cenozoic AnD34 discontinuities, partly copying older VD12 and ApD12 setting (by NW-SE trending AnD3) structures. Basemap by Grecula and Kobulský (eds., 2009; reproduced with permission), having added marks of structural research. B – Visualization of results of structural research in the region A by Németh et al. (2017). The blue rectangle shows orientation of young AnD3 and AnD4 planar structures, overprinting (cutting) older VD and ApD ones. Projection of planar structures in lower hemisphere.

Fig. 6. Revealed course and dip of AnD3 cleavage and joints (blue and red structural marks) and AnD4 joints (velvet and black marks, incl. young E-W trending fracturing in travertine mounds), distinguished by their overprinting relations, in outcrops at Dudince municipality, but also other localities in wider region around Dudince represent indications of importance of synthetic and antithetic megashears between simple shear faults of both – NW-SE and NE-SW directions – for the origin of E-W and N-S trending faults. These faults originate by merging of individual segments at their linear arrangement.

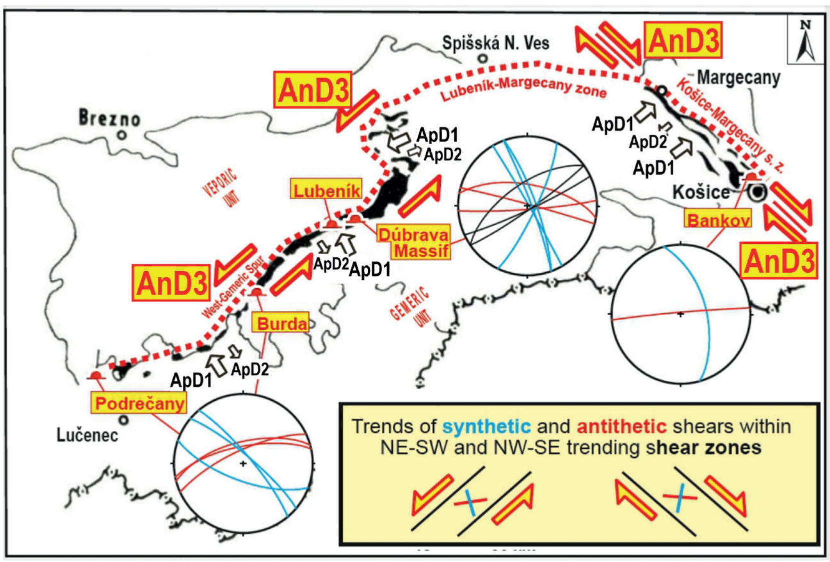


Fig. 7. Interpretation of the origin of AnD4 adits in caves present in magnesite bodies during late Alpine evolution (Németh in Gaál et al., 2017; reproduced with permission).

at the contact of eastern margin of Danube basin with Neogene volcanic area (Fig. 6; for location see dark blue rectangle in Fig. 3A). This kinematics was later confirmed by structural research attempting to explain the origin of caves in Upper Paleozoic magnesite bodies present along the contact zone of Gemeric and Veporic lithotectonic units and representing relatively rare phenomenon (Fig. 7).

Displacement along selected faults revealed by dilatometry

The comprehensive summary of results from all dilatometric monitoring sites, including the interpretation of results, is a topic of another paper (in preparation), so here we present dilatometric results from two sites only, located in southern part of Internal W. Carpathians (Fig. 8).

Izabela adit, Ipeľ (N 48°34'2.98"; N 19°42'59.76") – the place of installation of the device is in the Stolické vrchy Mts locality in the cadastral territory of the Ipeľský Potok village. The surrounding of monitored fault is built of Paleozoic metamorphic and igneous rocks, belonging to Veporic lithotectonic unit (LTU). The only device, installed on this site in 2002, is monitoring one of the most important fault systems of the Western Carpathians running through the Ipeľ river valley – the Muráň-Maľcovce

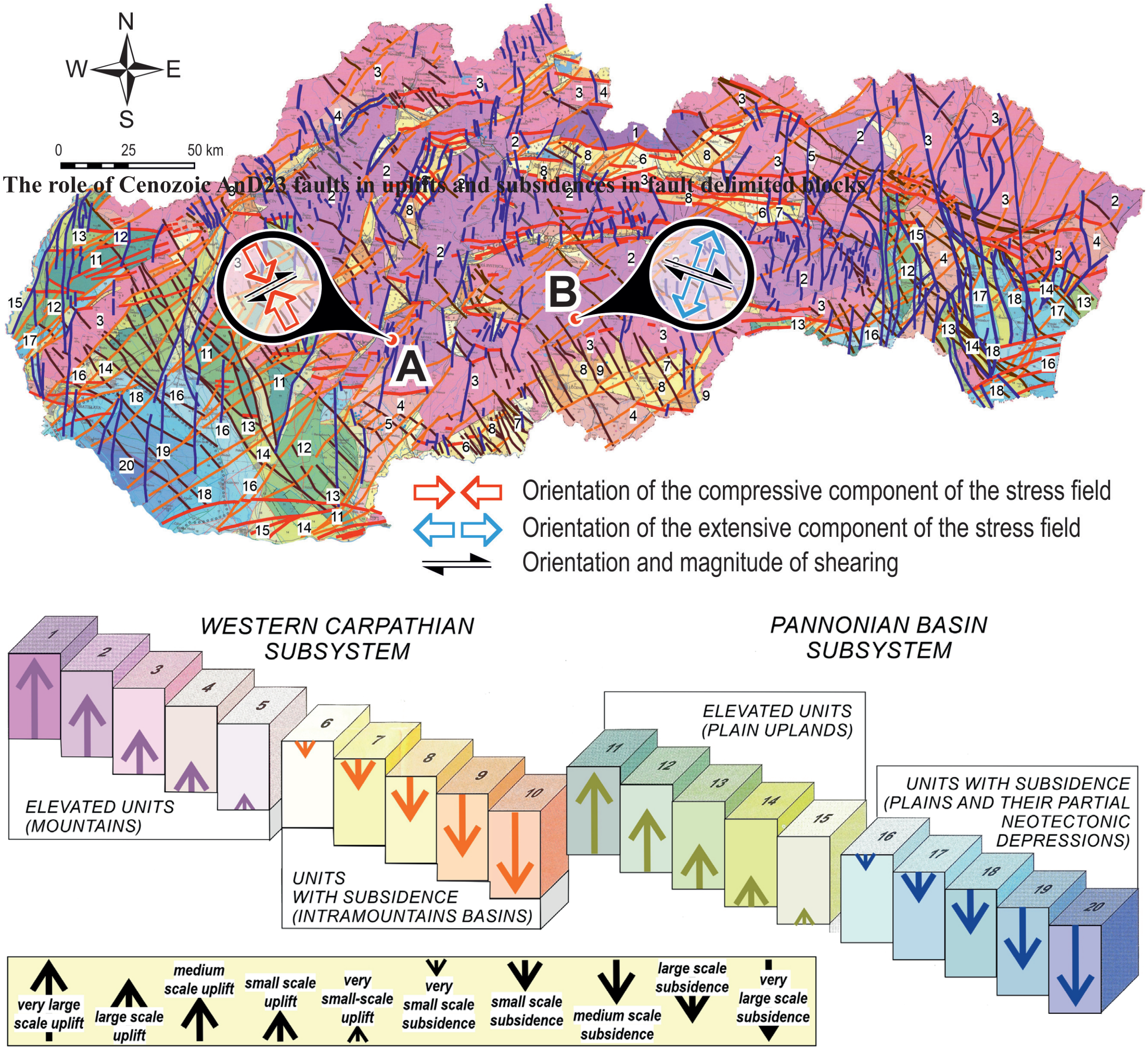


Fig. 8. Display of trends of long-term movements on tectonic faults in selected locations: A – the Hodruša-Hámre (the All Saints' mine adit), B - Ipeľ (Izabela adit) in the Western Carpathians with TM-71 installation. Base map indicates uplifts and subsidences of individual blocks during AnD34 phases, being visualized in diagram below the map. Both, Neotectonic map with slightly modified diagram are taken after Maglay (ed., 1999; reproduced with permission). Map highlights the courses of NW-SE, NE-SW, E-W and N-S trending faults (correspondingly with Fig. 3B.)

Fig. 9. Morphological examples of AnD4 N-S and E-W trending structures (several of many thousand). A–C – The Nízke Tatry (Low Tatra) Mts: A – Main ridge on both sides of the Chopok peak (2024 m a.s.l.); B – Subsidiary mountain ridges of Prašivá (1667) and Baňa (1859) peaks branching off from the main ridge and the Litvorova dolina valley between them; C – Rock cliffs of Pusté (1501) parallel with the main ridge; D – The Vysoké Tatry (High Tatra) Mts – Parallel N-S trending ridges of Klin (2176), Bystrá (2248) and Kriváň (2494) peaks; E–H – The East Slovakian segment of Klippen Belt represents prominent AnD3 reactivated NW-SE trending tectonic zone, being cut by numerous E-W trending faults forming elongated cliffs of this direction: E–F – "The Sleeping Monk" cliffs south of Kyjov village. Its general E-W course contradicts to NW-SE trending general course of Beskydok (730) ridge as a part of the Klippen Belt; G – Haligovské skaly cliffs and H – Aksamitova skala partial ridge; G–H – located to N and ENE of Haligovce village with tectonic situation corresponding to that described at photographs E–F. (Author of all photographs: Z. Németh.)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system (Pospíšil et al., 1986; Dvořák et al., 2005) with its southern part – the Muráň-Divín system, consisting of several parallel NE-SW faults (Pospíšil et al., 1989). In the monitoring period, the vertical component predominates (89 %) having decreasing character. The direction of the extensional component of the stress field is NE–SW. The minor horizontal component, representing only about 11 % of the total movement, has a dextral character, both altogether representing the steep dextral subsidence of north-eastern block.

Hodruša-Hámre (N 48°27'59.58"; N 18°49'26.49") – the TM-71 device was installed in 2005 in the All Saints mine adit, located in Štiavnické vrchy Mts within the Hodruša-Hámre village cadaster. The monitored tectonic structure penetrates the quartz-diorite porphyry of the middle part of stratovolcano. Even if the resulting long-term movement is only a tenth of millimeter, indicating minor dextral horizontal component of ENE-SWW direction. The vertical component is a moderate uplift at the NW-SE oriented compressional component of the stress field.

Discusion

The research of Cenozoic (Neo-Alpine) regional faults and shear zones in the Western Carpathians has more than forty years tradition. In the beginning, their kinematics and

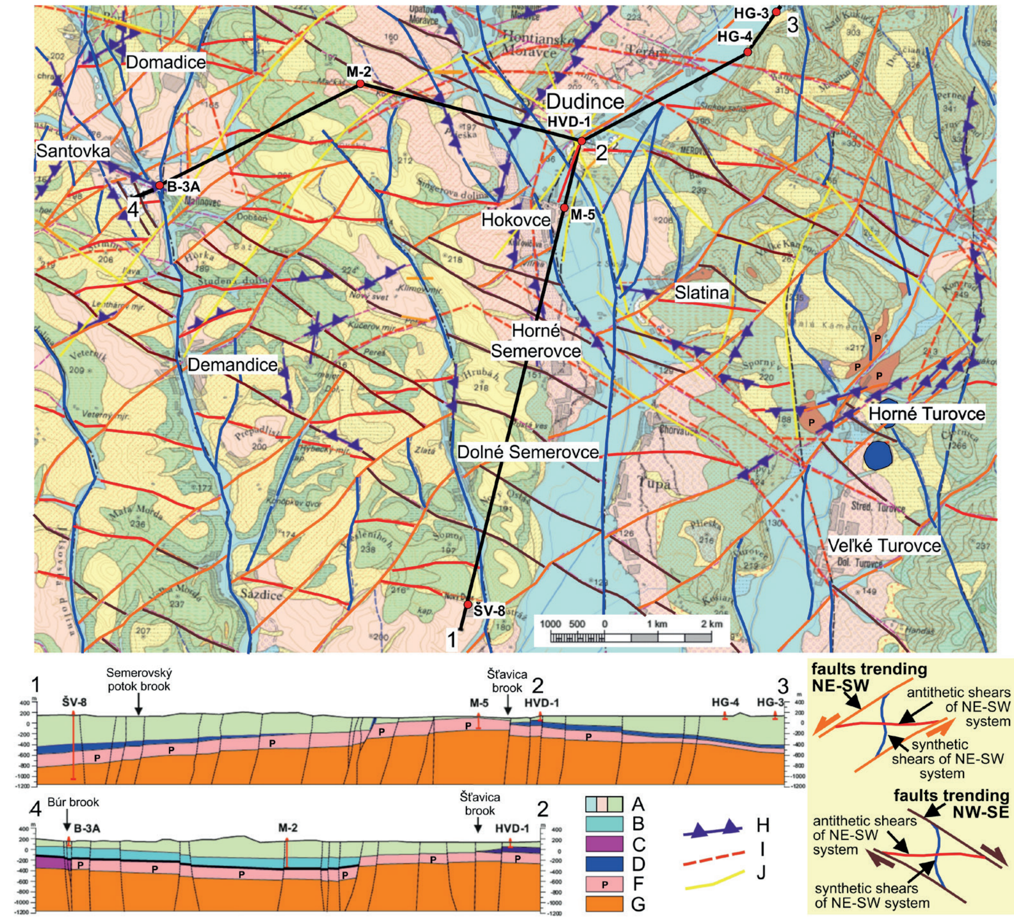

Fig. 10. Distribution of AnD3 and related AnD4 faults in the wider surrounding of Dudince municipality located in the southern part of Central Slovakia Neogene Volcanic Field. Base map by Konečný, ed., et al. (1998). Lithology: A – Quaternary and Neogene sequences undivided; Dominantly in cross-sections: B – Limestones and sediments of the Choč nappe undivided; C – Permian and Triassic cover of the Northern Veporicum; D – Quartzites and other rocks of Föderata Group undivided; E – Permian sequences of Revúca Group; D–E – cover of Southern Veporic zone; F – Lower Paleozoic basement rocks of Southern Veporicum undivided. Based on geological mapping, reambulation and structural research (Németh, 2017) there was revealed an extended net of faults of generally four directions: AnD3 faults with simple shear kinematics – system trending NE–SW (mainly sinistral shearing; coloured orange) and NW–SE (dextral; dark brown). Both systems have developed their own antithetic shears (generally E–W – subequatorial direction; red) and synthetic shears (generally N–S direction; blue) interconnecting individual faults. At linear position of several antithetic or synthetic fault segments and appropriate regional stress field, individual E–W or N–S segments can join, forming new (AnD4) regional faults trending E–W of N–S (visualization is in yellow rectangle right down). Course of individual fault systems was proved also by earlier geophysical research by Linsser method (H), weight boudaries (I) and gB geoelectrical methods (J; Šefara, 1976; Tkáčová, 1978 in Melioris et al., 1986).

overprinting relations were not fully clear. Owing to high degree of symmetricity of concave arc bending of the W. Carpathian belt, this region represented an ideal study area to find answers to the above-mentioned ambiguities.

Among first visualizations of a dense net of AnD3 and AnD4 faults in the W. Carpathians (expressed in present XD nomenclature) belong map of photolineations (Pospíšil et al., 1986; Fig. 1 ibid.) and sketch of conjugate system of shear zones trending generally NW–SE and NE–SW in the Gemeric region of Internal W. Carpathians by Grecula et al. (1990; Fig. 3 – copied in this paper). After these pioneering works, numerous high quality structural and tectonic researches have been focused on prominent W. Carpathian NE–SW trending shear faults of Alpine age, e.g.: Muráň fault (cf. Pospíšil et al., 1989; Marko, 1993; Gerátová et al., 2022), Pohorelá line (Hók & Vojtko, 2011), Carpathian Shear Corridor (Marko et al., 2017), but also regional faults trending NW–SE – Mýto-Tisovec fault (penetrating crystalline basement and Muráň plain; Marko & Vojtko, 2006), Pravno fault (in the Žiar Mts; Fekete et al., 2013).

The AnD4 uplift was documented mainly in zones trending subequatorial, e.g.: Vikartovce zone (Marko et al., 2010; Vojtko et al., 2011a, b), Kozie chrbty Mts and the western part of Hornád Depression (Sůkalová, 2011), Spišská Magura and Eastern Tatra Mts (Vojtko et al., 2010) and the Tatra Mts (Králiková et al., 2014).

Comprehensive studies about Cenozoic deformation and stress field, reflected also in genesis of AnD3 and AnD4 faults, were published by Kováč (2000), Kováč & Plašienka (2002) and Kováč et al. (2002), but also from the Orava region (Pešková et al., 2009) and the northern Laborec drainage basin (Vojtko et al., 2012).

Presently the topic of subequatorial and submeridian trending lineaments based on products of Neogene volcanism was highlighted by Bacsó (2023). It is long time accepted that faults trending N–S and E–W in prevailing cases cut older AnD3 faults (and all older structures as well) and therefore represent the youngest discontinuities, being by us classified as AnD4 generation of faults. Our present paper highlights again a special genetic concept explaining the origin of these faults in continental conditions (earlier presented in Gaál et al., 2017, and Bačová et al., 2017), interpreting that faults trending N–S and E–W can originate at appropriate nearly linear arrangements of fault segments oriented N–S and E–W – synthetic and antithetic shears among faults of AnD3 faults trending NW–SE and NE–SW, so faults of both genetic types are closely interconnected. Merging of fault segments of the same spatial orientation at an appropriate linear arrangement requires also appropriate orientation of the stress field. This topic is included in following treatise.

Within the orogenic cycles, the close interconnection of XD3 and XD4 intra-plate processes (as shown in the W. Carpathians – owing to genetic relations of AnD4 faults with AnD3 strike-slip faults), similarly as close interconnection of earlier XD0, XD1 and XD2 orogenic phases (rifting – subduction – collision – post-collisional unroofing, presented by XD labelling methodology in our earlier papers, e.g. Németh, 2021, 2024 – in print) show meaningfulness of the use of the principle of orogenic (Wilson) cycles at study and description of geologic (geodynamic, tectonic, metallogenic, etc.) processes.

Conclusion

This article deals with the youngest – AnD3 and AnD4 phases of Cenozoic Neo-Alpine orogenic cycle. The principles stated in this study are valid also for other orogenic cycles and other territories besides Western Carpathians, or even besides European continent.

Their role in terminating phase of orogenic cycle (XD4) and in originating new one ($X^{+1}D0$ phase) is indicated. The role and young ages of systems of N-S / E-W directed faults with dominating pure shear kinematics are explained owing to the high level of knowledge concerning the Cenozoic evolution of the Western Carpathians, encompassing the results of geological mapping, structural research, but also dilatometric registration of present faults microkinematics.

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Neoalpínske zóny výzdvihu a poklesu v Západných Karpatoch: produkt kinematickej aktivity na kenozoických regionálnych zlomoch smeru SZ – JV a SV – JZ v orogenetickej fáze AnD3 a mladších subekvatoriálnych (V – Z) a submeridiánnych (N – S) zlomoch v orogenetickej fáze AnD4

Článok opisuje vertikálne pohyby blokov hornín v dôsledku kinematickej aktivity na regionálnych zlomoch dvoch kenozoických neoalpínskych orogenetických fáz v Západných Karpatoch, AnD3 a AnD4 (v zmysle novej geodynamickej klasifikácie litotektonických jednotiek a tektonických štruktúr, tzv. XD indexovania; Németh, 2021; obr. 1). Počas orogenetickej fázy AnD3 boli generované hlavne zlomy párového systému strižných zón, a to dominantne pravostranné horizontálne posuvné zlomy smeru SZ – JV a ľavostranné horizontálne posuvné zlomy smeru SV – JZ. Následná orogenetická fáza AnD4, ktorá je v Západných Karpatoch najmladšia, sa prejavovala vznikom regionálnych zlomov subekvatoriálneho (V – Z) a submeridiánneho (S – J) smeru s dominantnou vertikálnou zložkou pohybu. Dezintegrácia vrchnej kôry kinematickou aktivitou uvedených (AnD3 a AnD4) zlomov vytvorila v západokarpatskej orogénnej zóne blokovú stavbu v závere neoalpínskeho orogenetického cyklu a jednotlivé bloky zaznamenali vzájomný výzdvihovo-poklesový charakter pohybu. Blokový výzdvih či pokles sa prejavil v morfológii územia a bol ďalej zvýrazňovaný vonkajšími geologickými činiteľmi [napr. ďalším zvýrazňovaním priebehu horských hrebeňov (obr. 10) či prehlbovaním údolí].

Článok interpretuje možný prvopočiatok genézy zlomov s priebehom v smere S – J a V – Z, charakteristických pre orogenetickú fázu AnD4. Kinematickou aktivitou strižných zón smeru SV – JZ a SZ – JV už počas orogenetickej fázy AnD3 sa posunmi v rámci týchto diagonálnych strižných zón začali generovať tzv. syntetické a antitetické strihy medzi paralelnými zlomami. V oboch prípadoch – v prípade systému smeru SV – JZ aj smeru SZ – JV – mali syntetické strihy generálnu orientáciu v smere S – J a antitetické strihy generálnu orientáciu v smere V – Z. V prípade tektonicky veľmi exponovaného územia vznikala v orogenetickej fáze AnD3 vysoká hustota syntetických a antitetických strihov – segmentov budúcich zlomov. Ak sa takého segmenty vytvorili v línii, reprezentovali oslabenú zónu, z ktorej sa následne v orogenetickej fáze AnD4 vygenerovali kontinuálne zlomy s priebehom v smere S – J alebo V – Z. Vzájomné priestorové vzťahy zlomov párového systému AnD3 a orientácie súvisiacich syntetických a antitetických strihov zobrazuje diagram v pravej dolnej časti obr. 7.

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