УДК 551.243(477.8) DOI: https://doi.org/10.24028/gj.v45i6.293308

Characteristics structures of the mélange zones in the Ukrainian Carpathians

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Received 7 August 2023

Mélange is characterized by the block-in-matrix fabric in which rigid blocks of different sizes, lithologies, and ages are distributed in a ductile matrix. Though mélange is a significant component of orogenic belts, in the Ukrainian Carpathians, mélanges of tectonic origin have not been reported. We have described the mélange zones widespread in the Pieniny Klippen Belt, Marmarosh Klippen Zone, and the inner nappes of the Outer Ukrainian Carpathians, as well as the typical deformation structures developed within them.

The mélange matrix is characterized by a scaly fabric formed by cleavage surfaces and somewhere arranged in S-C structures. Lenticular clasts within the matrix show their long axis aligned to the tectonic foliation. Rotation of the boudins occurs against the shear direction following the formation of the S-C structures. The rigid clasts somewhere demonstrate sigma-type rotation structures. Some blocks within the mélange are highly fractured up to tectonic breccias.

The study of tectonic slicken-sides and other deformation structures within the Pieniny belt demonstrates the presence of regular stress fields correlated with the geodynamics of the Carpathian-Pannonian region. The main stress field indicates the SW-NE regional compression related to the formation of Carpathian nappes and S-N — trending dextral strike-slip faults. Our study in the Priborzhava quarries records the Oash right-lateral strike-slip fault zone. In the Pieniny Klippen Belt some oblique normal faults of the Carpathian direction are related to the Transcarpathian Depression formation. The study showed that the mélange zones in the inner part of the Ukrainian Carpathians were formed largely due to strike-slip movements. In contrast, in the outer part of the Carpathian orogen, they formed mainly due to thrusting.

Key words: tectonic mélange, Outer Ukrainian Carpathians, Pieniny Klippen Belt, Marmarosh Klippen zone, stress field.

Introduction. Mélange is a significant component of orogenic belts. The term «mélange» [Greenly, 1919] is descriptive, defining a mappable (at 1:25,000 or smaller scale) body of internally disrupted and mixed rocks in a pervasively deformed matrix [Festa et al., 2019 and references therein]. Mélange is characterized by the block-in-matrix fabric, which means rigid blocks of different sizes, lithologies, and ages are distributed in a duc-

Citation: *Hnylko, O., Murovskaya, A., & Bohdanova, M.* (2023). Characteristics structures of the mélange zones in the Ukrainian Carpathians. *Geofizicheskiy Zhurnal*, *45*(6), 67—86. https://doi.org/10.24028/gj.v45i6.293308.

tile matrix. Mélange is fragmented and mixed masses of rocks lacking stratal continuity. The so-called «monomictic mélange» is composed of mixed rocks of the same formation or a similar lithological type (for example, only flysch rocks), and the «polymictic mélange» represented by rocks of completely different lithology can be distinguished.

«Broken formation» defines a disrupted rock unit where stratal disruption and fragmentation occur without mixing, and lithological and chronological identity is preserved. Broken formation is commonly characterized by gradually transition from a bedded and partially coherent succession to a highly disrupted or dismembered block-in-matrix fabric [Festa et al., 2019].

Festa et al. [2019] used the term mélange as a description without genetic significance. Adjectives indicating the formation process of the block-in-matrix rock unit are used to distinguish tectonic, sedimentary, and diapiric mélange types. In this case, «sedimentary mélange» is equivalent to olistostrome, which defines block-in-matrix complexes formed by sedimentary (gravitational) processes. The term «olistostrome» [Flores, 1955] has a genetic connotation, representing a product of mud/debris flows accompanying submarine landslides.

In the presented work, we use the term «mélange» as a genetic definition after [Hsü, 1968; Cowan, 1974; Gansser, 1974; Sengör, 2003] that restricted the term to define complexes originated by tectonic strain. In the Ukrainian Carpathians, most of the best-expressed olistostromes are identified in several zones related to the frontal parts of the great nappes [Hnylko, 2011a]. They have been described in the Marmarosh Klippen Zone [Kruglov, 1965] and at the front of the Marmarosh [Byzova, 1965], Chornohora [Gruzman, Smirnov, 1985], Dukla [Glushchenko, 1972; Glushchenko et al., 1980; Hnylko et al., 2021], Silesian [Astakhov, 1989] and Boryslav-Pokuttya nappes [Kulchitskiy, 1977; Hnylko, 2014].

Olistostromes containing exotic clasts derived from the preflysch and/or platform basement uplifted and exposed to mass-wasting at the basin margin are also depicted in the Ukrainian Carpathians [Hnylko et al., 2021 and references therein].

At the same time, mélanges of tectonic origin have not been described in the Ukrainian Carpathians. Only some mélange zones were previously described within the strike-slip and thrust zones [Hnylko, 2011a] and mélange/broken formation were characterized in some thrust zone of the Skyba Nappe [Bogdanova, 2022].

The presented work aims to describe some typical deformational structures developed in the mélange/broken-formation zones of the Ukrainian part of the Pieniny Klippen Belt, Marmarosh Klippen Zone, and Outer Carpathians. We also consider some restoration of stress fields in mélange zones, understanding them as tectonic structures marking regional fault zones and/or suture zones. Understanding the nature of these structures is important for clarifying the structure of the Carpathian orogen and the subsequent reconstruction of its evolution. Their study is necessary for the construction of geological maps, the search for minerals, and the prediction of dangerous geological phenomena, as well as for education.

Geologic outline. *Carpathian orogen* is a fold-and-thrust convex arcuate belt that links with the Eastern Alps to the west and stretches into the Balkan chain to the south. It is the product of Alpine orogeny and consists of destructed and reduced formations of the Tethys Ocean. Traditionally, the orogen is divided into the Inner (Central) Carpathians and Outer (Flysch) Carpathians. The Inner Carpathians contain the crystalline metamorphic massifs with the pre-Alpine rock complexes (Variscan and more ancient orogens), which are the remnants of the microcontinents/continental fragments of the Tethys Ocean. These complexes are disrupted and reworked into the thick-skinned nappes. Such large continental fragments are known as the Alcapa and Tizsa-Dacia terranes which come to the surface as crystalline massifs and are submerged under the Neogene Pannonian basin system [Csontos, Vörös, 2004; Kováč et al., 2016, 2017; Schmid et al., 2020 and references therein].

In Ukraine, the part of the *Tizsa-Dacia Terrane* is the Marmarosh Crystalline Massif including the Marmarosh thick-skinned basement nappes and the Marmarosh Klippen Zone (Fig. 1). In the Romanian territory, the basement nappes are overthrust by the uppermost Transylvanian Nappes containing Triassic-Jurrassic ophiolites [Săndulescu, 1988]. Marmarosh Klippen Zone consists of Lower Cretaceous olistostrome/conglomerate deposits with clasts of metamorphic and sedimentary rocks derived from the Marmarosh Massif as well as the blocks of Mesozoic mafic and ultramafic rocks. These deposits are overlain by the Upper Cretaceous-Paleogene marls, shales, and sandy sediments. Marmarosh Klippen Zone sedimentary succession belonged first to the sedimentary cover of the Marmarosh crystalline massif, and later, it was torn off from the basement and transformed into the Vezhany Nappe [Kruglov, 1986; Hnylko et al., 2015 and references therein].

The *Alcapa Terrane* fragment is buried under Neogene deposits of the Transcarpathian Depression in the Ukraine near Uzhgorod and Chop [Hnylko, 2011b].

Pieniny Klippen Belt, being only several km wide but at least 500 km long, represents a complex suture zone of the Alpine Tethys dividing the Cretaceous basement/cover thrust stack of the Central Western Carpathians from the Cenozoic accretionary complex of the Outer Carpathians [Golonka at al., 2006, 2018; Plašienka, Soták 2015; Schmid et al.,

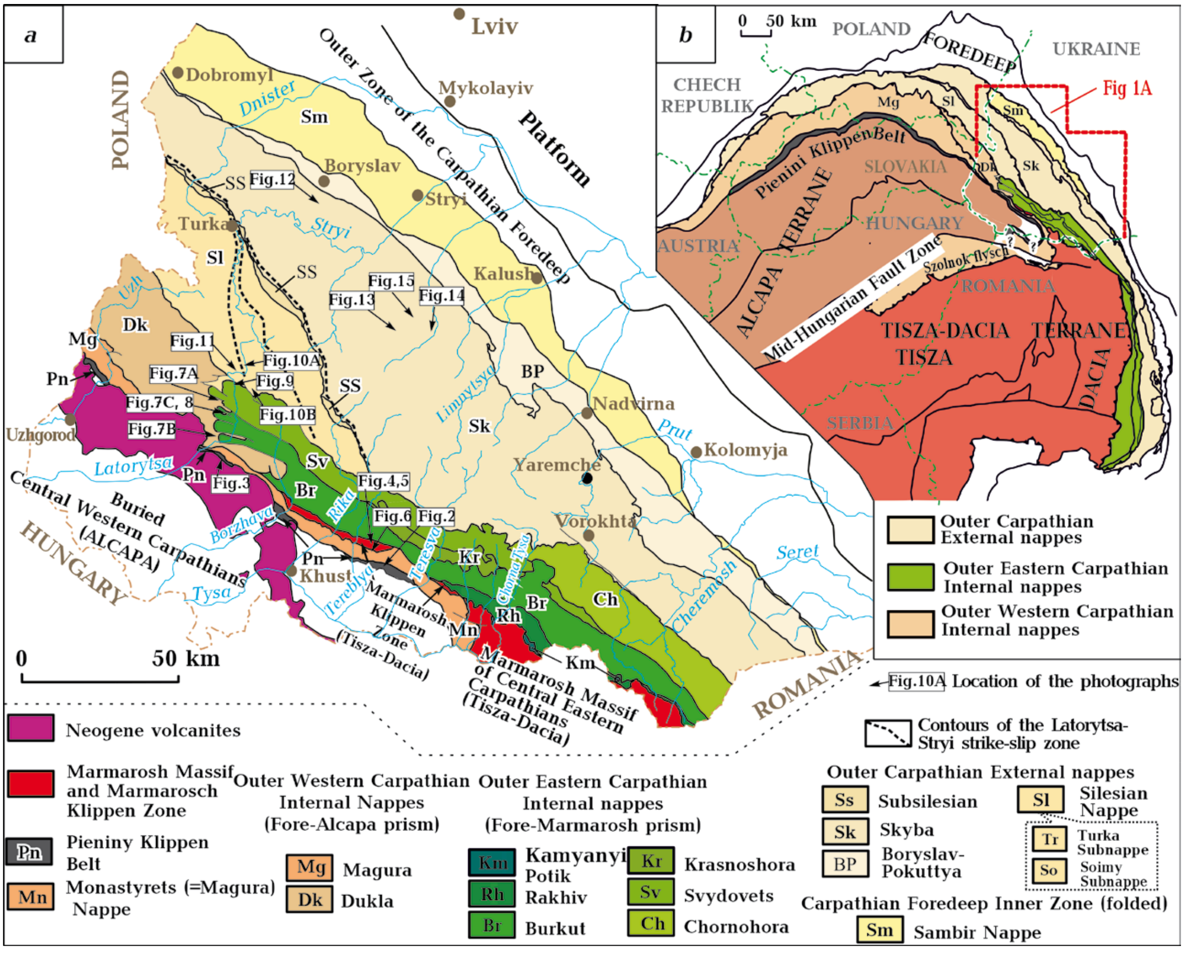

Fig. 1. Main tectonic units of the Ukrainian Carpathians [Hnylko, 2011b, Hnylko et al., 2021 modified] and location of the photographs (*a*) (see Fig. 2—11). Tectonic setting of the Ukrainian Carpathians, position of the terranes and main geological boundaries after [Săndulescu, 1988, 2009; Kováč et al., 2016, 2017; Csontos, Vörös, 2004; Horvath, Galacz, 2006; Oszczypko, 2006; Schmid et al., 2020] simplified and partly modified (*b*).

2020]. Pieniny Klippen Belt turns to the SE into the Central Carpathians, where it wedges (together with flysch Magura/Monastyrets Nappe, see below) between the Alcapa and Tisza–Dacia terranes [Hnylko, 2011b; Schmid et al., 2020]. The Jurassic-Paleogene rocks filling the Pieniny Klippen Belt are strongly deformed, up to a tectonic mélange [Plašienka, Soták, 2015 and references therein].

The *Outer Carpathians* consist of stacked thin-skinned nappes considered as the Cretaceous-Neogene accretionary prism formed as a result of subduction of the Carpathian sedimentary flysch basin basement beneath both the Alcapa and Tisza-Dacia terranes. These nappes consist of allochthonous Cretaceous-Neogene, mainly flysch sediments uprooted from their original position [Csontos, Vörös, 2004; Horvath, Galacz, 2006; Oszczypko, 2006; Hnylko, 2012; Kováč et al., 2016, 2017; Schmid et al., 2020].

In Ukraine, the two nappe systems (accretionary palaeoprisms) located in the Outer Western Carpathians and Outer Eastern Carpathians adjoin «laterally» [Horvath, Galacz, 2006; Hnylko, 2011b, 2012]. The first system, represented by the Outer Western Carpathian Internal flysch nappes (Fore-Alcapa inner accretionary prism: Magura and Dukla nappes), was built in the foreland of the Alcapa Terrane in the Paleogene. The second one, comprising the Outer Eastern Carpathian Internal flysch nappes (Fore-Marmarosh inner prism: Kamyanyi Potik, Rakhiv, Burkut, Krasnoshora, Svydovets, and Chornohora nappes), was formed in front of the Tisza-Dacia Terrane during the Cretaceous—Paleogene. The Outer Carpathian External flysch-molasse nappes (Silesian, Sub-Silesian, Skyba, and Boryslav-Pokuttya nappes) were incorporated within amalgamated inner accretionary prisms and were developed as the outer part of the newly formed combined accretionary prism ahead of both the Alcapa and Tisza-Dacia conjugate terrains during the Oligocene—Miocene. Finally, the combined prism was thrust onto the Carpathian Foredeep in the Miocene [Hnylko, 2011b, 2014; Krobicki et al., 2014] (Fig. 1).

The Outer Carpathian Magura Nappe turns to the SE into the Central Carpathians, where it was called Monastyrets Nappe [Byzova, Beer, 1974; Oszczypko et al., 2005] wedged (together with Pieniny Klippen Belt, see above) between the Alcapa and Tisza-Dacia terranes [Hnylko, 2011].

In addition, some tectonic nappes may have changed their original form as a result of post-nappe deformations, including strike-slip and/or lateral extrusion movements [Hnylko, 2017].

Materials and methods. The visible structures of the mélange/shear zones exposed in the Pieniny Klippen Belt, Marmarosh Klippen Zone, and Outer Carpathians were studied (Fig. 2) and described according to descriptions of the similar structures given in the works [McClay, Insley, 1986; McClay, 1992; Starzec et al., 2015; Fossen, 2016]. Structural analysis and geological mapping were used to study structural forms.

Fig. 2. Isolated blocks or «klippen» composed of competent Jurassic to Lower Cretaceous limestones exposed in quarries. Pieniny Klippen Belt. The village of Mala Uholka, Transcarpathian region.

The kinematic method and Win-Tensor program were applied to reconstruct paleo stresses on the base of a set of slicken-sides [Devlaux, Sperner, 2003]. The theoretical principles of the kinematic method are based on the dislocation theory of plasticity [Gintov, 2005 and references therein]. The deformation process in the massif of rocks occurs due to displacement along differently oriented fractures, layering planes, and other weakened zones with the formation of slip strokes on surfaces polished by friction (slicken-sides). According to the main postulate of the kinematic method, the direction of movement along the surface of a slicken-side corresponds to the direction of tangential stress on its surface. We reconstructed the main stress axes σ1, σ2, σ3, and the shape factor of the stress tensor R=(σ2–σ3)/(σ1–σ3), which indicates the type of stress state: R=1 corresponds to the mode of uniaxial tension, R=0 corresponds to the mode of uniaxial compression, and R=0.5 determines the shear mode. The Win-Tensor program also provides separation of all slicken-sides into a number of sets corresponding to different stress fields.

Description. ***Pieniny Klippen Belt.*** In Ukraine, the Pieniny Klippen Belt (PKB) is filled mainly with the mélange characterized by block-in-matrix fabric formed by isolated blocks or «klippen» composed of competent Jurassic to Lower Cretaceous limestones surrounded in a soft matrix, consisting of mainly Upper Cretaceous Puchov red marls. The mélange is unconformably overlain by Eocene conglomerates [Kruglov, 1986; Hnylko et al., 2015]. Large limestone blocks, up to tens and hundreds of meters in size, are often exposed in quarries (see Fig. 2), where, as a rule, their contacts with the matrix are not visible. These blocks and clasts are represented by rigid

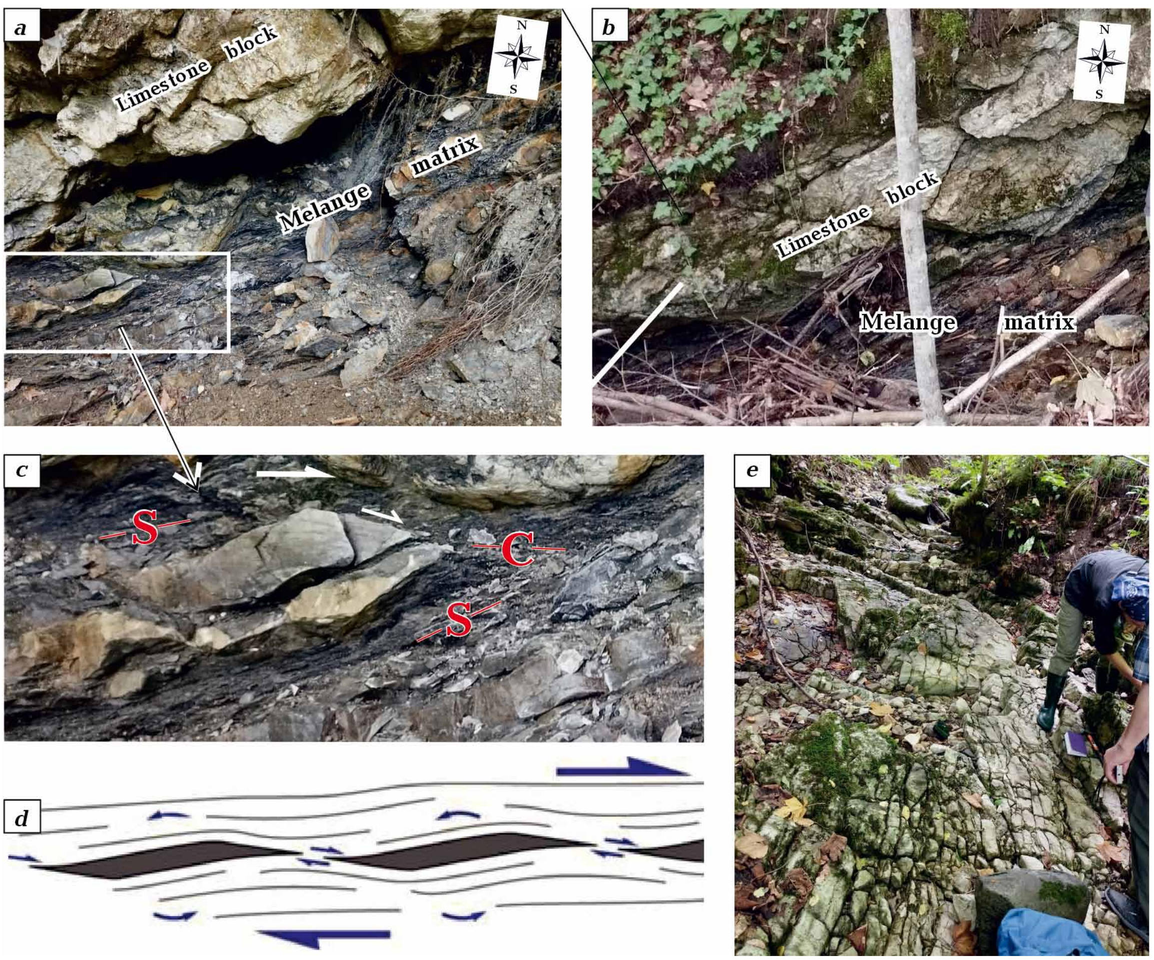

Fig. 3. Pieniny Klippen Belt mélange with block composed of rigid Maiolica-like limestones of the Tithonian — Neocomian Svalyava Formation and matrix represented by red and green-gray crushed Cretaceous marls of the Puchov and Tysalo formations exposed along the Kvasnyi Stream — the left tributary of the Dysynka Stream in the Latorytsa River Basin near the village of Stroyno, Transcarpathian Region: *a* — melange matrix aligned to the tectonic foliation and lense-shaped boudins; *b* — block/matrix contact; *c* — melange matrix characterized by a scaly fabric and boudins rotated in accordance with the formation of the S-C structures, against the right sense shear direction; *d* — rotation of the boudins against the shear direction after [Fossen, 2016, Fig. 15.13 and 16.24]; *e* — the strongly fractured competent limestone of Tithonian—Neocomian Svalyava Formation.

rocks of various sedimentary facies (from deep-water to shallow-water) studied in detail in Polish and Slovak segments of BKB as well as exotic rocks [Kruglov, 1986; Plašienka, Soták, 2015; Golonka et al., 2018 and references therein].

A characteristic block/matrix contact is exposed in the Kvasnyi Stream — the left tributary of the Dysynka Stream in the Latorytsa River Basin (see Fig. 1 for photo location). The rigid block, up to tens of meters in size, is composed of micritic light gray Maiolica-type limestone with silicon intercelations of the Svalyava Formation (Tithonian—Neocomian). The limestone has been transformed into tectonic breccia near the contact with matrix (Fig. 3, *a*—*c*). In general, the competent Svalyava limestone exposed along the stream is strongly fractured (Fig. 3, *e*). Near this contact, the mélange matrix is represented by red and green-gray crushed Cretaceous marls of the Puchov and Tysalo formations (Fig. 3, *a*—*c*). It is characterized by a steep dipping scaly fabric locally arranged in shear zones with S-C structures (Fig. 3, *a*, *c*) as described by Festa et al. [2019] (Fig. 3, *d*) in the mélanges. Lenticular clasts, layer remnants, and boudins of these marls embedded within the scaly matrix show their long axis aligned to the tectonic foliation (Fig. 3, *a*, *c*). Rotation of the boudins occurs against the shear direction following the formation of the S-C structures, as shown in Fig. 3, *c*, *d*.

Marmarosh Klippen Zone. The main part of the Marmarosh Klippen Zone (MKZ) consists of Lower Cretaceous olistostrome/conglomerate deposits with clasts/olistoliths derived from the Marmarosh Massif as well as the blocks of Mesozoic mafic and ultramafic rocks. The olistostrome matrix is fragmentarily exposed along the Mala Uholka and Velyka Uholka rivers (Teresva River basin,

Fig. 4. Marmarosh Klippen Zone. Lower Cretaceous olistostrome/conglomerate deposits exposed along the Velyka Uholka River (Teresva River basin, Transcarpathian region): *a*, *b* — debris-flow deposits of the olistostrome matrix, where clasts of metamorphic and sedimentary rocks are scattered in the mud-sandy unstratified sediments; *c* — olistolith of Jurassic-Early Cretaceous limestone.

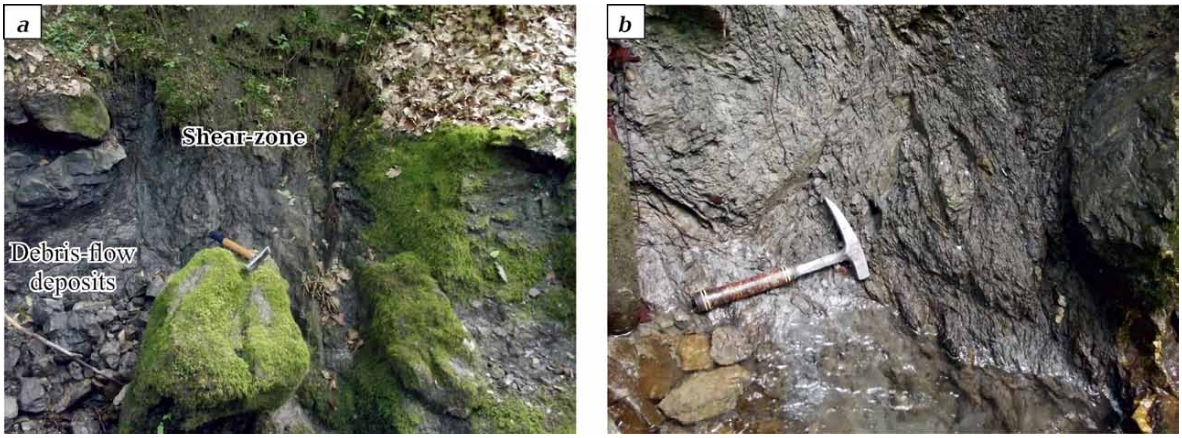

Fig. 5. Debris flow deposits of the Marmarosh Klippen Zone olistostrome. Velyka Uholka River (Teresva River basin, Transcarpathian region): *a* — debris flow deposits with sheared mud-sandy matrix, *b* — sub-vertical tectonic foliation (i.e., cleavage).

Thranscarpathian region) and represented by the typical debris-flow deposits, where clasts of metamorphic and sedimentary rocks are scattered in the mud-sandy unstratified sediments (Fig. 4, *a*, *b*). The large olistoliths of Jurassic-Early Cretaceous limestones are presented here (Fig. 4, *c*). In some outcrops, the mud-sandy matrix is sheared and deformed by cleavage planes, which split the matrix into millimeter-to centimeter-long lens-shaped scales (Fig. 5, *a*, *b*).

As a rule, tectonic foliation (i.e., cleavage) is sub-vertical with sub-horizontal striation, which suggests strike-slip movement. The surfaces of limestone blocks within the olistostrome are bounded on all sides by tectonic slicken-sides, which indicates superimposed tectonic processes. The MKZ, which bears traces of both gravitational and tectonic genesis, demonstrates processes of deformation that transformed the sedimentary olistostrome formation into a tectonic mélange.

In the contact zone between the MKZ and the more internal Monastyrets Nappe, the deformed Paleogene flysch deposits (Sushmanets Formation) [Hnylko, Hnylko, 2016] are developed. Fragments of S-folds and drugfolds with sub-vertical hinges are observed here along the Velyka Uholka River (Fig. 6). They suggest the left sense strike-slip movement along this contact.

Fig. 6. Fragment of the S-fold with sub-vertical hinges in the contact zone between the Marmarosh Klippen Zone and more internal Monastyrets Nappe. Velyka Uholka River (Teresva River basin, Transcarpathian region).

In the ***Outer Ukrainian Carpathians (OUC)***, mélanges are widely developed in the junction area, where the Outer Eastern Carpathian Internal flysch nappes on the one hand and the Outer Western Carpathian Internal flysch nappes on the other are converged at the Borzhava and Latorytsa river basins (see Fig. 1). The mélanges are made up of the deformed variegated shales and thin- to medium-bedded gray flysch (Upper Cretaceous—Paleocene) of the *Western Carpathian Dukla Nappe*. They are located near the rigid psammites of the Eastern Carpathian Burkut and Svydovets nappes. These shales and flysch are dissected by the sub-vertical shear-zones up to a few meters wide (Fig. 7, *a*, Fig. 1).

In the shear zones, the deposits are boudinaged and disrupted and demonstrate a mé-

Fig. 7. Shear zones: mélanges and broken formations developed in the junction area, where the Outer Eastern Carpathian Internal flysch nappes on the one hand and the Outer Western Carpathian Internal flysch nappes on the other are converged: *a*, *b* — subvertical shear-zones in the Cretaceous flysch of the Dukla Nappe of the Western Carpathians, (*a* — the village of Holubyne, Pynya River: right tributary of the Latorytsa River, Transcarpathian Region; *b* — the village of Uklin, Mala Pynya River, Latorytsa River basin, Transcarpathian Region); *c* — Cretaceous red and gray shales of the mélange matrix and sandstone block in the mélange near contact between the Dukla Nappe of the Western Carpathians and the Burkut Nappe of the Eastern Carpathians (Zalom Stream: left tributary of the Mala Pynya River, Latorytsa River basin, Transcarpathian Region).

lange block-in-matrix structure in which small elongated lenticular sandstone clasts up to a few centimeters and decimeters in size are embedded in the shale matrix (Fig. 7, *b*, *c*). Blocks reach the size of several meters up to a few tens of meters and are filled with bedded flysch and sandstones. The rigid sandstone blocks are, as a rule, highly fractured up to tectonic breccia (Fig. 7, *a*). Some layers' remnants up to the first centimeters and decimeters thick are intensively folded and included in the shaly matrix here, including the remnants of folds with sub-vertical hinges (Fig. 8, *b*). The mélange matrix is characterized by a scaly fabric formed by cleavage surfaces. Scaly fabric is locally arranged in S-C structures, indicating a left sense of the shearing (Fig. 8, *c*). The cleavage surfaces and elongated blocks in the mélange, as well as the hinges of small folds (Fig. 7, 8, *a*—*c*), are usually placed sub-vertically, suggesting strike-slip type kinematics. Broken formations, i.e., disrupted deposits in which the primary strata sequence can still be recognized, are also represented here (Fig. 8, *d*).

Broken formations are also developed in the *Eastern Carpathian Svydovets Nappe* near this Eastern/Western Carpathian junction area. A good example of such formations is the deformed Cretaceous flysch exposed along the Latorytsa River near the village of Abranka. Continuous sandstone layers of this flysch are fractured and interbedded by intervals of matrix displaying scaly fabric that includes smaller sandstone clasts. In addition, small shear zones are developed here in which a mélange block-in-matrix structure is manifested (Fig. 9, *a*, *b*). The tectonic folia-

Fig. 8. Mélange and broken formation near the contact between the Dukla Nappe (Western Carpathians) and the Burkut Nappe (Eastern Carpathians). Zalom Stream: left tributary of the Mala Pynya River, Latorytsa River basin, Transcarpathian Region. *a* — highly fractured up to tectonic breccia rigid sandstone block in the mélange; *b* — sandstone block and folds with sub-vertical hinges included in the shaly mélange matrix; *c* — mélange matrix characterized by a scaly fabric arranged in S-C structures indicating left sense of the shearing; *d* — broken-formations, i.e. disrupted deposits in which the primary strata sequence can still be recognized.

tion is subvertical, which suggests strike-slip movement with sub-horizontal principal axes of compression and extension.

In the Outer Carpathian External flysch-molasse nappe system, the strike-slip *Latorytsa-Stryi Zone* has been distinguished on the southeastern termination of the Silesian Nappe [Hnylko, 2011b; Hnylko, Hnylko, 2016]. The Latorytsa-Stryi Zone forms the submeridional regional shear belt, up to a few km wide (see Fig. 1). It is filled with mappable duplexes (up to hundreds of meters — a few kilometers in size) surrounded by the tectonic breccias, mélange/broken formations, and intensive folding zones [Hnylko, 2011b]. These duplexes are filled with≡ysch, predominantly of the Oligocene Krosno Formation. Small right-lateral strike-slip faults and folds with sub-vertical hinges are developed in the shear zone area (Fig. 10, *a*, *b*). An example of such a duplex-like structure is the so-called «Smozhe Structure» developed in the basin of the Stryi River [Hnylko, Hnylko, 2010]. Generally, in the *Silesian Nappe*, the thrust zones and fault-related drag folds with sub-horizontal hinges are widely developed (Fig. 11).

In the Outer Carpathian External *Skyba Nappe*, the steep and gently inclined thrust zones and fault-related inclined drag folds with sub-horizontal hinges are also widely

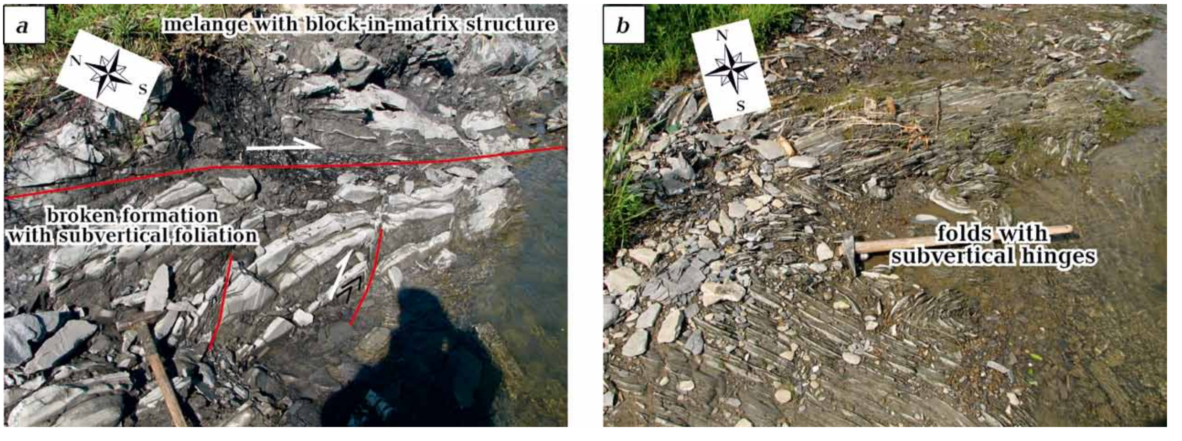

Fig. 9. Broken formation developed in the Cretaceous deposits of the Eastern Carpathian Svydovets Nappe near the Eastern/Western Carpathian junction area. Latorytsa River near the village of Abranka, Transcarpathian Region: *a* — sub-vertical tectonic foliation, *b* — folds with sub-vertical hinges.

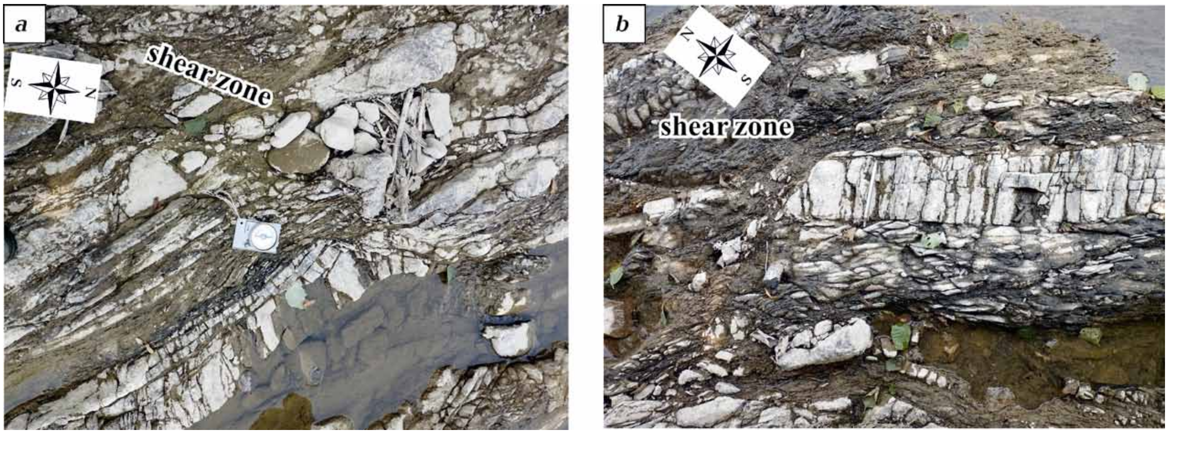

Fig. 10. Mélange and broken formation in the strike-slip Latorytsa-Stryi Zone located on the southeastern termination of the Silesian Nappe: *a* — mélange and broken formation with right-lateral strike-slip faults and drag folds with subvertical hinges (Latorytsa River near the village of Nyzhni Vorota, Transcarpathian region); *b* — folds with subvertical hinges (Vicha River near the city of Volovets, Transcarpathian region).

developed (Fig. 12). The main vergence of such structures is directed to the northeast. It coincides with the general vergence of the large thrust sheets of the Skyba Nappe.

Here, the detachment zones filled with duplexes and drag folds are exposed (Fig. 13).

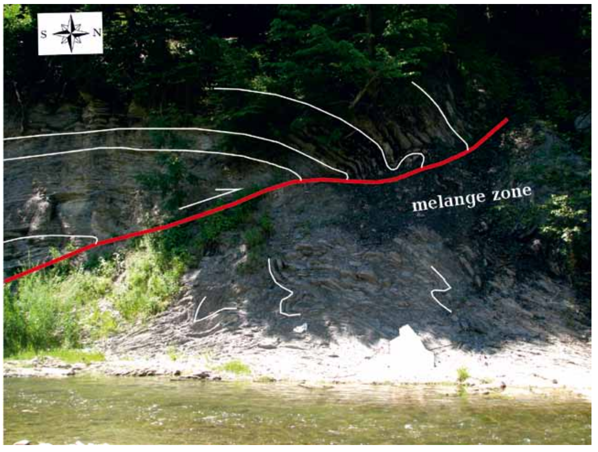

Fig. 11. Thrust zone and fault-related drag folds with sub-horizontal hinges, local thrust sheet in the Silesian Nappe. Oligocene. The village of Yalove, Latorytsa River, Transcarpathian region.

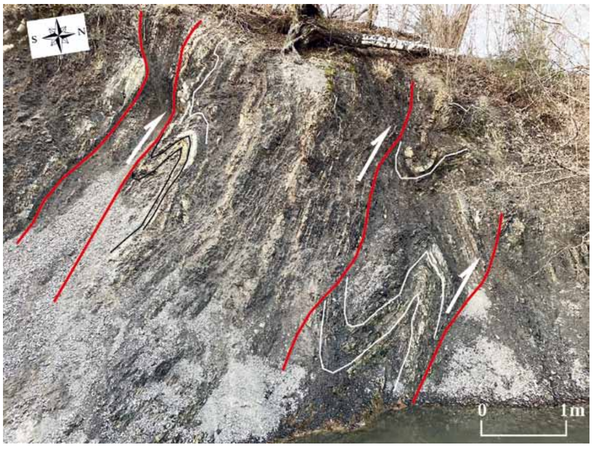

Fig. 12. Steep inclined thrusts and fault-related drag folds with sub-horizontal hinges. Oligocene Menilite Formation. Outer Carpathians, the external part of the Skyba Nappe, the city of Skhidnytsa, Lviv region.

Fig. 13. Detachment zone filled with duplexes and drag folds. Cretaceous-Paleocene Stryi Formation. The Outer Carpathians, Skyba Nappe, Mizunka River, Ivano-Frankivsk region.

The horses typically tend to dip toward the hinterland. Note that the sediments in the duplexes were folded, faulted, and rotated during the thrusting history, which suggests thrust direction. Buckle folds are observed in the Oligocene organic-enriched black shale strata of the Menilite Formation of the Skyba Nappe (Fig. 14). In such folds, a contrast in viscosity is presented, with the folded layer being more competent than the host rock. These host rocks are more intensively deformed in the hinge zone. On the whole, rounded folds with sinusoidal shape are formed, filled with a competent sandstone layer, which limit strongly deformed parasitic folds of the incompetent black shales in the hinge zone.

Active folding or buckling is a folding process that can be initiated when a layer is shortened parallel to the layering. A contrast in viscosity is required for buckling to occur. The result of buckling is rounded folds, typically parallel and more or less sinusoidal, similar to those shown in the Fig. 14. Buckling occurs when a competent layer in a less competent matrix is shortened parallel to the length of the layer [Fossen, 2016].

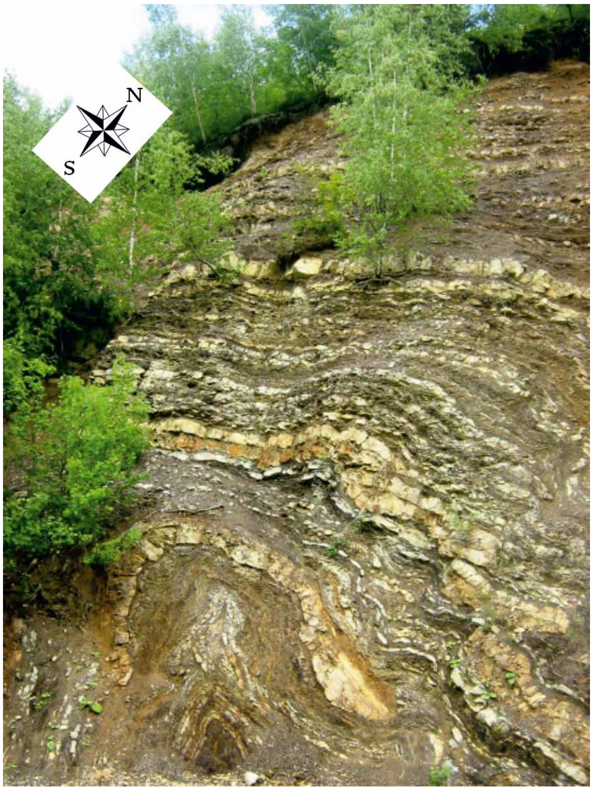

Fig. 14. Buckle fold in the Oligocene organic-enriched black shale strata of the Menilite Formatio. Rounded sinusoidal folds are filled with a competent sandstone layer; the host incompetent black shales are more intensively deformed in the hinge zone. The Outer Carpathians, Skyba Nappe, Svicha River basin, Ivano-Frankivsk region.

As a rule, the shear zones are developed in the frontal part of the thrust sheets of the Skyba Nappe, where the deposits are boudinaged, disrupted and somewhere demonstrated a mélange block-in-matrix structure in which small elongated lenticular sandstone clasts up to a few centimeters and decimeters in size are embedded in the shale matrix. The tectonic foliation is steep and gently inclined and tends to dip toward the hinterland. The mélange matrix is characterized by a scaly fabric locally arranged in the S-C structures. The rigid sandstone clasts and/or boudins somewhere demonstrate σ-types (sigma type) rotation structures. Mélanges are accompanied by broken formations, where stratal disruption and fragmentation occur without full mixing and block-in-matrix structure arranging.

Restoration of paleostresses in the Pieniny Klippen Belt. Considerating mélanges and broken formations as zones of tectonic deformation also assumes the possibility of structural analysis to determine the types of deformation and the corresponding stress fields. Within the Ukrainian segment of the Carpathians and Pieniny Klippen Belt, several tectonophysical studies have been carried out, which are summarized in [Gintov, 2005; Murovskaya et al., 2016, 2019].

We present the results of geological-structural studies in two Priborzhava quarries (Fig. 15, 16), which mine a huge limestone cliff consisting of several large blocks. In the new Priborzhava quarry, two large blocks are distinguished in the structure of the cliff, in which the stratigraphic sequence from the Lower Jurassic to the Berriasian has been restored. The blocks are broken into smaller pieces, surrounded by a crushed marly matrix (Fig. 15, *a*—*d*). The blocks and matrix bear traces of deformation: friction clays, slip surfaces, boudinage, brecciation, and crushing. They represent tectonic mélange.

We performed palaeostress reconstruction on 250 slicken-sides (tectonic mirrors) collected at eight sites (Table). The reconstruction indicates the predominance of strike-slip stress fields with compression axis trending SW-NE and N-S. On the stereograms of the tectonic mirror poles (Fig. 16, *a*, *g*), the largest maximum (1) corresponds to S-N trending slicken-sides, maximum (2) indicates tectonic mirrors of NW 315° strike, and maximum (3) relates to NE 60° striking slicken-sides. Most of the N-S trending tectonic mirrors are characterized by the dextral shear displacement component and were activated by SW-NE compression. The second pole's maximum (Fig.16, *a*) corresponds to steeply dipping faults of the Carpathian direction with dextral strike-slip offset activated by N-S compression.

The reverse-type stress fields are characterized by the SW-NE and N-S compression. The observed drag fold (Fig. 15, *g*) also indi-

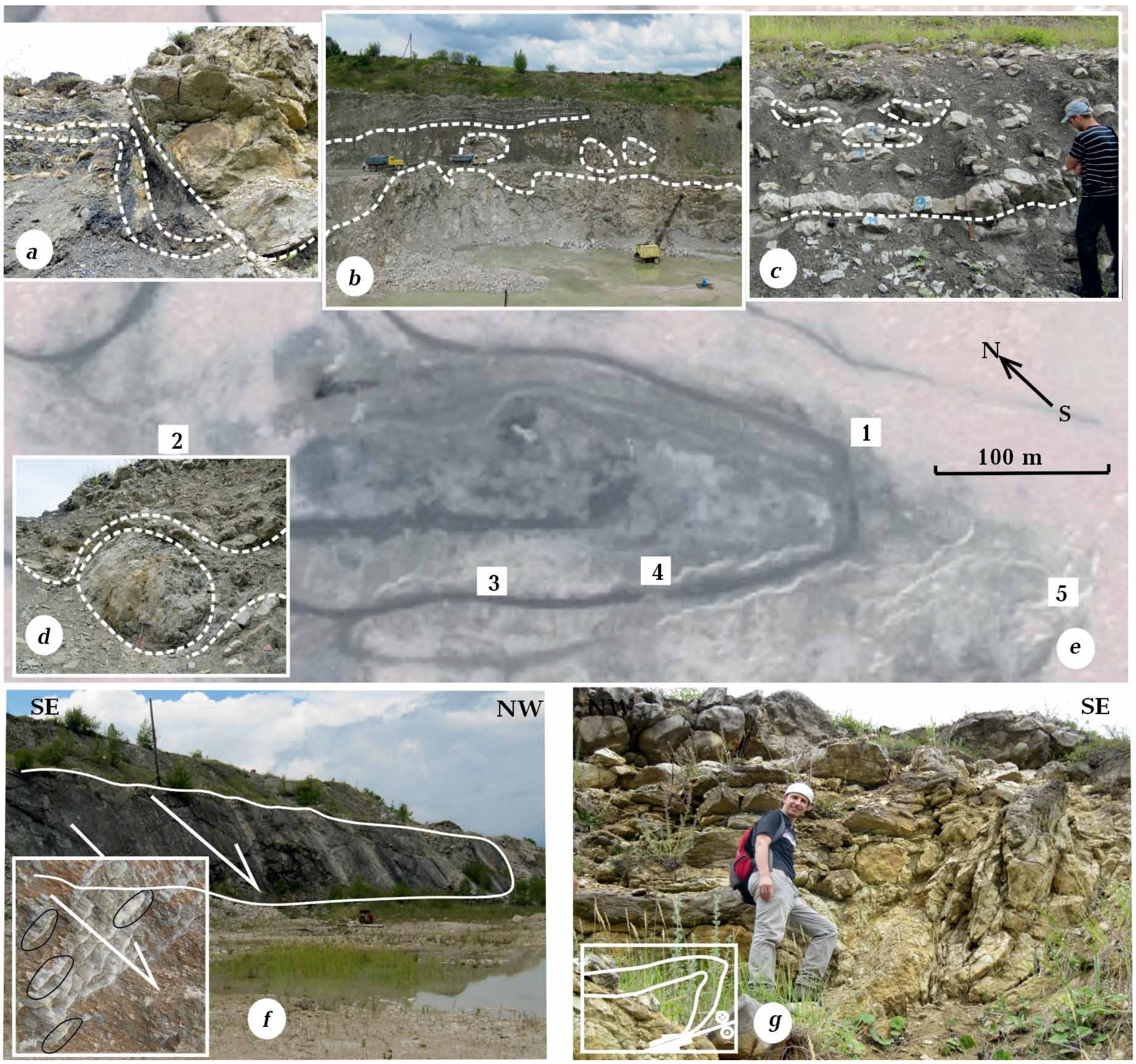

Fig. 15. Priborghava quarry producing a large limestone block in the Pieniny Klippen Belt, and observed deformation structures: *a*—*d* — tectonic mélange, represented by limestone clasts of round or lens shape, and matrix represented by sheared, mylonitized marls, E-position of the quarry and observation sites on the satellite image, *f* — large slicken-side of oblique normal type indicates transtensional environment, *g* — drag fold indicates compressional environment.

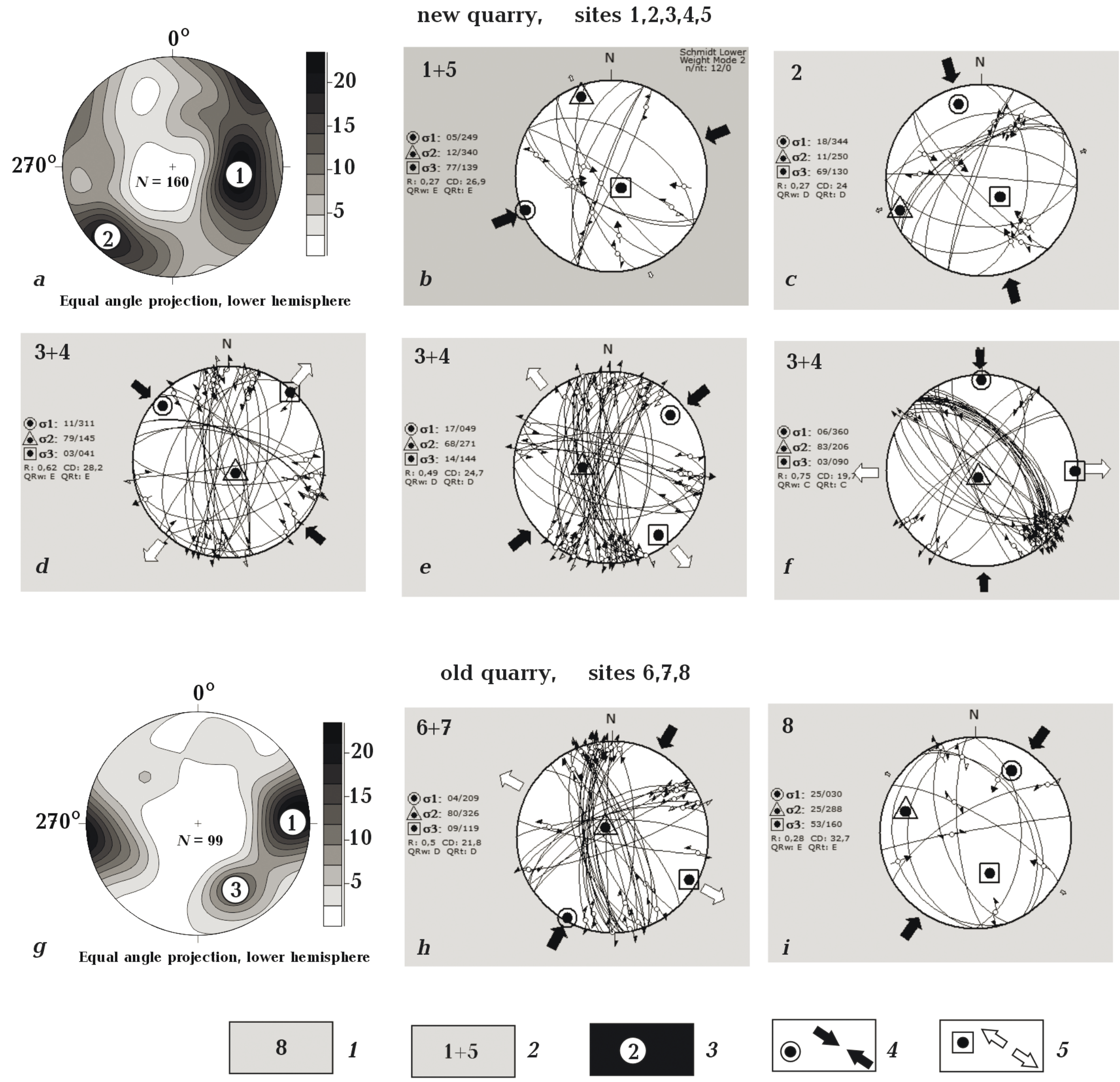

Fig. 16. Results of the interpretation of tectonic slicken-sides in two Priborghava quarries: *a*, *g* — stereograms of the slicken-sides poles concentration indicate two main orientations of the slicken-sides, *b*—*f*, *h*, *i* — kinematic stereograms for homogeneous sets of slicken-sides with reconstructed stress fields, mainly of strike-slip type; *1* — number of site (see Table), *2* — numbers of two sites, *3* — the poles concentration maximum and its number, *4* — axis and direction of compression, *5* — axis and direction of extension.

cates a compressional environment. Noteworthy is the huge slicken-side of the NW 320° strike dipping to the NE at 50—60°, traced along the entire side of the quarry, with kinematic sense changed from of strike-slip to a normal one, indicating a transtension environment (Fig. 15, *f*).

The study of small faults with slicken-sides within the Pieniny Klippen Belt provided the reconstruction of regular stress fields correlated to the geodynamics of the Carpathian-Pannonian region. We correlate the reverse and strike-slip stress fields with the SW 220° compression axis to the formation of the Carpathian accretionary prism of NE vergence. Due to the compression, both structures of horizontal shortening and vertical lengthening (thrusts), as well as structures of lateral extrusion (S-N trending dextral strike-slip fault), were formed [Murovskaya et al., 2016]. The reconstructed stress fields of strike-slip and reverse types with SE165°—SW215° compres-

T a b l e 1. Observation sites and reconstructed stress fields (see Fig. 15, 16)

Number Site	Latitude	Longitude	Compression axis σ1, plunge azimuth°/angle°	Extension axis σ3, plunge azimuth°/angle°	Type of deformation regime, R=(σ2–3)/(σ1–σ3)
1	48°19'55»	23°15'20»	20/9	152/77	Inverse, 0.84
2	48°20'4''	23°15´7''	344/18	130/69	Inverse, 0.27
2	48°20'4''	23°15´7''	107/18	336/63	Inverse, 0.17
3	48°19'58.2''	23°15'10.2''	49/17	144/14	Strike-slip, 0.49
3	48°19'58.2''	23°15'10.2''	360/6	90/3	Strike-slip, 0.75
3	48°19'58.2''	48°19'58.2''	311/11	41/3	Strike-slip, 0.62
4	48°19'56.2''	23°15'13.3''	49/17	144/14	Strike-slip, 0.49
4	48°19'56.2''	23°15'13.3''	360/6	90/3	Strike-slip, 0.75
4	48°19'56.2''	48°19'56.2''	311/11	41/3	Strike-slip. 0.62
5	48°19'51.6''	48°19'51.6''	20/9	152/77	Inverse, 0.84
6	48°20'26.3''	23°14'39.4''	209/04	119/9	Strike-slip, 0.5
7	48°20'25.9''	23°14'39.9''	209/04	119/9	Strike-slip, 0.5
8	48°20'22.1''	23°14'38.2''	30/25	160/53	Inverse, 0.28

sion axes are correlated to dextral strike-slip displacement along the Transcarpathian fault, separating the Outer Ukrainian Carpathians of the Transcarpathian Depression at the base of which are the buried Alcapa terraine.

The observed oblique normal faults oriented in the Carpathian direction with a SW 240°-trending extension axis obviously reflect the deformation regime of transtension and correlate to the Transcarpathian Depression formation. We consider the youngest deformation regime to be the transpressional one with the SW 215° compression axis. Its post-Pannonian age is confirmed by tectonophysical studies of young volcanics of the Vygorlat-Gutinsky ridge, describing dextral strike-slip displacements along the Transcarpathian fault [Shevchuk, Vasilenko, 2015].

Conclutions. Mélanges (mixed complexes of tectonic origin) of block-in-matrix fabric and broken formations with incomplete disturbance of the sedimentation layers have developed in the Ukrainian Carpathians. In the Outer Carpathians, the so-called «monomictic mélange», composed of mixed rocks of a similar lithological type (mainly flysch rocks), is distributed. In the Pieniny Klippen Belt suture, the mélange is «polymictic» and composed of various sedimentary, mainly calcareous facies (from deep-water to shallow-water ones).

In the Marmarosh Klippen Zone, the Early Cretaceous «polymictic» olistostrome with mud-sandy matrix and olistolits/clasts of the various metamorphic and sedimentary rocks, as well as the ophiolite fragments, are presented. In many places, the olistostrome is sheared and deformed up to a tectonic mélange.

The mélange matrix somewhere is characterized by a scaly fabric formed by cleavage surfaces. Scaly fabric is locally arranged in S-C structures. Lenticular clasts, layer remnants, and boudins embedded within the matrix show their long-axis aligned to the tectonic foliation (see Fig. 4, *a*, *c*). Rotation of the boudins occurs against the shear direction following the formation of the S-C structures likely as Fossen [2016] described it. The rigid clasts and/or boudins somewhere demonstrate sigma-type rotation structures. Some blocks in the mélange reach the size of several meters up to a few tens of meters, and the rigid sandstone blocks are somewhere highly fractured up to tectonic breccia (see Fig. 9, *a*). On the contrary to the mélange, the olistostrome matrix is not characterized by such scaly fabric and tectonic foliation; instead, it is characterized by typical sedimentary textures (see Fig. 5, *a*, *b*).

Generally, in the inner part of the Ukrainian Carpathians, including the Pieniny Klippen Belt, Marmarosh Klippen Zone, and internal nappes of the Outer Carpathians (see Fig. 1), the mélange zones are more widespread than in the external nappes. As a rule, the tectonic foliation (i.e., cleavage) in the mélange zones, as well as the hinges of the folds, is sub-vertical here, which suggests strike-slip movement with sub-horizontal principal axes of compression and extension in the inner part of the orogen.

Mélanges and broken formations in the external nappes of the Outer Carpathians are, as a rule, related to the steep and gently inclined thrust zones. The shear zones are developed in the frontal part of the thrust sheets, where the deposits are boudinaged, disrupted, and somewhere demonstrated a mélange block-in-matrix structure. Fault-related drag folds with sub-horizontal hinges are widely developed here. The detachment zones filled with duplexes and drag folds are also exposed (see Fig. 14).

The study of sets of small faults with slicken-sides within the Pieniny Klippen Belt provided the reconstruction of regular stress fields correlated to the geodynamics of the Carpathian-Pannonian region. The northeastern vergence of the fold-nappe structure of the Ukrainian Carpathians and reconstructed stress fields indicate SW-NE regional compression. In the compression field, S-N trending strike-slip faults were activated and formed. The Oash dextral strike-slip fault zone is recorded by our study in the Priborzhava quarries. We also correlate several oblique normal faults trending in the Carpathian direction and activated in the transtension regime with SW 240° oriented extension axis to the Transcarpathian Depression formation. Therefore, the mélange zones in the inner part of the Ukrainian Carpathians were formed largely due to strike-sleep movements. In contrast, in the outer part of the Carpathian orogen, they were formed mainly due to thrust movements.

Acknowledgement. The study was fulfilled within the projects «Geodynamics and Mesozoic-Cenozoic evolution of the Ukrainian Carpathians in the context of the formation of potentially oil and gas-bearing deposits» (project № III-14-21), «Development of technologies for exploration and ecological conversion of hydrocarbon and ore critical and strategic raw materials of the southwestern part of the East European craton and the Ukrainian Carpathians» (project № B-II-11-23) of the National Academy of Sciences of Ukraine and supported by the Research grants reserved for Ukrainian researchers entitled «Tectonic architecture of northern Carpathians from geophysical and geological data» of Department of Chemistry, Life and Environmental Sustainability of University of Parma, Italy.

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Характерні структури зон меланжів в Українських Карпатах

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Зони меланжу характеризуються структурою, яка представлена жорсткими блоками різного розміру, літології та віку, огорнутими пластичним матриксом. Хоча меланж є значним компонентом орогенних поясів, в Українських Карпатах меланжі тектонічного походження фактично не вивчались. Описано деякі зони меланжів, поширені у Пенінському поясі, Мармароській кліповій зоні та у внутрішніх покривах Українських Зовнішніх Карпат, а також типові деформаційні структури, розвинені в них.

Матрикс меланжу характеризується лускоподібною текстурою, утвореною поверхнями кліважу, які подекуди формують S-C структури. Лінзоподібні класти в матриксі орієнтовані своєю довгою віссю вздовж тектонічної фоліації. Обертання будин відбувається проти напрямку зсуву у відповідності до формування S-C структур. Жорсткі класти подекуди формують структури обертання сигма-типу. Деякі блоки в меланжі дуже катаклазовані і представлені тектонічними брекчіями.

Дослідження тектонічних дзеркал та інших деформаційних структур у межах Пенінського поясу демонструють наявність регулярних полів напружень, які корелюються з геодинамікою Карпато-Паннонського регіону. Основне поле напруження вказує на регіональне стиснення з південного заходу на північний схід, пов'язане з утворенням карпатських покривів і субмеридіональних правосторонніх зсувних

розривів. Оашська зона правобічних зсувних розривів зафіксована нашими дослідженнями у Приборжавських кар'єрах. Косі скиди карпатського напрямку в межах Пенінського поясу ми пов'язуємо з формуванням Закарпатської западини.

Наше дослідження показало, що зони меланжів у внутрішній частині Українських Карпат утворилися переважно внаслідок зсувних переміщень, тоді як у зовнішній частині Карпатського орогену вони сформувались більшою мірою внаслідок насувоутворення.

Ключові слова: тектонічний меланж, Зовнішні Українські Карпати, зона П'єнінських скель, зона Мармароських скель, поля напружень.