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Extensional structures in the Outer Ukrainian Carpathians (case of field study of the Menilite Formation in the frontal part of the Skyba Nappe at the Verkhnye Synyovydne village)

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Структури розтягу у Зовнішніх Українських Карпатах (на прикладі польового дослідження менілітової світи у фронтальній частині Скибового покриву у селищі Верхнє Синьовидне)

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Ключові слова: Зовнішні Карпати, менілітова світа, структура розтягу, скидовий розлом, поле напружень.

The article represents results field study of mainly extensional structures including faults and associated folds within well-known outcrop of the Oligocene Menilite Formation located in frontal part of the Outer Carpathians (Skyba Nappe) near the village of Verkhnie Synyovydne. Most of studied faults are of normal type, and thrust faults are also observed. The latter ones are associated with drag folds and stack-like compression duplexes. The normal faults are mainly of listric-type ones and represented by zones of brittle breccias. The kinematics of normal faults is recorded by flexural-like drag folds and near-vertical striations on the slicken-sides. Based on a set of tectonic mirrors, we reconstructed an extension steress field, with a horizontal axis of maximum extension σ3 across strike of the Skyba Nappe. Intermediate axis σ2 of the reconstructed stress field is also horizontal and directed along the Skyba nappe, and its value is close to the maximum extension σ3. Vertical striations on the tectonic mirrors overlap horizontal striation and are clearly the youngest.

Normal faults are interpreted as reflecting the most latest extensional stage developed during the rapid growth of the orogen. The extensional stage could be caused by the detachment of the heavy oceanic slab from the lighter platformian continental crust partly subducted under the Outer Carpathians, which led to isostatic uplift of the orogen and so-called 'orogen collapse'. In addition, normal faults in the flysch allochthone could be formed as a consequence of the direct influence of normal faults fixed in the Carpathian autochthone platformian basement.

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Introduction

The Outer (Flysch) Carpathians are usually considered as a fold-and-thrust belt, which was formed under compressional forces as a result of significant reduction of the initial flysch sedimentary basin substrate (Oszczypko, 2006; Gagala et al., 2012; Kováč et al., 2016; Nakapeliuch et al., 2018; Golonka et al., 2021; Roger et al., 2023 and references therein). In the Ukrainian Carpathians, the main regional structures traditionally studied by field mapping survey are nappes and thrusts (Shakin, 1976; Kruhlov, 1986; Matskiv et al., 2003, 2009; Kruhlov, Hursky, 2007; Matskiv, 2009).

In addition to compressional structures, structural-kinematic studies have recorded extensional deformations within the Skyba and Boryslav-Pokuttya frontal nappes of the Outer Carpathians (Vikhot, Bubnyak, 2011; Bubnyak et al., 2013; Gintov et al., 2014; Murovska et al., 2019). It was also noted that the Boryslav-Pokuttya Nappe is characterized by the presence of a large number of transverse strike-slip and normal faults (Kruhlov, 1986).

According to geophysical and well data, the large normal and strike-slip faults have been recorded on the East/West European platform submerged under the Carpathian thrust-and-fold belt (Kruhlov, 1986; Kolodiy, 2004; Zayats, 2013): see also sections to the geological map of the Ukrainian Carpathians (Shakin, 1976).

Large-scale synorogenic extensions were recorded in the hinterland of the Ukrainian Outer Carpathians in the Transcarpathian Neogene Basin originated on the Alcapa/Tisza-Dacia terranes (Matskiv et al., 2003, 2009; Matskiv, 2009; Prykhodko, Ponomareva, 2018; Murovskaya et al., 2023, 2025).

A system of normal faults shaping geomorphology is recorded in the Polish Western Carpathians (Jankowski, Margielewski, 2014). These normal faults are depicted on some geological maps (e.g. Jankowski, 2021). Researchers note, that the normal fault system could have formed during strike-slip movements and, especially, during the extensional stage (gravitational collapse) after the compressional stage of the Carpathian evolution (Jankowski, Margielewski, 2014, 2021).

1. Geological setting of the study area and characteristics of the Menilite Formation

The Outer (Flysch) Carpathians are usually considered as an accretionary wedge that grew in front of the Alcapa and Tisza-Dacia terranes now located in particular in the Central Western and Central Eastern Carpathian respectively (Fig. 1). The Outer Carpathians are thrust over the Neogene Carpathian Foredeep, which in places is divided into the inner deformed part (the Sambir Nappe) and the outer part composed of almost undeformed Miocene molasse lying on the subsided margin of the adjacent European Platform. The Outer Carpathians in Ukraine are formed by tectonic nappes filled with deformed mainly Cretaceous-Miocene flysch and, partly, Neogene molasse. The flysch is represented by turbidites and similar deposits, and also contains (hemi)pelagic sediments. The outermost and lowermost tectonic units of the Outer Carpathians are the Skyba and Boryslav-Pokuttya nappes. The Skyba Nappe is formed by a number of tectonic thrust-sheets ('skybas') such as Berehova, Oriv, Skole, Parashka, Zelemyanka ones in the studied area (see Fig. 1) (Vialov et al., 1981; Matskiv et al., 2009; Hnylko et al., 2022 and references therein).

The Oligocene (in places also Lower Miocene) Menilite Formation is the part of the continuous Cretaceous-Miocene flysch succession of the Outer Carpathians (Vialov et al., 1988). Menilite Fm. is characterized by the presence of organic-riched black shales, which are considered as the main oil-generating strata of the Carpathians (Picha, Golonka, 2005; Sachsenhofer, Koltun, 2012).

The accumulation of the black organic-riched sediments in the remnant Carpathian Basin occurred as a result of the closure of the oceanic basin in the area of the future Alps at the Eocene-Oligocene boundary (due to collision of a fragment of Gondwana with Eurasia) and the closing of the oceanic strait between the World Ocean and the remnant Carpathian Basin. The latter one evolved into the segment of the Paratethys – a system of isolated and semi-isolated basins. As a result, the circulation of bottom oxygen-enriched currents significantly weakened or ceased, which led to a lack of oxygen at the bottom of the sedimentary basins and effective protection of organic matter from oxidation (Picha, Golonka, 2005; Kotarba et al., 2009; Kováč et al., 2016).

The studied outcrop is located on the steep right bank of the Opir River on the eastern outskirts of the village of Verkhnye Synyovydne (Lviv region). The rocky cliffs of this bank expose a continuous succession of Eocene and Oligocene deposits of the Oriv Skyba of the Skyba Nappe: thick-bedded sandstones of the Vyhoda Fm. (Lower-Middle Eocene), marl and olistostrome of the Popeli Fm. (Middle Eocene–Lower Oligocene), and dark-colored deposits of the Menilite Fm. (Oligocene) (Hnylko et al., 2022). The latter one are considered in this paper (see Fig. 1).

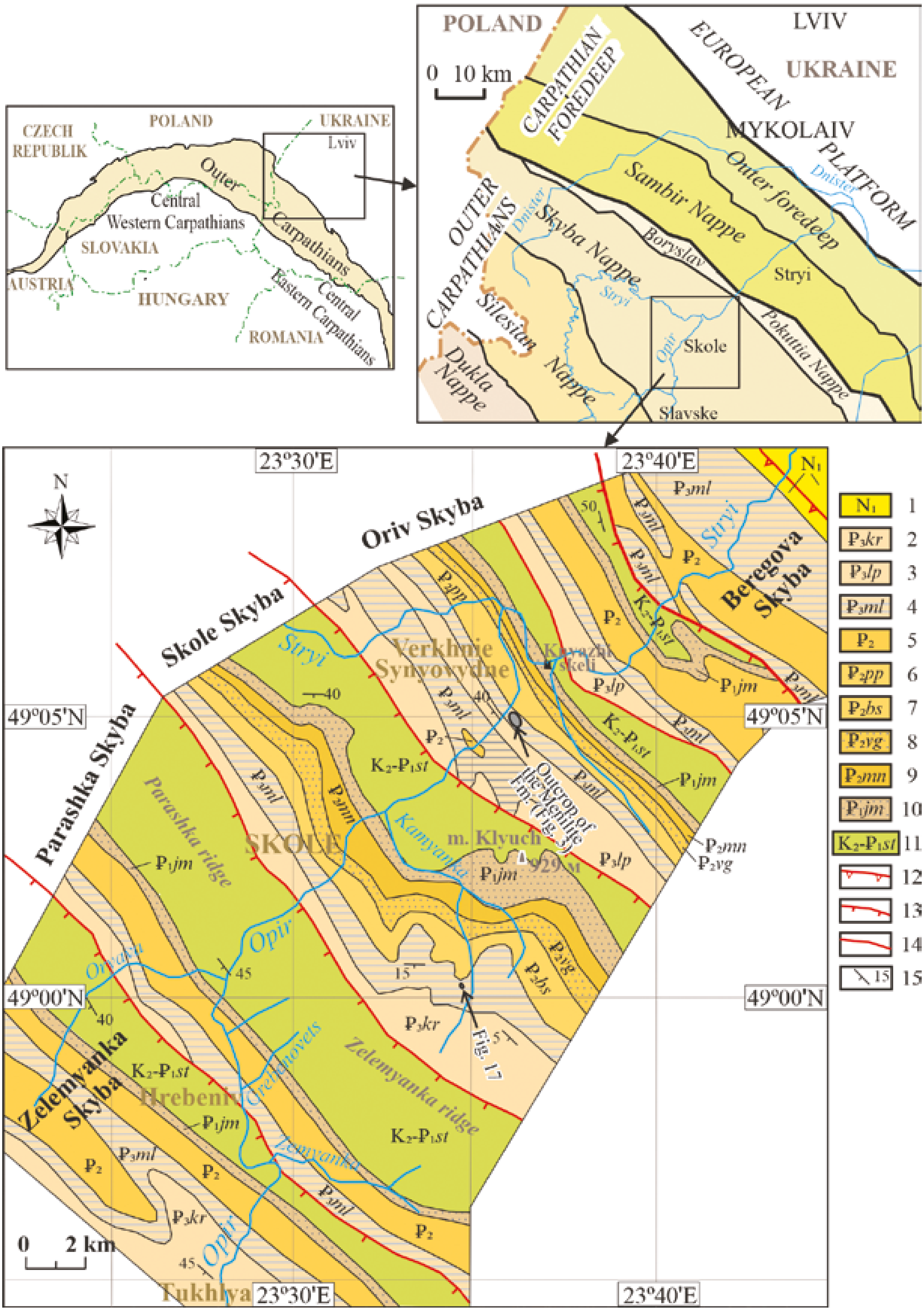

Fig. 1. Tectonic setting (top) and geological map (bottom) of the study area (vicinity of the villages of Verkhnye Synyovydne) with the location of the outcrop studied, map after (Hnylko et al., 2022); legend: *1* – Miocene molasse; *2* – Krosno Fm. (Oligocene): gray flysch; *3* – Lopyanets (middle Menilite) Fm. (Oligocene): gray flysch with black shales; *4* – Menilite Fm. (Oligocene): black shales, sandstones; *5* – undivided Eocene deposits: 'Hierogliphic Flysch'; *6* – Popeli Fm. (Eocene-Oligocene): marls, conglobreccias (debris flow deposits); *7* – Bystrytsia Fm. (Eocene): green flysch; *8* – Vyhoda Fm. (Eocene): sandstones; *9* – Manyava Fm. (Paleocene–Eocene): green and variegated flysch (with red and green shales); *10* – Yamna Fm. (Paleocene): sandstones; *11* – Stryi Fm. (Upper Cretaceous–Paleocene): gray flysch; *12* – frontal thrust of the Skyba Nappe; *13* – thrust of individual thrust-sheets(='skybas'); *14* – fault; *15* – bedding dip/Az

2. Method and data

In 2024–2025, geological and structural studies of the Oligocene Menilite Fm in the frontal part of the Skyba Nappe were conducted. Mesoscale deformation structures observed in outcrops were mesured and described – brittle faults and associated folds, in particular, drag folds and duplexes as kinematic indicators, according to (Fossen, 2016).

We applied the kinematic method and the Win-Tensor program (Delvaux, Sperner, 2003) to reconstruct palaeo stress based on a set of slickensides. The study of small faults with slickensides provides a reconstruction of the regular stress fields correlated with the geodynamics of the Ukrainian Carpathians (Murovskaya et al., 2025; Murovska et al., 2019; Hnylko et al., 2023).

In the tectonic interpretation of paleostress fields, we used the post-subduction extension model (Fig. 2) (Malavielle, 1993; Vänderhoeghe, Teysser, 2001), in accordance with the upper crust is stretched along listric faults including under its own weight. This gravitational collapse of the orogen is preceded by a collisional stage associated with compression and growth of the orogen.

3. Results

The studied outcrop of the Menilite Formation is located in a ledge (up to 15 m high) of an abandoned quarry, accessible by road from the suspension bridge over the Opir River near the Laboratory of Field Geological and Environmental Research of the Ivan Franko National University of Lviv (Fig. 3). The Menilite Formation is represented by thin rhythmic flysch – interbedded black and dark brown bituminous non-carbonate shale-like mudstones (15–20 cm thick) and thin (up to 5–15 cm) layers of light gray and gray polymictic fine-grained sandstones.

The bedding pattern of the strata is fairly consistent: sediments dip gently to the southwest. The overall monoclinal structure of the strata is complicated by faults and folds, with dip angles increasing significantly near the faults (see Fig. 3). The rocks are subject to both fault-related folding and brittle fracturing.

An important element of mesostructural paregenesis is tectonic foliation (cleavage) in the mudstone layers. The spatial orientation of tectonic foliation usually coincides with the orientation of the bedding. Boudinage and bending of sandstone layers, which are more competent than the bulk of the mudstone, are often observed. Competent sandstone layers and clasts vary in size and shape, sometimes having a lenticular shape. Sandstone buddins are separated by extensional and shear fractures, sometimes bounded by tectonic surfaces with slickensides. Slickensides are also observed on the bedding plane.

3.1. Description of deformation structures

The main faults within the outcrop are depicted in panoram (see Fig. 3). Each fault is marked by an observation site, and the northernmost fault is marked by two sites (1 and 2). All of the faults depicted in Fig. 3 are of normal type. However, thrust faults, which are generally parallel to bedding surfaces, were also observed in the outcrop. Let us first consider these latter structures.

3.1.1. Thrust faults are represented by thick (approximately 1–2 cm) zones of intensely foliated black argillites (more intensely than the surrounding formations). Brittle deformations (tectonic breccias) are not observed here. The foliation is located subparallel to the bedding planes, i.e. these are layered detachments (flat). Sometimes the detachments intersect the bedding at gentle angles (ramp), forming structures of the flat-ramp-flat type (Figs. 4, 5). These faults are associated with thrust-drag folds (see Fig. 5, left) and stack-shaped compression duplexes (see Fig. 5, right).

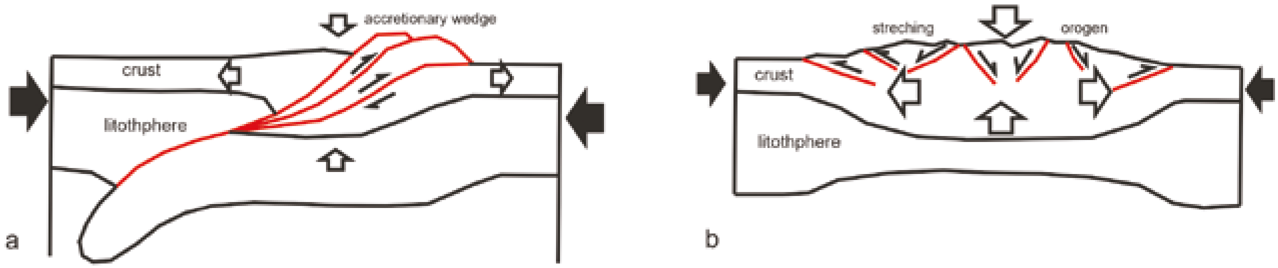

Fig. 2. Orogen evolution as an interplay of collisional compression forces (black arrows) and gravitational extension forces (light arrows): *a* – orogen formation due to subduction and collision; *b* – extension of a mature orogen due to gravity, slightly modified after (Malavielle, 1993; Vänderhoeghe, Teysser, 2001)

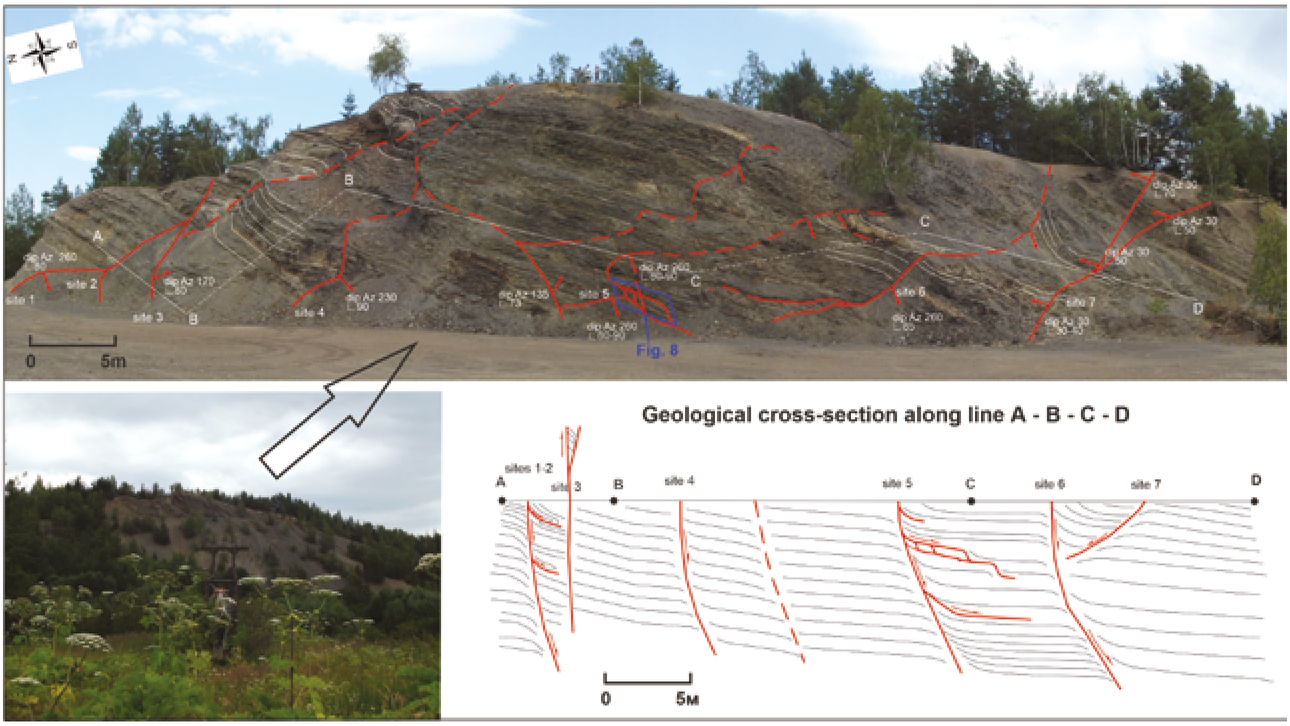

Fig. 3. Panorama of the outcrop: Menilite Fm. (Oligocene) in the ledge of an abandoned quarry on the eastern outskirts of Verkhnye Synyovydne village on the right bank of the Opir River, opposite the Laboratory of Field Geological and Ecological Research of the Ivan Franko National University of Lviv. Red lines indicate normal faults, and red arrows indicate dip Az of the faults (dip Az of the faults are also labeled next to these arrows) (top). Simplified geological cross-section of the outcrop along the solid white A–B–C–D line (bottom left); offset along the fault strikes are taken into account and indicated by the dashed white lines in the panorama

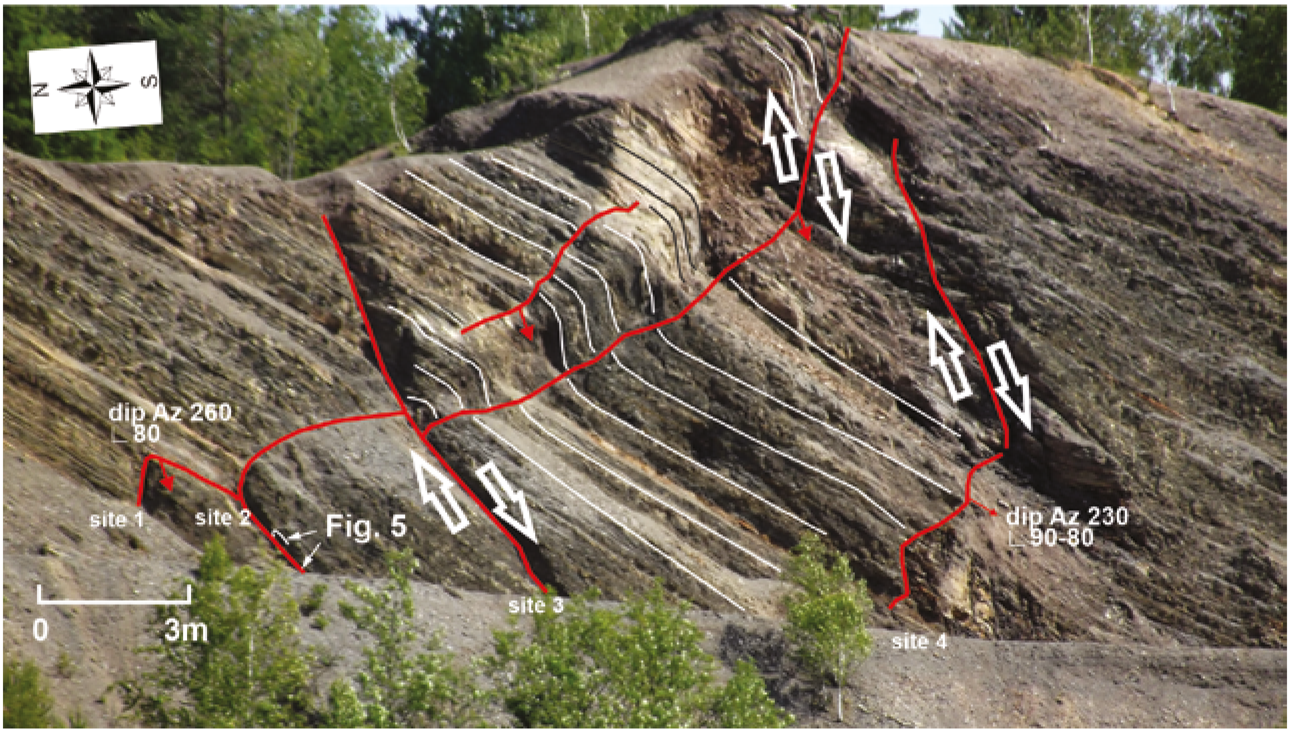

Fig. 4. The northernmost normal fault (and its associated flexure) extends from site 1 to site 2 and to the quarry hill summit. The flexural bend of the bedding represents drag fold, indicating normal type kinematics – subsidence of the southwestern hanging wall of the fault (here and below, subsidence of the hanging wall and uplift of the footwall is shown by large white arrow)

3.1.2. Normal faults shown in Fig. 3 are described sequentially at the observation sites recording these faults. Sites 1 and 2 are located on the northernmost fault, which can be traced from these sites to the top of the quarry hill (see Figs. 3, 4). The fault is represented by a zone 3–10 cm thick filled with brittle breccias

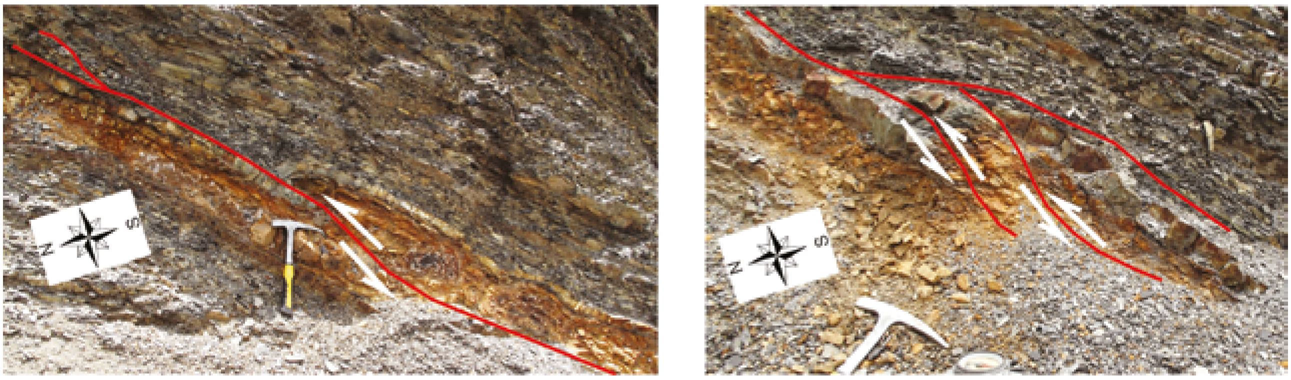

Fig. 5. Thrust fault and connected deformations: a near-thrust drag fold (left); stack-liked compression duplexes (right). The fault form flat-ramp-flat structures: flat segment follows bedding and ramp segment cutting the bedding at gentle angles. The fault is expressed by intensely cleaved narrow zones and is not accompanied by brittle deformation

(Fig. 6, left). The breccias are composed of black, brittle, crushed clayey rock with small inclusions of hard sandstone and siltstone clasts. The flexural bends of the sedimentary layers associated with the fault represent drag folds, indicating normal-type displacements – the subsidence of the southwestern hanging wall of the fault (see Figs. 4, 6). The fault is subvertical in its upper part and dips steeply (80°) at Az 260°. In Fig. 3, it is clear that its lower part becomes more gentle and follows bedding plane (Az. dip 220–230⁰, dip angles 30–40⁰). That is, this normal fault is of the listric shape (see Fig. 6).

Site 3 marks a subvertical normal fault (dip Az170⁰, dip angle 80⁰), offset of the hanging wall is indicated by bending and conformal fit of sedimentary layers to the fault surface (Fig. 7).

Site 4 is located on another fault (dip Az 230⁰, dip angle 80–90⁰) (see Fig. 3), expressed by a zone, up to 5–15 cm thick, of black brittle breccias – a crushed clay mass with inclusions of more rigid – sandstone clasts.

Site 5 represents a fragment of a normal fault (Figs. 3, 8), in which the fault planes coincide with the bedding (flat) and intersect it (ramp), delimiting individual tectonic lenses (horses), the accumulation of which forms extensional duplexes.

At sites 6 and 7, we observe two normal faults dipping toward each other, forming a graben-like structure (Figs. 3, 9). The faults are expressed by zones, 5–25 cm thick, of brittle tectonic breccias with black, crushed clay mass and inclusions of hard sandstone and siltstone clasts. Sometimes, as they approach crushing zones, the bedding angles of the rocks change dramatically – becoming significantly steeper, forming drag folds indicating subsidence of the axial portion of the graben-like structure (see Fig. 9)

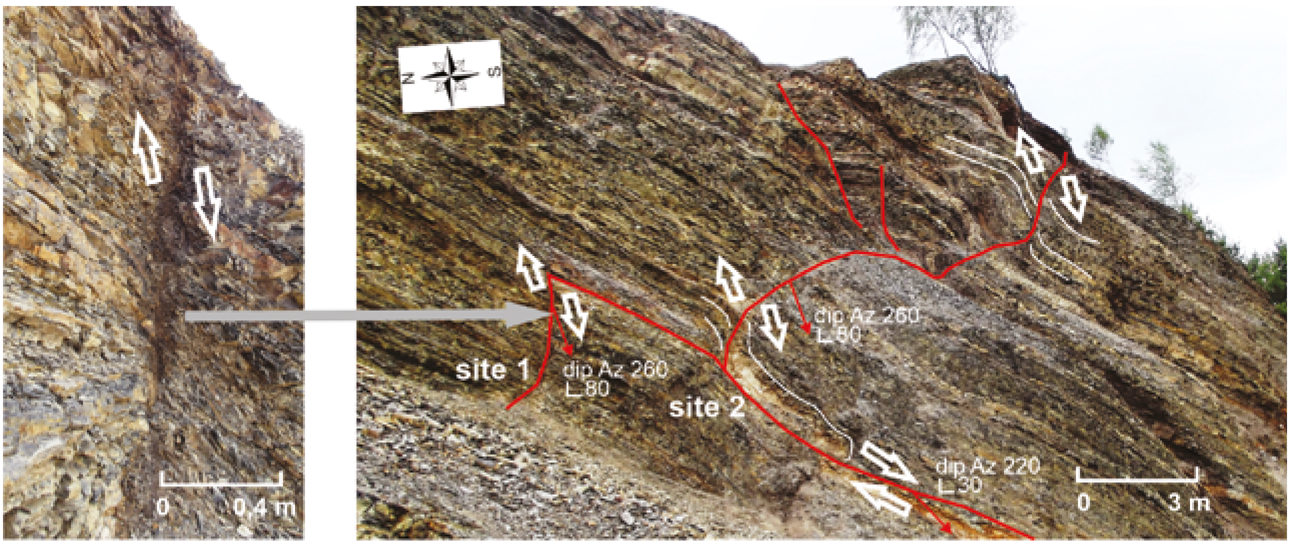

Fig. 6. The northernmost normal fault (sites 1 and 2 in Fig. 3) has a listric fault plane: the steep segment (dip angle 80°) changes downward to a gentle segment (dip angle 30°). White arrows indicate the movement of the hanging/foot walls, which is recorded by drag fold (the bending of layers in the fault zone is indikated by white lines)

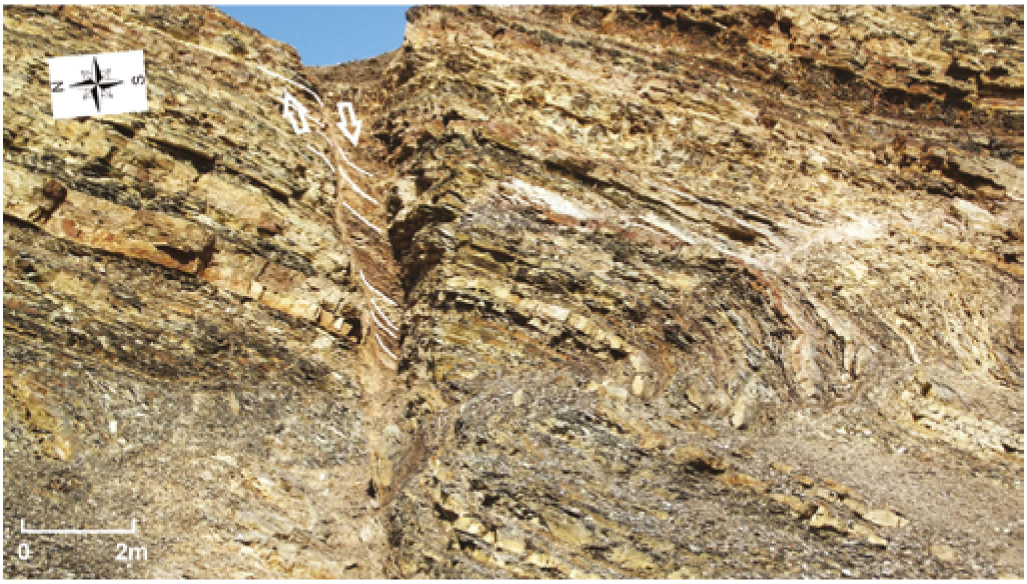

Fig. 7. Normal fault in site 3 (dip Az. 170° and dip angl 80°). Conform bedding adjacent to the fault indicates subsidence of the hanging wall (right)

Fig. 8. Fragment of normal fault zone (site 5). The fault planes coincide with the bedding (flat) and intersect it (ramp), forming a flat-ramp-flat pattern and creating extensional duplexes. The faults delimit individual tectonic lenses (horses), the accumulation of which forms the duplexes

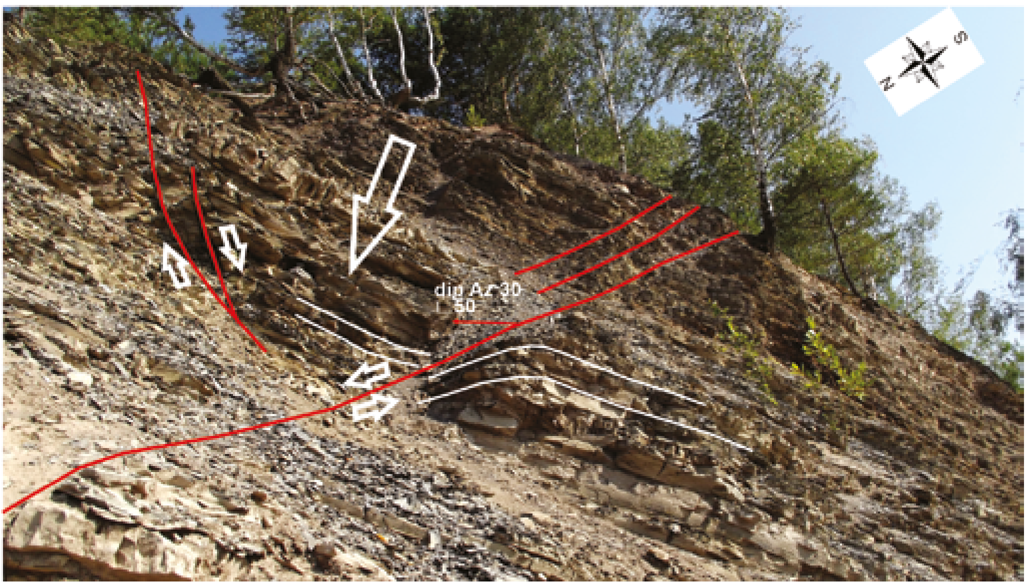

Fig. 9. Two normal faults (sites 6 and 7) dip toward each other and form a graben-like structure. Drag folds (bedding marked by white lines) indicate subsidence of the central part of the graben, as depicted by the large white arrow

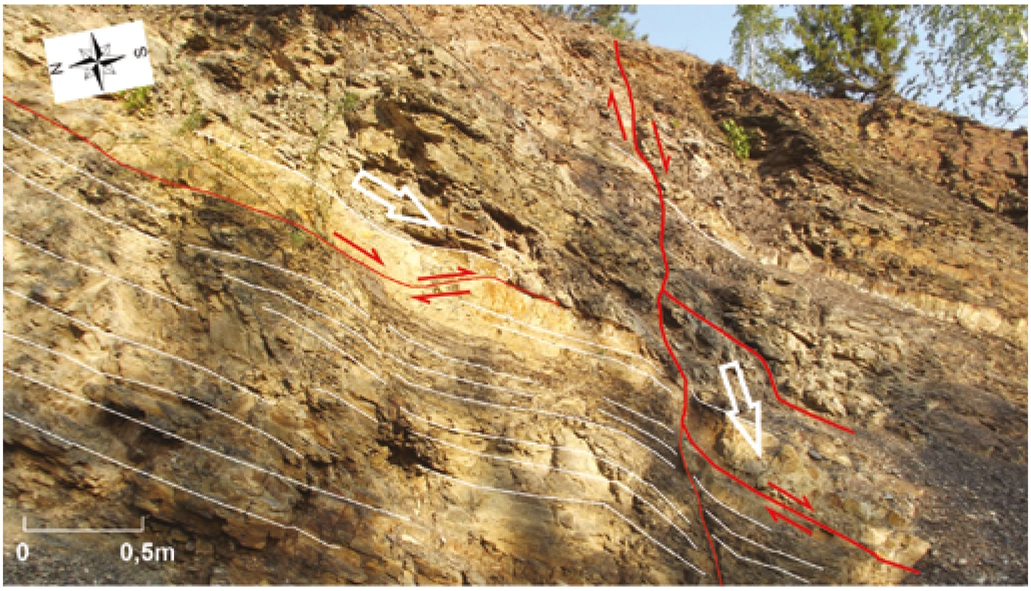

Fig. 10. Normal listric fault (site 8) is steep in its upper part, where it intersects the beds, and gentle in its lower part, where it follows the beds. White arrow indicates the of the hanging wall kinematics

Site 8 (Fig. 10) is located in the same abandoned quarry but beyond the outcrop shown in the panorama on Fig. 3, 50 m south of site 7. Here, in the steep quarry wall, the Menilite Fm. is also exposed, it is represented by thin- to medium-rhythmic flysch – interbedded black shale mudstones and gray sandstones and siltstones. The thickness of some sandstone beds reaches 0.2–0.4 m. The rocks in general, gently dip to the southwest; the monoclinal structure is disrupted by a number of small normal faults, steep in the upper part, where they intersect the sedimentary strata, and gentle in the lower part, where the faults follows bedding. That is, the normal faults are listric type. A thick (up to 0.4 m) sandstone layer broken by a normal fault records a small amplitude of this rupture – up to 0.4 m (see Fig. 10).

In the stady area, slickensides on normal fault planes are often present, on some of which tectonic striation clearly indicate the downthrown of the hanging wall and the normal kinematic (Fig. 11).

Fig. 11. Slickenside with striation (site 8) clearly indicates the subsidence of the hanging wall of the fault (white arrow), and are of normal type one

3.2. Pattern of the faults and bedding surfaces

All measured planes (bedding and tectonic mirrors) are presented as arcs on the lower hemisphere of the stereographic projection (Fig. 12), with the faults shown on the outcrop panorama (see Fig. 3) marked in red and with corresponding numbers.

The measured bedding planes dip southwest at angles of 15–25° in relatively undisturbed zones. Higher dip angles are observed near steep faults; the bedding planes increase in dip and change their strike from southwesterly (typically Carpathian) to approximately meridional. Thrust displacement along the bedding planes (dip angle 220°, dip angle 30°) along adjacent drag folds was also recorded (see Fig. 5).

We measured steep normal fault 1 (dip Az 260°) in sites 1 and 2, and faults parallel to it are also recorded in sites 5 and 6 (see Fig. 3). Two generations of slip grooves are present on the tectonic mirrors of this near N-S trending fault system. Subvertical slip grooves, indicating normal-type displacement, are predominate; they are sometimes superimposed on subhorizontal grooves of an older generation, indicating right-lateral displacement.

We measured steep normal fault 3 (dip Az 170°) in site 3 (see Fig. 3). Systems of steep, nearly vertical faults 1 (dip Az 260°, dip angle 80°–90°) and 3 (dip Az 170°, dip angles 80°–90°) are mutually orthogonal and may represent a conjugate shear pair.

In site 7 we measured a listric normal fault 7, dip Az 30°, the dip angles of which flattened out from 70° in the upper part of the outcrop to 30° in the lower part of the outcrop (site 7 in Fig. 3). The strike of the normal faults coincides with the strike of the

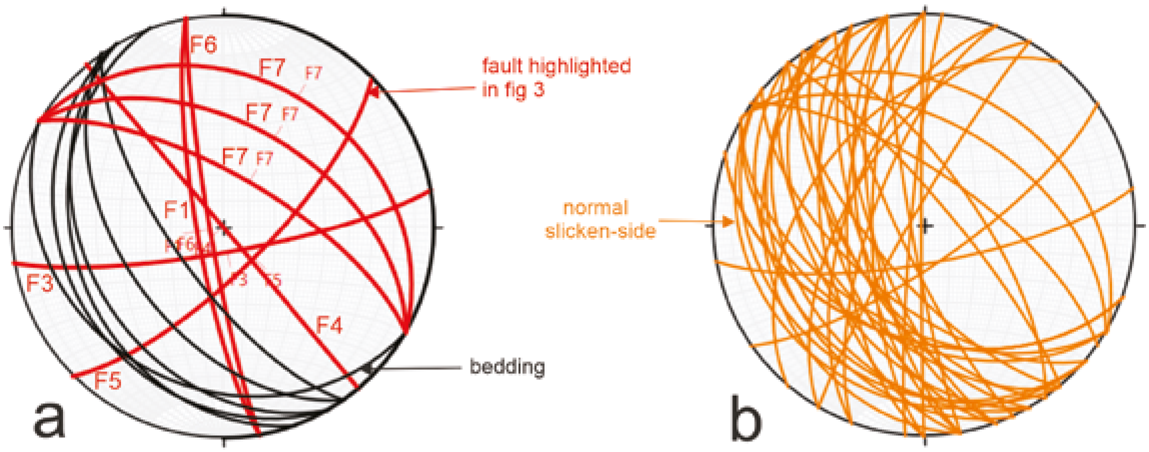

Fig. 12. Interplay between faults and bedding planes depicted on the lower hemisphere stereographic projection: a) faults (in red) are labeled as the corresponding sites on the outcrop panorama (see Fig. 3); bedding planes are in black; b) all measured slickensides of normal type

bedding, but the normal faults have the opposite northeast dipping. The normal fault system along surfaces 1, 3, and 7 (dip Az 260° dip angle 80° in site1; dip Az 170° dip angle 80° in site 3; and dip Az 30°, dip angle 30°–70° in site 7) were formed or activated under horisontal extension. see Fig 12.

3.3. Pattern of slickensides

Patterns of 41 slickensides and slickenlines are presented on the stereographic projection and diagrams (Figs. 13 and 14, respectively).

The tectonic mirrors with slickensides are trending in the azimuth of strike range of 300°–360° and have dip angles of 45°–80°. Their orientation corresponds to two main directions relative to the general strike of the Ukrainian Carpathians: longitudinal (strike Az 300°–330°) and diagonal (strike Az 350°–10°).

The striation orientations diagram reveals a main maximum in the 220–240° azimuth range, which is orthogonal to the strike of the Ukrainian Carpathian. Considering the normal-type kinematics on the longitudinal listric faults (sites 1, 2, 5, and 7), we can assume that the Carpathian orogen is streching in an orthogonal direction and is eroding due to gravitational processes.

3.4. Paleostress reconstruction

Based on the set of slickensides, we reconstructed paleostress fields of two types (Fig. 15).

The stress field of universal extension (see Fig. 15a) predominates by the number of corresponding slickensides (36 of 41), its axis of maximum extension σ3 trends across the Carpathian strike (white arrows in Fig. 15*a*) 13a and the compression axis σ1 is vertical. The extension along the intermediate axis σ2 (green arrows in Fig. 15*a*) approaches the maximum extension σ3 in absolute value, as evidenced by the the coefficient R = 0.008, so the reconstructed stress field can be considered as field of universal horizontal extension. The field of universal extension may be a superposition of longitudinal and transverse extension.

As our field study reveals, extensional deformation is the most recent and occurs along inherited planes formed during previous stages of deformation (strike-slip and thrust faults, bedding). Normal fault of listric shape combine inherited elements of different primary origins into a single surface (for example, the steep surfaces of former strike-slips and the more gentle bedding surfaces).

We obtained a second stress field on the set of five tectonic mirrors with strike-slip and overthrust slickensides. This field is characterized by horizontal σ1 and σ3 axes and can be classified as strike-slip faulting with a southwest-oriented compression axis (black arrows in Fig. 15*b*). As σ1 and σ3 axis are horizontal, the field implies stresses associated with strike-slip rather than compression (the situation is typical in fold-and-thrust belts and is referred as the σ2 paradox, see (Tavania et al., 2015). In the study area, this field corresponds to steep faults with strike-slip displacements and gentle thrust displacements along the bedding. The compression is older than the extension, so the corresponding horizontal slip grooves are obscured by younger normal fault grooves. The southwest-trending compression field is better expressed in folded deformations. It corresponds to a system of regional thrust faults with a northeast vergence and adjacent drag folds (see Fig. 1).

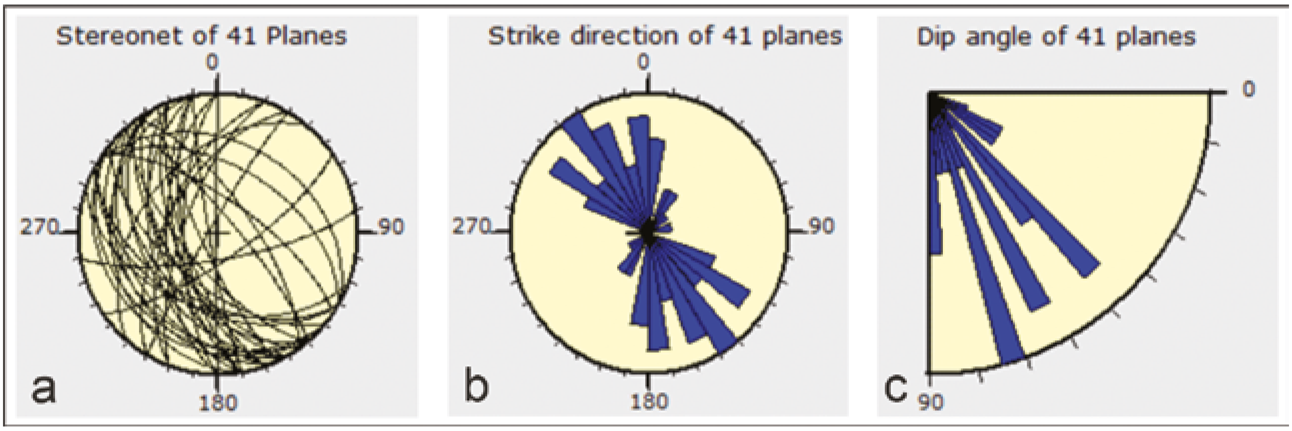

Fig. 13. Pattern of strike direction of 41 slickenside planes: *a* – the planes depicted as arcs on the lower hemisphere, *b* – strikes of the planes on the circular diagram, *c* – dip angles of the planes on the circular diagram

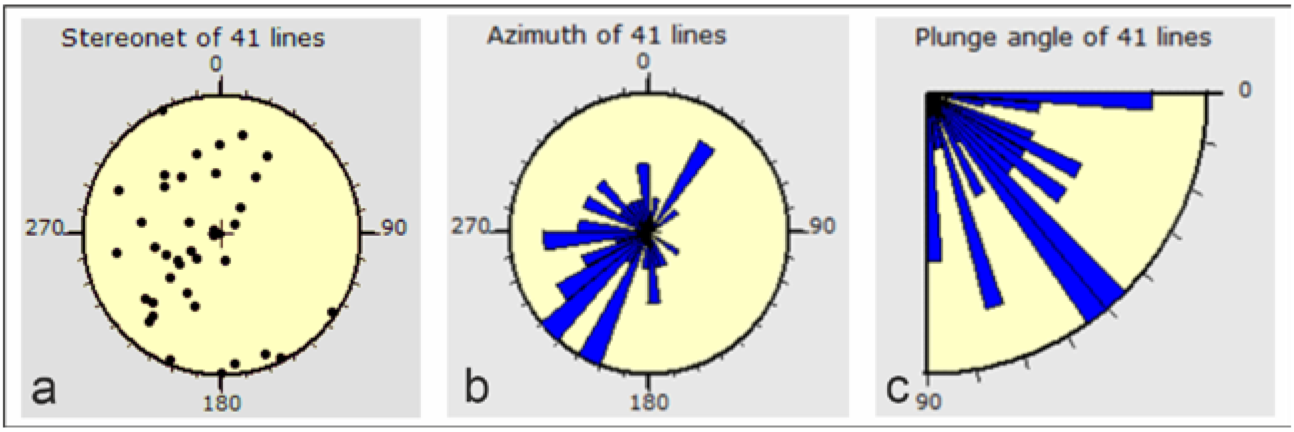

Fig. 14. Pattern of plunges of 41 strietion lines: *a)* emergence points of the lines on the lower hemisphere; *b)* circular diagram of the lines plunge Az azimuths; *c)* circular diagram of the lines plunge angles

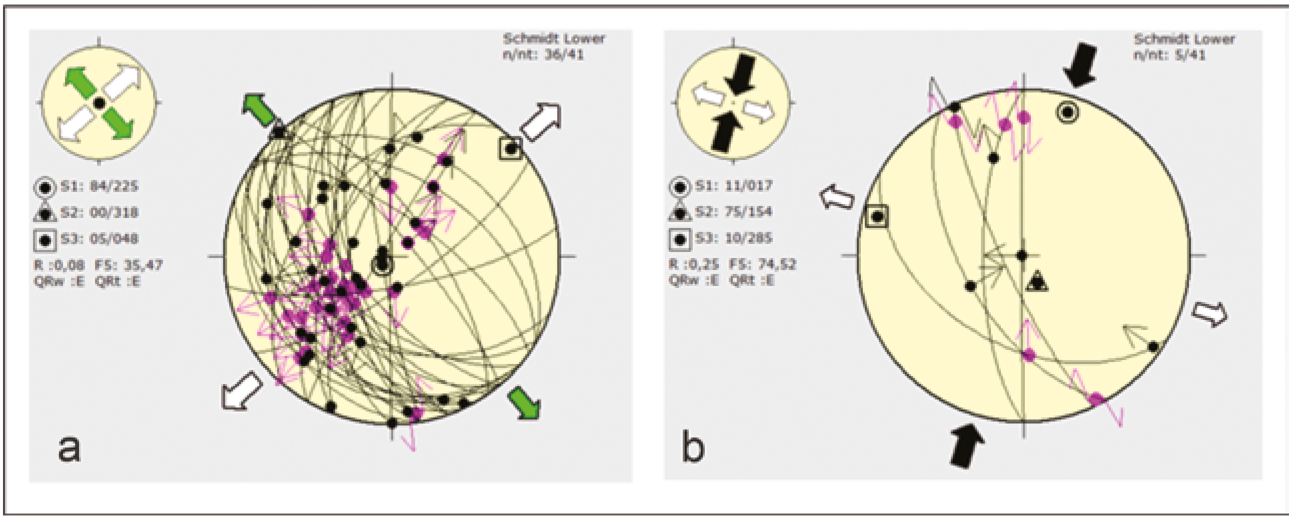

Fig. 15. Reconstruction of paleostress fields: *a)* universal extension based on a set of 36 tectonic mirrors; *b)* southwest-trending compression based on a set of 5 slickensides

4. Discussion

4.1. Normal faults in the autochthonous basement of Carpathian fold-and-thrust belt

Many of the world's most productive hydrocarbon systems are located in the forelands of fold-and-thrust belts. In the foreland of orogens worldwide, both longitudinal and transverse normal (i.e., extensional) faults are clearly visible in seismic images, see also review in (Matenco, Bertotti, 2000; Artoni et al., 2004; Artoni, 2013; Zayats, 2013; Tavani et al., 2015). Many fields, including hydrocarbon ones, are controlled by normal faults (Fossen, 2016; Starostenko et al., 2022).

In Ukraine, the largest known oil, gas condensate and gas deposits are discovered within the frontal part of the Carpathian orogen and the Foredeep Basin, which has stimulated intensive study by seismic exploration and deep drilling (Zayats, 2013; Kolodiy et al., 2004). On the European Platform, in the Carpathian Foreland and beneath the Ukrainian Carpathians, seismic surveys have recorded systems of along-strike and across-strike normal faults (Zayats, 2013). For example, on the reflection seismic profile P-2, the European Platform extends beneath the Carpathian allochthon along a system of normal faults in the basement, reaching a depth of approximately 14 km beneath its front (Fig. 16). The Forecarpathian normal fault displaces at 3-km the crystalline basement and the Neoproterozoic, Mesozoic, and Paleozoic complexes overlying it, as recorded by seismic exploration (Zayats, 2013).

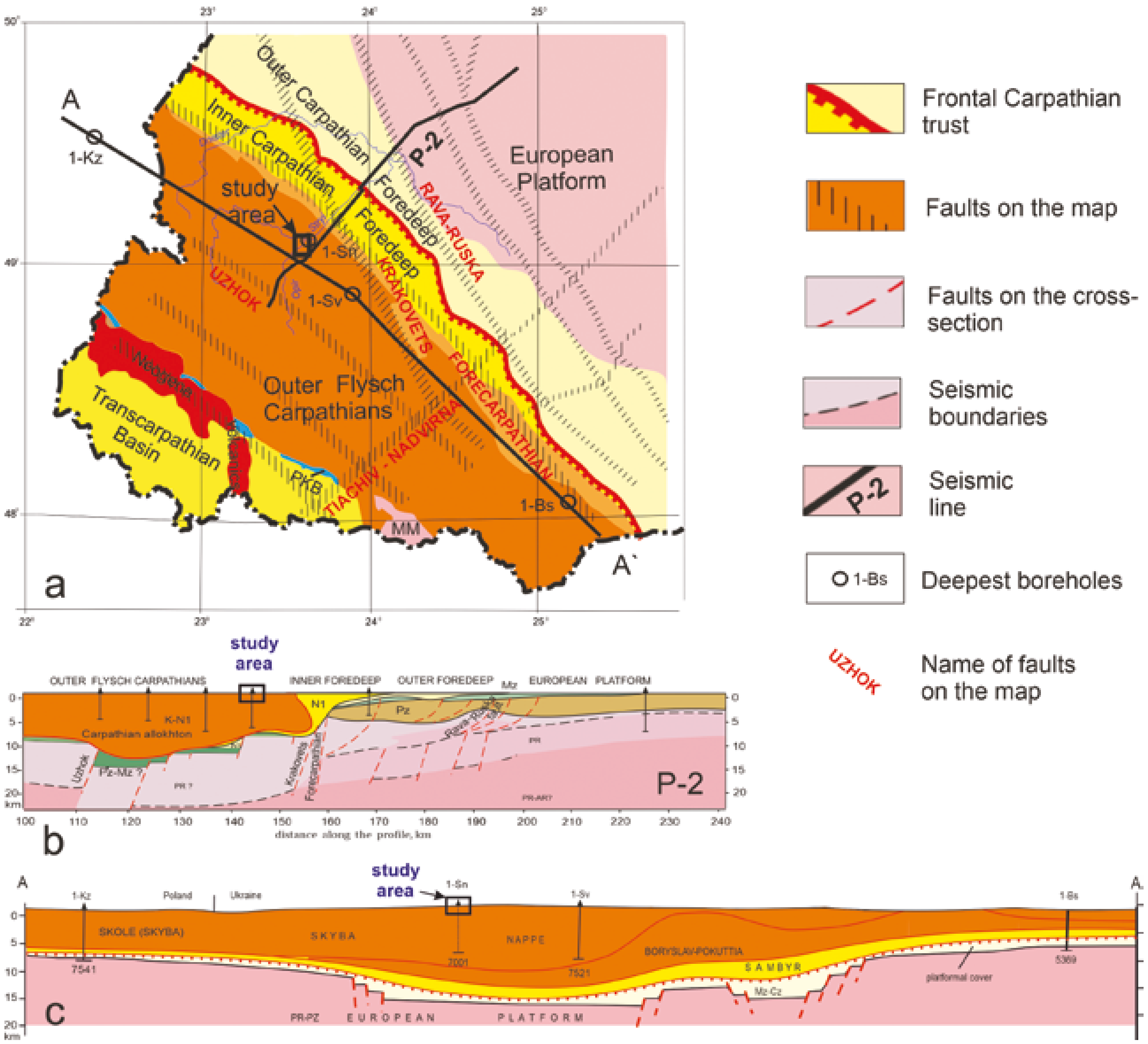

Fig. 16. Tectonic structure of the Ukrainian Carpathians: *a)* simplified tectonic scheme with deep faults including the faults in the European Platform partly overlapped by the Carpathian allochthon, after (Zayats, 2013); *b)* seismogeological cross-section along profile P-2, simplified after (Zayats, 2013); *c)* principal along-strike section of the Ukrainian Carpathians on line A-A` (Shlapinsky, 2012); the deepest wells: '1-Kz' – Kuzmina (Poland), '1-Sn' – Synyovydne, '1-Sv' – Shevchenkove, '1-Bs' – Biskiv

Orthogonal faults (normal and strike-slip) of the basement are suggested to separate segments of the European Platform beneath Ukrainian Carpathians with significantly different basement depths, as shown in the generalized cross-section through the frontal part of the Skyba Nappe, which passes through the deepest boreholes of the Ukrainian and Polish Carpathians (see Fig. 16c). The central segment of the Ukrainian Carpathians is characterized by the deepest occurrence of the autochthonous basement; boreholes deeper than 7 km (1-Synyovydne and 1-Shevchenkove) have not even penetrated the Skyba Nappe, and the depth of the basement is estimated at approximately 14 km based on seismic data. In the southeastern segment of the Carpathians (Pokuttya-Bukovyna), relatively shallow basement (4000–5000 m) were studied by boreholes 1-Sergii, 1-Biskiv, 3-Petrovets, and 3-4-Lopushna. In the Polish Carpathians, the deep borehole '1-Kz' – Kuzmina entered autochthonous deposits of the European Platform at a depth of approximately 7 km. Segments of the basement with different depths can be separated by normal faults (Shlapinsky, 2012; Zayats, 2013). The basement faults can affect the structure of the Carpathian allochthon, in places they cut through its deposits (Kolodiy, 2004).

The extensional structures in the Carpathian underthrusted autochthonous basement are explained by the weight of the Carpathian allochthon (accretionary wedge) and the (sub)oceanic lithosphere slab, which, during the Miocene, was subducted under its own weight into the lighter asthenosphere and pulled the continental crust (European Platform) into the subduction zone beneath the Carpathians (Royden, 1988; Roger et al., 2023 and references therein). As a result, the underthrust structures of the European Platform were extended, forming normal faults that could penetrate further into the flysch allochthon. This is one way how the normal faults of the final deformation stage described in the paper could have formed.

4.2. Timing of exhumation and extension

The normal faults in the studied outcrops (see Fig. 3) as well as in the surrounding areas of the Skyba Nappe are characterized by pronounced brittle ruptures – zones of tectonic breccias (Fig. 6, left; Fig. 17), indicating deformation occurred in a fully lithified state. At the same time, the observed thrust structures are expressed by zones of intensely sheared black argillite without brittle deformations (see Fig. 5). This may indicate that thrusting movements occurred in relatively plastic rocks (possibly at some depth and/or in incompletely lithified sediments). Furthermore, as already noted, horizontal slip grooves from the compressional stage are 'worn out' by normal fault movements. Thus, this confirms the view that normal faults clearly arose after the formation of thrust faults and record the later deformational stage of extension.

The tectonic evolution of the Polish-Ukrainian Carpathians was characterized by significant syn- to post-thrusting exhumation (Mazzoli et al., 2010; Andreucci et al., 2013). The results of low-temperature thermochronometry in Ukrainian Carpathians show burial maxima in the central units of the wedge (up to 6 km, after (Andreucci et al., 2014) and up to 5,5 km, after (Roger et al., 2023)). Exhumation occurred by means of a first rapid stage between ca. 12 and 5 Ma followed by a slower stage from ca. 5 Ma to the present. Timing and spatial pattern of exhumation are compatible with post-thrusting erosion enhanced by isostatic uplift (Andreucci et al., 2014).

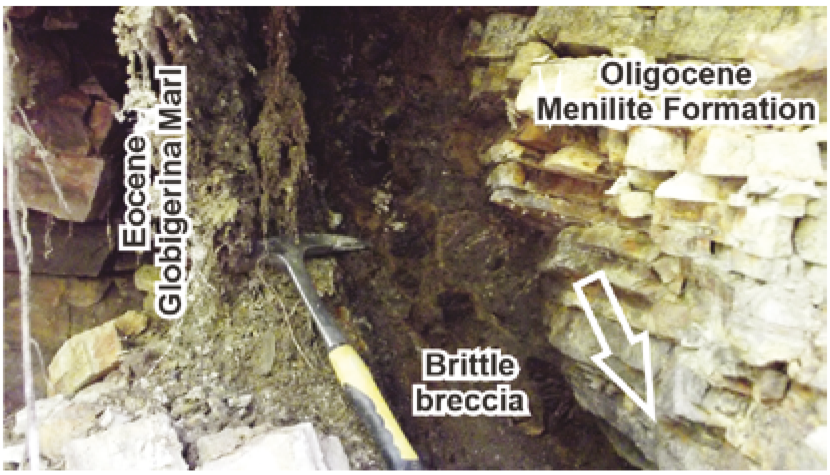

Fig. 17. Normal fault zone in the deposits of the Skole Skyba (Skyba Nappe). Eocene Globigerine Marl in the footwall and the Oligocene Menilite Formation in the hanging wall of the normal fault. The brittle deformation zone (tectonic breccias) of the strike-slip fault is visible. Kamyanka River, Lviv region near the city of Skole (see Fig. 3 for location)

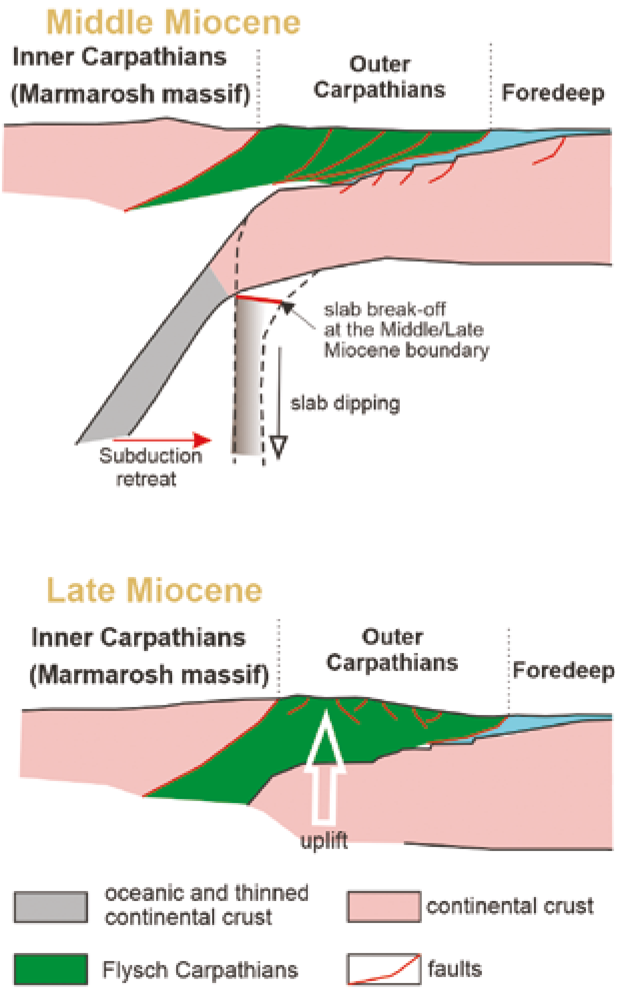

Fig. 18. Schematic palinspastic reconstruction of the final stage of the Ukrainian Carpathians development (after Murovskaya et al., 2025, simplified and modified). The extension at the final stage could be caused by the detachment of heavy oceanic plate (slab break-off) from the roots of the orogen, its isostatic uplift and collaps

The integration of low-temperature thermochronometry and cross-section balancing indicates significant uplift of the Ukrainian segment of the Carpathian orogen (up to 7 km) during the period 2–12 Ma as a result of isostasy, while the surface portion of the orogen underwent extension under gravitational forces (Nakapelyukh et al., 2017, 2018).

The formation of large-scale mass-transport deposits in the synorogenic Lower Miocene Polyanytsa and Vorotyshche formations (Hnylko, 2014), the emplacement of clastic dikes (Alokhin et al., 2018), and the formation of large submarine slumps could have occurred under synorogenic extensional conditions. Large olistolites of the Menilite weakly lithified shales could be sliding from submarine elevations along low-angle faults (Hnylko, 2014).

4.3. Palinspastic reconstruction of the final stage of the Ukrainian Carpathians formation

During the post-subduction stage, the subducted (sub)oceanic plate could be separated from the continental plate (slab break-off) and began to sink into the asthenosphere (Murovskaya et al., 2025 and references therein), that ceased rapid isostatic uplift of the orogen, exhumation, and, consequently, the extension of the newly formed arcuate mountain belt and the formation of normal faults (Fig. 18). This ultimately led to the so-called 'orogen collapse', see (Fossen, 2016). Therefore, the revealed by this study normal faults may have been formed during the post-subduction stage.

Conclusions

In the study area at the village of Verkhnye Synyovydne the Menilite Formation (Oligocene) is outcroping. It is represented by fine-rhythmic intercalation of black and dark-brown bituminous non-carbonate shale mudstones and light-gray and dark-gray polymictic fine-grained sandstones and siltstones. The overall monoclinal structure of the formation is complicated by faulting and folding. The main faults observed are of normal-type, and thrust faults are also present. The latter ones are associated with thrust folds and stack-like compression duplexes. Normal faults are expressed by thin zones of brittle breccias, their kinematics are recorded by drag folds. The normal faults often become more gentle downwards, taking on a listric form. The fault surfaces combine inherited elements of different primary origins into a single surface (for example, steep surfaces of former strike-slips and more gentle bedding surfaces).

Based on a set of measured slickensides, we reconstructed an extensional paleostress field with a horizontal axis of maximum extension, across the Ukrainian Carpathian trend. We also reconstructed an older compressional stress field, with a southwest-oriented compressional axis. The extension is most extensively manifested in brittle displacements and is likely the youngest.

The observed normal faults reflect the most late extensional stage of the orogen development. These normal faults were formed during rapid growth of the orogen, exhumation, and, consequently, the extension of the newly formed arcuate mountain. The orogene growth could be caused by the detachment of the heavy oceanic slab from the lighter platformian continental plate partly subducted under the Carpathians, leading to isostatic uplift of the orogen. In addition, normal faults in the flysch allochthone could be formed as a consequence of the direct influence of normal faults fixed in the Carpathian autochthone platformian basement.

У статті представлені результати польових досліджень переважно структур розтягу, включаючи розломи та пов'язані з ними складки, в межах відомого відслонення менілітової світи олігоцену, розташованого у фронтальній частині Зовнішніх Карпат (Скибовий покрив) поблизу села Верхнє Синьовидне, уточнено їх будову та кінематику і розглянуто можливий їх генезис. Відслонення розташоване на правому березі р. Опір в селищі Верхнє Синьовидне Львівської області, навпроти бази проведення навчальних практик студентів геологічного факультету Львівського національного університету ім. Івана Франка. Більшість досліджених розломів є скидами, також спостерігаються насуви. Останні пов'язані зі складками волочіння та стогоподібними дуплексами стиску. Скиди переважно лістричниго типу – субвертикальні вгорі та пологіші внизу, вони представлені зонами крихких брекчій. Кінематика скидів фіксується флексуроподібними складками волочіння та майже вертикальними борознами волочіння на дзеркалах ковзання. На основі вивчення тектонічних дзеркал ми реконструювали поле напружень розтягу з горизонтальною віссю максимального розтягнення σ3 поперек простягання Карпат, зокрема і Скибового покриву. Проміжна вісь σ2 реконструйованого поля напружень також горизонтальна та спрямована вздовж простягання Скибового покриву, а її значення близьке до максимального розтягнення σ3. Вертикальні борозни на тектонічних дзеркалах перекривають горизонтальні та є явно наймолодшими.

Скиди інтерпретуються як відображення найпізнішої стадії розвитку орогену - його розтягу під час швидкого підйому гірської споруди. Стадія підйому і розтягу могла бути спричинена відривом важкої океанічної плити від легшої платформної континентальної плити, частково субдукованої під Зовнішні Карпати, що призвело до ізостатичного підняття орогену та так званого «колапсу орогену». Крім того, скиди у флішовому алохтоні могли утворитися внаслідок прямого впливу скидів, зафіксованих у платформному піднасуві (автохтоні) Карпат.

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