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TECTONIC PALEOSTRESS FIELDS EVOLUTION AND CALCITE VEINS FORMATION IN THE SOUTHEASTERN PART OF THE UKRAINIAN CARPATHIANS DURING THE CENOZOIC TIME

Purpose. The main purpose of this paper is to study tectonic paleostress field evolution, its influence on the calcite veins formation and fluid flow in the southeastern part of the Ukrainian Carpathians during the Cenozoic time. The objects of our studies are joints parageneses, slickensides and veins in the Cretaceous sandstones located over the Chornohora, Dukla, Porkulets and Rakhiv nappes in the southeastern part of the Ukrainian Carpathians. **Methods.** To reconstruct the stress-strain state structural-paragenetic and kinematic methods were used. Fabric 8, StereoNett 2.46, and Tensor software was used to process the data and to determine the principal axes of paleostress field (σ_1, σ_2, σ_3). Slickenside data were processed by using kinematic method with some modern modifications for the Carpathian region. Special attention was paid to the veins in the host rocks. **Results.** Within the study area we found 16 natural outcrops, 850 joints, 300 veins and 50 slickensides. Further, we described veins structural features and paleostress fields that could initiate joints formation. Not at all outcrops calcite veins were found. The statistically reliable number of carbonate veins was identified only at few study points. It is very important to study not only veins structural features but mineralogy, morphology, crystal microdefects, and fluid inclusions as well. **Originality. For the first time** we reconstructed tectonic paleostress fields evolution in the southeastern part of the Ukrainian Carpathians during the Cenozoic time by using data on joints and slickensides. The most active tectonic movements, deformation and carbonate veins formation are attributed to the strike-slip and tension paleostress fields. Strike-slip paleostress fields are defined as the youngest, and their tension axes are orientated in NE-SW and NW-SE directions. The number of calcite veins within the Dukla and Porkulets nappes is much more greater than that within the Chornohora and Rakhiv ones. Almost all veins strike in north-west direction. Ancient joints could be reactivated and filled with calcite simultaneously with subsequent tension regimes. **Practical significance.** Paleostress fields originated at the end of folding-faulting stage indicate that the strike-slip deformation regime changed due to tension in two directions (SE and SW tension axes). The detailed study of veins showed that their formation is the result of newly formed and reactivated joints and fractures filled by the matter due to the younger mechanical deformations. Calcite filled shear and tension joints formed as the result of different deformation regimes, starting from the folding-faulting stage. We conclude that intensive migration of fluids, including hydrocarbons fluids, took place at the end of folding-faulting stage of the Ukrainian Carpathian tectonic evolution.

Key words: joints, slickensides, paleostress fields, calcite veins, fluid migration, Rakhiv nappe, Porkulets nappe, Chornochora nappe, Dukla nappe.

Purpose

Analysis of publications [Ratschbacher et al., 1993a, 1993b; Roure et al., 1993; Nemcok, 1993; Nemcok et al., 1998; Fodor et al., 1999; Matenco et al., 1997; Matenco, Bertotti, 2000; Ciulavu et al., 2000; Konon, 2001; Nemcok et al., 2006; Gintov et al., 2011, 2013] providing important data on geodynamics of various parts of the Carpathians shows that detailed studies of joints and slickensides are very important in the reconstruction of stress-strain state and geodynamics within the regions of complex tectonic history. This allows to reconstruct the paleostress fields evolution and detect the deformation regimes and phases, which acted during the major tectonic evolution stages within the study area.

Paleostress fields and geodynamics of fault zones attract the particular interest. Fault zones occupy only a small part of the Earth's crust but undoubtedly they are very important structures that control mechanical properties, especially permeability, of rocks and fluid flow. Faults have great influence on fluid migration. For example, hydrocarbons migration, ore deposits formation, and different hydrothermal flows are very often controlled by faults [Faulkner et al., 2010; Molli et al., 2010; Minissale, 2004]. The study of veins gives information on water-rock interaction, metasomatic process and changes of fluid features during fluid migration and vein formation in the host rocks.

Veins are the result of active fluid flow in host rocks and their formation depends on the fracturing process because the majority of veins are formed by filling fracture free space with minerals. Features of mineral aggregates and veins morphology depend on their fracturing mechanism [Faulkner et al., 2010].

However, while conducting observations aimed at studying structural, tectonic and physical features of the Ukrainian Carpathians, little attention has been paid to the veins investigation and their mineralogy. At the same time, while investigating the mineralogy of veins, researchers scarcely consider bedding, relation of active fluid flow during veins formation and tectonic evolution of the region [Bratus and Lomov, 1996; Matviyenko et al., 2004; Holovchenko and Popivnyak, 2009]. To achieve our goal, i.e. to study joints and veins in the Cretaceous flysch deposits of the SE part of the Ukrainian Carpathians, we used complex tectonophysical and mineralogical methods.

The main purpose of this paper is to study tectonic paleostress field evolution and its influence on the calcite veins formation, and fluid flow in the southeastern part of the Ukrainian Carpathians during the Cenozoic time. The objects of our research are joints parageneses, slickensides and veins in the Cretaceous sandstones within the Chornohora, Dukla, Porkulets and Rakhiv nappes located in the southeastern part of the Ukrainian Carpathians. Field work, tectonophysical and structural studies were conducted within the Chorna Tysa and Tysa rivers valley (Fig. 1) in 2011–2015.

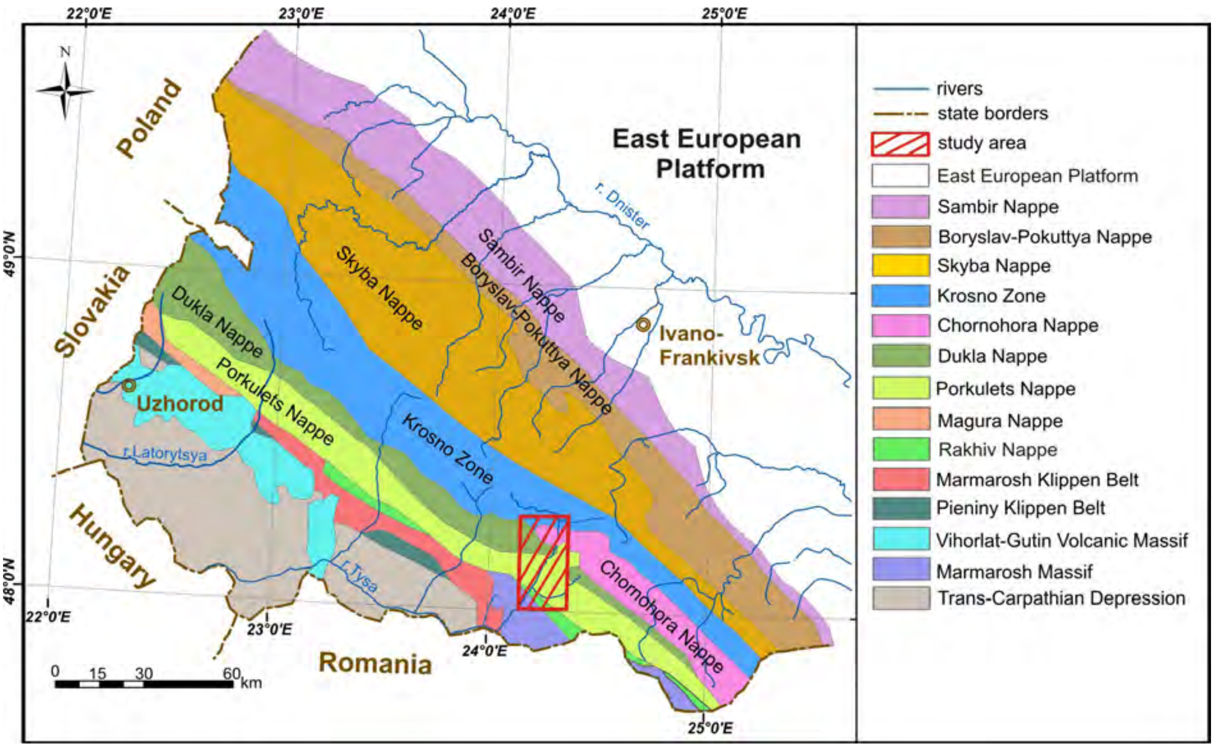

Fig. 1. Simplified tectonic map of the Ukrainian Carpathians and location of the study area (following Kruglov 1986)

Methods

To reconstruct the stress-strain pattern we applied the structural-paragenetic method. For data processing and determining the principal axes of paleostress field (σ_1, σ_2, σ_3) we used Fabric 8, StereoNett 2.46 and Tensor software. Structural-paragenetic method was described in detail by Prof. O.B. Gintov [Gintov, 2005]. According to the methodology of structural-paragenetic analysis, joints are divided into 3 groups, based on their hypothetical formation time:

1) joints formed prior to the folding process – directed subvertically (75°–90°) relative to the initial bedding of the deposits; 2) joints formed during folding-faulting process –directed oblique (25°–75°) relative to the initial bedding of the deposits; 3) joints formed during post-folding phase (generally affected by modern tectonic processes) – subvertical ones (75°–90°) in relation of the actual bedding of deposits.

The major systems of RR' and LL' joints types in these groups were assigned after distinguishing. Major systems of joints were measured and the main parameters (σ_1, σ_2, σ_3) were processed using Fabric 8 and StereoNett 2.46 to determine the main paleostress fields.

Slickenside data were processed using kinematic method [Angelier, 1984; Guschenko, 1987] with some modern modifications applicable for the Carpathian region (inverse method) [Gintov, 2005]. Data being processed includes those on fault plane, slickenlines bedding and fault kinematic types.

The relative age of structural element formations was determined by the correlation between various structural elements. It was important to identify joint and slickensides conformation. Main parameters of paleostress fields were processed using Tensor. Among these are the following: axis – σ_1 (compression), σ_2 (average), σ_3 (strain), and the coefficient R.

Integrated usage of both methods (structural-paragenetic and kinematic) provides more complete information on evolution history of the paleostress fields within the study area. The structural-paragenetic method helps to identify paleostress fields in the early stages of deformation.

During field works we produced a detailed description of veins morphology and mineral content as well as mineralogical changes in the host rocks. Specific attention was paid to the veins intersections and displacements, yielding information on the sequences of individual minerals and mineral association formations in veins. The most important features in these cases are: the intersection of veins, idiomorphism of early minerals over the later ones, micro cracks in crystals filled with later minerals, brecciation, and minerals replacement. Migration of fluids and subsequent joints filling may occur on reactivated joints formed during the early tectonic stages.

Results

The study area is located in the SE part of the Ukrainian Carpathians. It crosses the Rakhiv, Porkulets, Dukla and Chornohora nappes of the Outer Carpathians (see Fig. 1).

In general, the Rakhiv nappe overthrusted by the Kamyanyy Potik unit and the Marmarosh Massif, and overthrust the Porkulets nappe. The minimal distance of overthrusting is several kilometers. The Rakhiv nappe consists of the Lower Cretaceous (mainly Valanginian–Hauterivian) black and dark-gray, mainly thin and medium-bedded sandstone, siltstone and claystone as well as grey or dark-grey, pelitomorphic limestone and marble interlayers [Slaczka et al., 2006; Matskiv et al., 2005] (Fig. 2).

The Porkulets nappe (3–5 up to 18 km width) consists of the Lower Cretaceous (Barremian–Albian) flysch of the Bila Tysa and Burkut formations (see Fig. 2).

The Bila Tysa formation consists mainly of grey sandstones and claystones. Thin-bedded flysch (thickness is not more than 0.1–1 m) consists of calcareous mudstones, siltstones, and sandstones.

The Burkut formation locally replaces the Bila Tysa formation. In the lower part of section it consists of grey massive sandstones or conglomerates and claystones. Sandstone pack (approx. 1.5 m width) and dark grey or green mudstone thin rhythms pack (approx. 3 m thick) are typical. The upper part of this section consists of massive grey sandstone packs (more than 6 m width, rarely up to 10–12 m) with green and grey claystone and siltstone interlayers. The total thickness is about 1000 m [Slaczka et al., 2006].

The Jurassic deposits (Trostianets vulcanites, J_1tr) are outcropped on the Porkulets and Duklya nappes border.

The Dukla and Chornohora nappes within the study area consist of the Early Cretaceous-Eocene sediments (Shypit (K_1sp), Porkulets (K_{1-2}pr), Yalovychor (K_2jl), Chornogolova (K_2-P_2ch) formations). Several researchers [Shlapinskyy, 2012] combine these two units in one complex Dukla-Chornohora nappe due to the similar lithological composition and history of their development.

The Shypit formation in lower part of the section consists of dark gray, black siliceous claystones interbedded by marls, sandstones and siltstones. In the upper part medium and thick beds of grey siliceous sandstones interbedded with dark gray and black, sometimes greenish-gray siliceous mudstones and siltstones are found. The Porkulets formation consists of green and red sandstones, mudstones with red marls. The Yalovychor formation consists of rhythmical flysch interbedded with sandstones, limestones, and marls. The Chornogolova formation consists of sandstones and grey shales (see Fig. 2). In the study area there are several faults that can play an important role in the migration of fluids: thrusts delineating nappes and the Rakhiv-Tysa fault (north-south strike) (see Fig. 2).

Research findings on joints and slickensides. Within the study area we observed 16 natural outcrops, more than 850 joints, 300 veins and 50 slickensides.

Palaeostress fields were reconstructed per the various groups of joints (joints formed prior to the folding-faulting process, during folding-faulting process and after folding-faulting process) and slickensides at each study point (**OP**) for different nappes (Table 1, 2, 3 and Fig. 3)

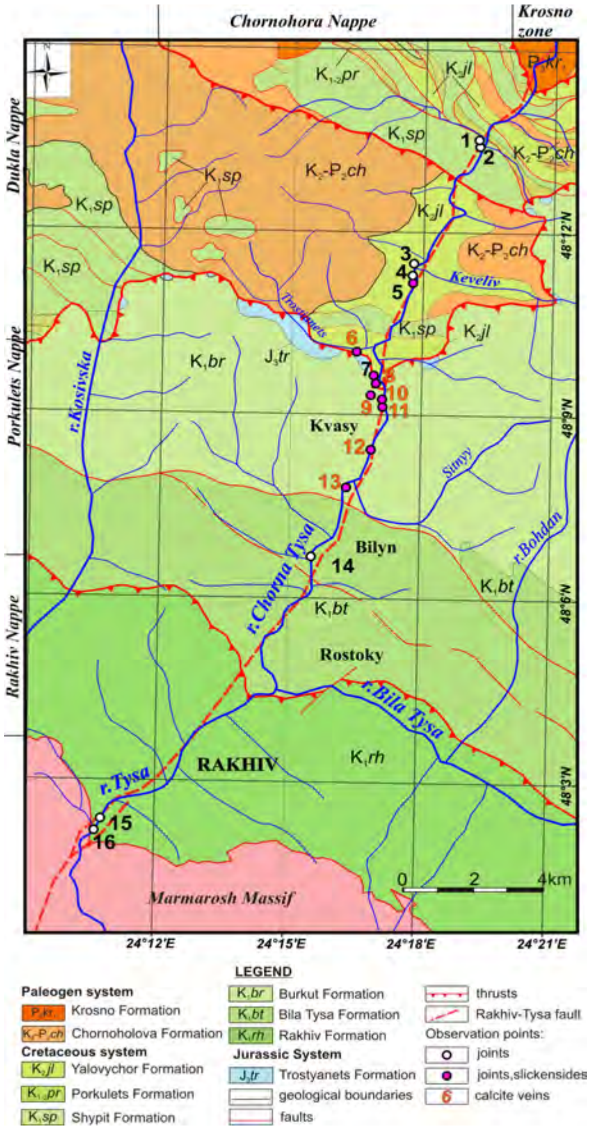

Fig. 2. Geological map of the Rakhiv area (following Matskiv et al., 2005 and Fedorin, 1983)

Table 1

Paleostress fields showing main axis (σ_1 and σ_3) directions at the Chornohora and Dukla nappes with in the Chorna Tysa river valley

OP	Prefolding-thrusting stress fields			Folding-faulting stage stress fields			Post folding-thrusting stress fields					Formation
	Chornohora Nappe											
1	σ_1 005/05 σ_3 275/03				σ_1 084/02 σ_3 348/26			σ_1 357/14 σ_3 088/03				Shypit, K_1sp
2			σ_1 054/12 σ_3 322/10			σ_1 103/05 σ_3 012/19	σ_1 063/13 σ_3 331/10	σ_1 358/12 σ_3 226/10				
	Dukla Nappe											
3			σ_1 229/03 σ_3 319/02				σ_1 237/07 σ_3 329/13		σ_1 090/00 σ_3 180/05			Yaloyychor, K_2jl
4					σ_1 079/03 σ_3 347/30	σ_1 343/06 σ_3 251/13				σ_1 298/01 σ_3 029/11		
5					σ_1 034/04 σ_3 125/07		σ_1 234/01 σ_3 144/08					
6	σ_1 357/01 σ_3 266/06				σ_1 204/12 σ_3 301/27					σ_1 135/11 σ_3 041/13		
7	σ_1 016/14 σ_3 107/06			σ_1 195/00 σ_3 286/84	σ_1 069/02 σ_3 338/27			σ_1 173/17 σ_3 270/21		σ_1 306/03 σ_3 215/09		
8		σ_1 257/06 σ_3 116/03			σ_1 211/09 σ_3 119/17	σ_1 096/02 σ_3 188/20		σ_1 355/04 σ_3 264/03	σ_1 086/03 σ_3 176/01	σ_1 150/02 σ_3 059/12		

compression; tension; fracture diagrams; slickenside diagrams

Palaeostress fields within the Chornohora nappe (see Table 1). We identified paleostress fields in the Low Cretaceous sediments (the Shypit formation) (**OP 1, 2**). By joints formed prior to the folding-faulting stage, paleostress fields with following directions of principal axes were detected: σ_1 – 005/05°, σ_3 – 188/05° (**OP 1**); σ_1 – 054/12°, σ_3 – 322/10° (**OP 2**). Strike-slip paleostress fields formed during the folding-faulting stage: σ_1 – 084/02°, σ_3 – 348/26° (**OP 1**); σ_1 – 103/05°, σ_3 – 012/19° (**OP 2**).

The youngest paleostress fields defined by nearly vertical joints (actual bedding – 75°–90°) are as follows: σ_1 – 357/14°, σ_3 – 088/03° (**OP 1**); σ_1 – 063/13°, σ_3 – 331/10° and σ_1 – 358 / 12°, σ_3 – 226/10° (**OP 2**).

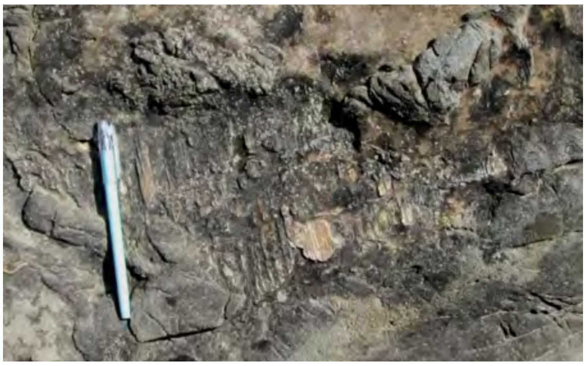

Fig. 3. Example of the slickensides in Burkut sandstones (OP 11, calcite slickenfibres)

Palaeostress fields within the Dukla nappe (see Table 1). Mesostructures were measured in the Upper Cretaceous sediments (the Yalovychor formation) at six outcrops close to the Keveliv stream outfall (**OP 3-8**) (see Fig. 2). All identified paleostress fields are of strike-slip types.

Such earliest paleostress fields were reconstructed per the joints directed subvertically (75°–90°) in relation to the initial bedding of deposits: σ_1 – 357/01°, σ_3 – 266/06° (**OP 6**); σ_1 – 016/14°, σ_3 – 107/06° (**OP 7**); σ_1 – 257/06°, σ_3 – 116/03° (**OP 8**); σ_1 – 229/03°, σ_3 – 319/02° (**OP 3**).

Few paleostress fields: 1. of NE–SW compression: σ_1 – 079/03°, σ_3 – 347/30° (**OP 4**); σ_1 – 204/12°, σ_3 –301/27° (**OP 6**); σ_1 – 069/02°, σ_3 – 338/27° (**OP 7**); 2. of NW-SE compression: σ_1 – 343/06°, σ_3 – 251/13° (**OP 4**); σ_1 – 096/02°, σ_3 – 188/20° (**OP 8**) were distinguished by joints directed obliquely 25°–75° relative to the initial bedding of deposits data processing. The youngest reconstructed stress fields are: 1. of NE–SW compression: σ_1 – 237/07°, σ_3 – 329/13 (**OP 3**); σ_1 – 234/01°, σ_3 –144/08° (**OP 5**); 2. of NE tension: σ_1 – 090/00°, σ_3 – 180/05° (**OP 3**); σ_1 – 086/03°, σ_3 – 176/01° (**OP 8**); 3. of NE–SW tension: σ_1 – 298/01°, σ_3 – 029/11° (**OP 4**); σ_1 – 150/02°, σ_3 – 059/12° (**OP 8**).

Using kinematic method few deformation regimes were determined: pure tension deformation regimes with σ_1 – 195/00°, σ_3 – 286/84° (**OP 7**) and strike-slip deformation regimes of NE–SW directed compression axes: σ_1 – 034/04°, σ_3 – 125/07° (**OP 5**); σ_1 – 211/09°, σ_3 – 119/17° (**OP 8**). These deformation regimes show trusting process in the region. At post folding-trusting stage the following paleostress fields were active: of NE compression (σ_1 – 173/17°, σ_3 – 270/21° (**OP 7**) and σ_1 – 355/04°, σ_3 – 264/03° (**OP 8**)) and of SW–NE compression (σ_1 – 135/11°, σ_3 – 041/13° (**OP 6**) and σ_1 – 306/03°, σ_3 – 215/09° (**OP 7**)).

Palaeostress fields within the Porkulets nappe (see table 2). Mesostructures at the Porkulets nappe were studied in the Low Cretaceous sediments (the Bila Tysa and Burkut formation).

Joints and slickensides were measured at six outcrops (OP 9-14) within the valleys of the Chorna Tysa river, Trostianets and Sitnyy streams close to Kvasy and Bilyn villages.

By subvertical joints, formed due to prefolding-faulting process, two strike-slip paleostress fields were determined: 1. of WE directed compression axes and NS directed tension axes: σ_1 – 265/16°, σ_3 – 174/03° (**OP 9**); σ_1 – 271/05°, σ_3 – 001/11° (**OP 10**); σ_1 – 095/06°, σ_3 – 004/04° (**OP 12**); σ_1 – 097/07°, σ_3 – 188/05° (**OP 14**); 2. of NE–SW directed compression axes: σ_1 – 042/02°, σ_3 – 132/07° (**OP 11**); σ_1 – 216/10°, σ_3 – 124/07° (**OP 12**); σ_1 – 205/04°, σ_3 – 114/05° (**OP 12**) (see Table 2).

During folding-faulting stage the following strike-slip paleostress fields were active: 1. of NE–SW directed compression axes: σ_1 – 048/03°, σ_3 – 318/07° (**OP 10**); σ_1 – 061/05°, σ_3 – 329/22° (**OP 11**); σ_1 – 243/01°, σ_3 – 153/26° (**OP 12**); σ_1 – 232/07°, σ_3 – 326/29° (**OP 13**); 2. of WE directed compression axes σ_1 – 266/01°, σ_3 – 176/31° (**OP 14**).

The youngest paleostress fields determined by nearly vertical joints are as follows:

1. strike-slip fields of NE–SW directed compression: σ_1 – 043/03°, σ_3 – 312/13° (**OP 9**); σ_1 – 248/02°, σ_3 – 157/26° (**OP 11**); σ_1 – 049/01°, σ_3 – 139/11° (**OP 12**);

2. strike-slip fields of N–S directed compression: σ_1 – 187/28°, σ_3 – 094/06° (**OP 9**); σ_1 – 357/06°, σ_3 – 089/17° (**OP 10**); σ_1 –176/06°, σ_3 – 083/11° (**OP 11**); σ_1 – 018/05°, σ_3 – 109/08° (**OP 14**);

3. strike-slip fields of W–E directed compression: σ_1 – 276/09°, σ_3 – 184/07° (**OP 9**); σ_1 – 264/19°, σ_3 – 173/03° (**OP 11**); σ_1 – 082/06°, σ_3 – 173/04° (**OP 12**); σ_1 – 090/00°, σ_3 – 180/12° (**OP 14**);

4. strike-slip fields of NE–SW directed compression: σ_1 – 330/00°, σ_3 – 241/21° (**OP 11**); σ_1 – 324/15°, σ_3 – 056/08° (**OP 13**);

5. pure tension fields of NW–SE directed tension: σ_1 – 020/50°, σ_3 – 131/16° (**OP 11**); σ_1 – 236/56°, σ_3 – 136/08° (**OP 13**); and of NE–SW direction – σ_1 – 316/55°, σ_3 – 056/07° (**OP 14**).

Using kinematic method we identified several deformation regimes. During folding-faulting stage the following deformation regimes were active : pure compression (σ_1 – 082/19°, σ_3 – 230/68° (**OP 11**); σ_1 – 239/16°, σ_3 – 061/74° (**OP 13**)) and strike-slip (σ_1 – 227/05°, σ_3 – 317/06° (**OP 11**); σ_1 – 033/17°, σ_3 – 128/17° (**OP 13**). Strike-slip deformation regime of N–S directed compression (σ_1 – 347/12°, σ_3 – 079/09° (**OP 10**); σ_1 – 005/10°, σ_3 – 275/04° (**OP 11**); σ_1 – 180/05°, σ_3 – 271/08° (**OP 13**)) was determined based on the prevalence of slickensides.

Also, such strike-slip paleostress fields as σ_1 – 270/13°, σ_3 – 179/07° (**OP 12**); σ_1 – 108/14°, σ_3 – 016/08° (**OP 9**); σ_1 – 120/03°, σ_3 – 028/23° (**OP 11**); σ_1 – 107/16°, σ_3 – 016/05° (**OP 13**) were reconstructed. Besides, pure tension paleostress fields were determined per several slickensides: σ_1 – 003/71°, σ_3 – 138/14° (**OP 12**); σ_1 – 132/69°, σ_3 – 226/01° (**OP 13**).

Table 2

Paleostress fields showing main axis (σ_1 and σ_3) directions within the Porkulets nappe in the Chorna Tysa river valley

OP	Prefolding-faulting stress fields			Folding-faulting stage stress fields			Post folding-faulting stress fields					Formation
	Porkulets nappe											
9		$\sigma_1$265/16 $\sigma_3$174/03					$\sigma_1$043/03 $\sigma_3$312/13	$\sigma_1$187/28 $\sigma_3$094/06	$\sigma_1$276/09 $\sigma_3$184/07	$\sigma_1$108/14 $\sigma_3$016/08		Burkut, K_1bt
10		$\sigma_1$271/05 $\sigma_3$001/11			$\sigma_1$048/03 $\sigma_3$318/07			$\sigma_1$357/06 $\sigma_3$089/17; $\sigma_1$347/12 $\sigma_3$079/09				Burkut, K_1bt
11			$\sigma_1$042/02 $\sigma_3$132/07	$\sigma_1$082/19 $\sigma_3$230/68	$\sigma_1$061/05 $\sigma_3$329/22; $\sigma_1$227/05 $\sigma_3$317/06		$\sigma_1$248/02 $\sigma_3$157/26	$\sigma_1$176/06 $\sigma_3$083/11; $\sigma_1$005/10 $\sigma_3$275/04	$\sigma_1$264/19 $\sigma_3$173/03	$\sigma_1$330/00 $\sigma_3$241/21; $\sigma_1$120/03 $\sigma_3$028/23	$\sigma_1$020/50 $\sigma_3$131/16	Burkut, K_1bt
12		$\sigma_1$095/06 $\sigma_3$004/04	$\sigma_1$216/10 $\sigma_3$124/07		$\sigma_1$243/01 $\sigma_3$153/26		$\sigma_1$049/01 $\sigma_3$139/11		$\sigma_1$082/06 $\sigma_3$173/04; $\sigma_1$270/13 $\sigma_3$179/07		$\sigma_1$003/71 $\sigma_3$138/14	Burkut, K_1bt
13			$\sigma_1$205/04 $\sigma_3$114/05	$\sigma_1$239/16 $\sigma_3$061/74	$\sigma_1$232/07 $\sigma_3$326/29; $\sigma_1$033/17 $\sigma_3$128/17			$\sigma_1$180/05 $\sigma_3$271/08		$\sigma_1$324/15 $\sigma_3$056/08; $\sigma_1$107/16 $\sigma_3$016/05	$\sigma_1$236/56 $\sigma_3$136/08; $\sigma_1$132/69 $\sigma_3$226/01	Burkut, K_1bt
14		$\sigma_1$097/07 $\sigma_3$188/05				$\sigma_1$266/01 $\sigma_3$176/31		$\sigma_1$018/05 $\sigma_3$109/08	$\sigma_1$090/00 $\sigma_3$180/12		$\sigma_1$316/55 $\sigma_3$056/07	Bila Tysa, K_1bt

Palaeostress fields within the Rakhiv nappe (see Table 3). Joints and slickensides were examined in the Low Cretaceous sediments at the thrust zone (the Rakhiv formation, **OP 15, 16**) in the Tysa river valley near Rakhiv town.

The earliest paleostress fields determined by subvertical joints, formed prior to the folding–trusting process are: σ_1 – 185/09°, σ_3 – 275/01° (**OP 16**); σ_1 – 272/01°, σ_3 – 002/07° (**OP 15**).

During the folding-faulting stage several paleostress fields were active: 1. pure compression of NE–SW compression: σ_1 – 233/22°, σ_3 – 352/51° (**OP 15**); σ_1 – 078/06°, σ_3 – 338/66° (**OP 16**); 2. strike-slip of N–S directed compression: – σ_1 – 192/12°, σ_3 – 283/08° and W–E directed compression: σ_1 – 085/01°, σ_3 – 354/22° (**OP 16**).

The youngest paleostress fields reconstructed by nearly vertical joints are strike-slip paleostress fields: 1. of NE–SW directed compression: σ_1 – 049/03°, σ_3 – 318/04° (**OP 16**); σ_1 – 019/07°, σ_3 – 289/01° (**OP 15**); 2. of W–E directed compression: σ_1 – 087/00°, σ_3 – 357/13° (**OP 15**); σ_1 – 080/02°, σ_3 – 350/10° (**OP 16**); 3. Of NE–SW directed tension: σ_1 – 312/12°, σ_3 – 042/01° (**OP 16**).

Table 3

Plaeostress fields showing main axis (σ_1 and σ_3) directions within the Rakhiv nappe in the Tysa river valley

OP	Prefolding-faulting stress fields			Folding-faulting stage stress fields			Post folding-faulting stress fields					Formation
	Rakhiv nappe											
15		$\sigma_1$272/01 $\sigma_3$002/07		$\sigma_1$233/22 $\sigma_3$352/51	$\sigma_1$192/12 $\sigma_3$283/08	$\sigma_1$085/01 $\sigma_3$354/22		$\sigma_1$019/07 $\sigma_3$289/01	$\sigma_1$087/00 $\sigma_3$357/13			Rakhiv, K_1rh
16	$\sigma_1$185/09 $\sigma_3$275/01			$\sigma_1$078/06 $\sigma_3$338/66			$\sigma_1$049/03 $\sigma_3$318/04		$\sigma_1$080/02 $\sigma_3$350/10	$\sigma_1$312/12 $\sigma_3$042/01		

Structural features of calcite veins. Veins are rather complicated objects to study. It is very important to observe not only vein structural features but also mineralogy, morphology. Further we describe veins structural features and paleostress fields capable to control formation of joints filled by calcite.

Not all outcrops show calcite veins. Only at few study points we identified statistically reliable number of carbonate veins (see. Fig. 2): **OP 9-13** (the Porkulets nappe, Burkut formation), **OP 6**, **OP 8** (the Chornohora nappe, Yalovychor formation).

Calcite veins in flysch deposits of the Porkulets nappe. Calcite veins in the Burkut sandstones (**OP 13,** left bank of the Chorna Tysa river) are directed alike – strike is 205–215, dip angle is 15–85° (Fig. 4, A).

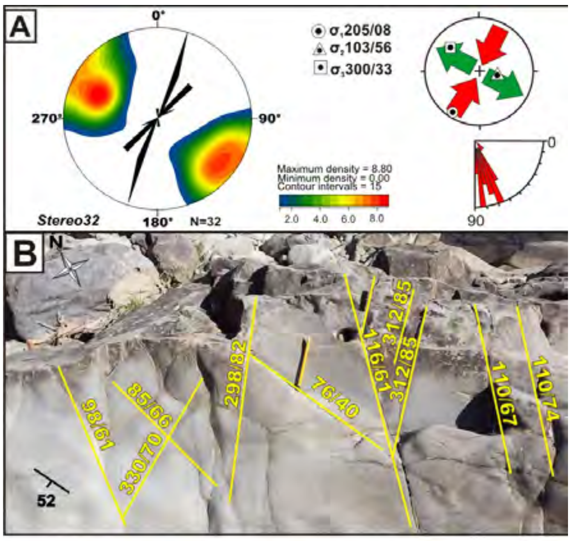

Fig. 4. Calcite veins in the Burkut sandstones: A) stereogram of pole in isolines, strike and dip angle rose diagrams of calcite veins and the main parameters of paleostress fields capable to cause joints formation; B) typical and almost vertical calcite veins at the Porkulets nappe (**OP 12**)

The same situation is at other study points within the Porkulets nappe (**OP 12,** left bank of the Chorna Tysa river). Fractures in the Burkut sandstones are filled with calcites. Veins are 0.1–0.5 cm width, straight, typically vertical (dip angle is 55–80°), strike direction is 200–240 (Fig. 4, B). Using structural-paragenetic method we reconstructed possible paleostress fields, which could cause the formation of joints, lately filled with calcite.

In the Rakhiv-Tysa fault zone geological structure is complicated. Numerous local faults (mainly sinistral strike slip ones, displacement approx. 1–1.5 m) are common in the Burkut sandstones (**OP 11** found in Kvasy village at the right bank of the Chorna Tysa river).

To process data obtained from calcite veins is the most complicated task. Ex facte, calcite filled chaotic fractures formed at different tectonic stages. However, we found out some regularity amongst them (Fig. 5).

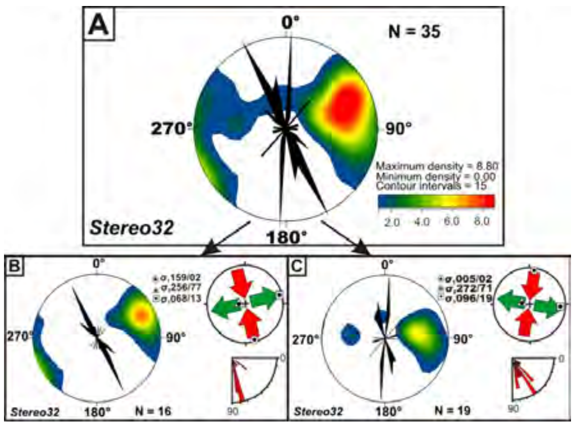

Fig. 5. Calcite veins in the Burkut sandstones (**OP 11**). Stereogram of poles in isolines, strike and dip angle rose diagrams of all (A), several thin (B) and thick calcite veins and the main parameters of the paleostress fields capable to cause joints formation

The greatest part of calcite veins is of unilateral direction, though it should be divided into two groups per their morphology and thickness. The first group is straight, thick, blocky calcite veins (0.3–2 cm) with a distinct boundary between the host rock and calcite vein.

The second group is composed of thin corrugated calcite veins (0.1–0.2 cm). These veins are multi-directed (see Fig. 5, A):

- thin calcite veins – strike is 10–340, dip angle is 40°–80° (see Fig. 5, B);
- thick calcite veins – strike is 315–330, dip angle is 75°–85°(see Fig. 5,C).

Several systems of joints in the Burkut sandstones (**OP 10**) are filled with calcite (Fig. 6, A–D). The earliest veins are of strike direction 180–250 and dip angle 60–70° (see Fig. 6). The next ones are tension veins directed alternatively (dip direction / dip angle): 264/75°, 350/62°, 70/89°. Formations of thick veins with inclusions of the host rocks out of joints indicate the reactivation of joints at tension regime. The youngest veins (180–240/65–85°) displace all earlier joints and veins (see Fig. 6, D).

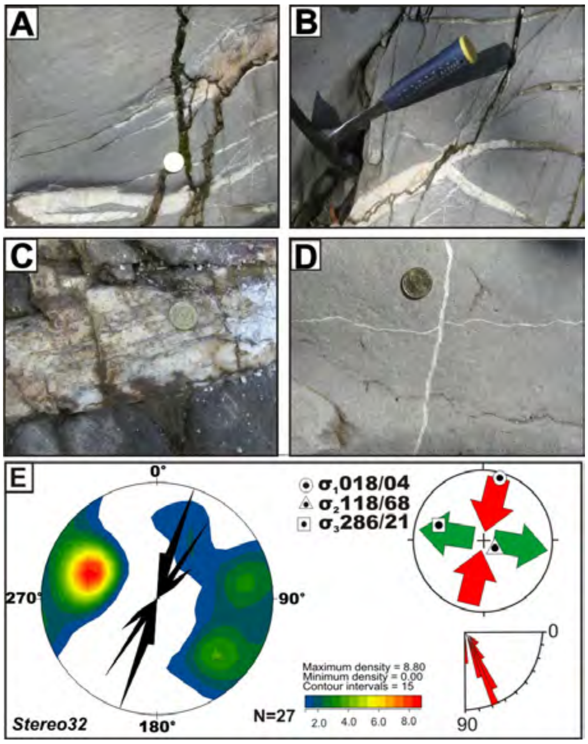

Fig. 6. Tension veins in the Burkut sandstones (A-D) and stereogram of pole in isolines, strike and dip angle rose diagrams of calcite veins and the main parameters of the paleostress fields capable to cause joints formation (E) (**OP 10**)

Veins filled with calcite and calcite plus Fe-Mn carbonates and quartz ("marmarosh diamonds") were identified at **OP 9**. These veins of different mineral composition were formed as a result of migration of different fluids and at different tectonic stages. Calcite veins are associated with the group of straight joints directed almost vertically – strike direction is 200–250, dip angle is 85–90° (Fig 7, A, B). Veins filled with calcite, quartz and Fe-Mn carbonates occur at sandstone and mudstone contact zones and are associated with a local sinistral strike-slip fault (Fig. 7, C).

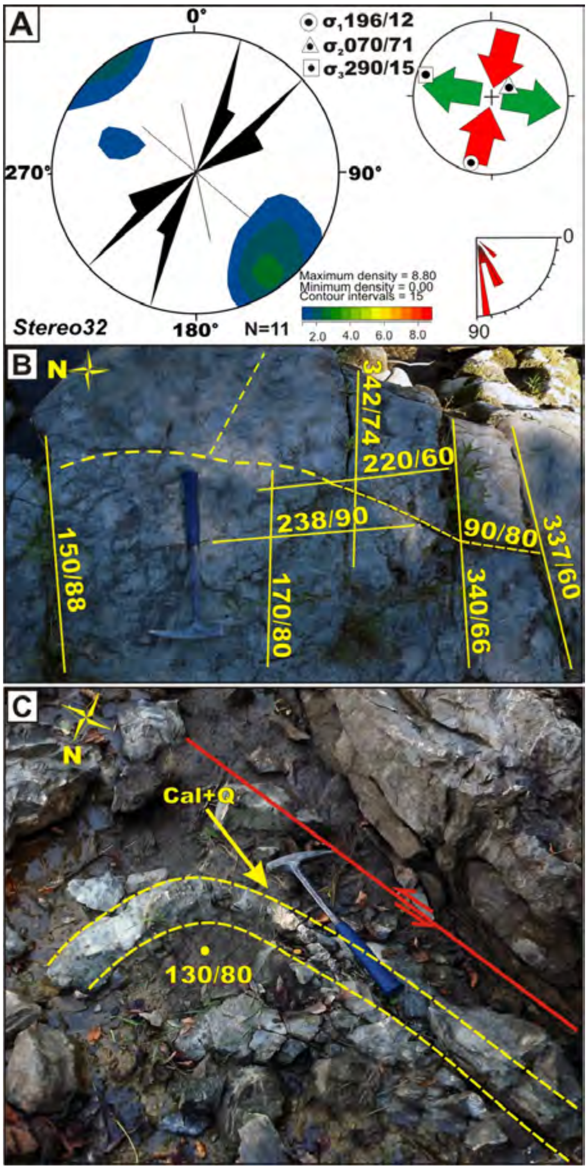

Fig. 7. Veins filled with calcite and calcite plus Fe-Mn carbonates plus quartz ("marmarosh diamonds"): A) stereogram of pole in isolines, strike and dip angle rose diagrams of calcite veins and the main parameters of paleostress fields capable to cause joints formation; B) almost vertical calcite veins in the curve of anticlinal fold (study point **OP** 9); C) veins filled with calcite and quartz located in the fold limb and controlled by sinistral strike-slip fault (study point **OP 9**)

Calcite veins in flysch deposits of the Dukla nappe. Calcite veins in the Yalovychor formation sandstones are vertical and intersect almost perpendicularly. Veins fill two systems of joints

(Fig. 8, A): the first system with strike direction of 200–220, dip angle 80–90°; and second with strike direction of 250–300, dip angle 40–90°. At the thrusting zone between the Porkulets and Dukla nappes (**OP 6**) the Yalovychor formation sandstones and mudstones are brecciated. Joints in sandstones, filled with calcite and Fe-Mn carbonates, are almost vertical – dip direction is 140-160, dip angle is 65–95° (Fig. 8, A).

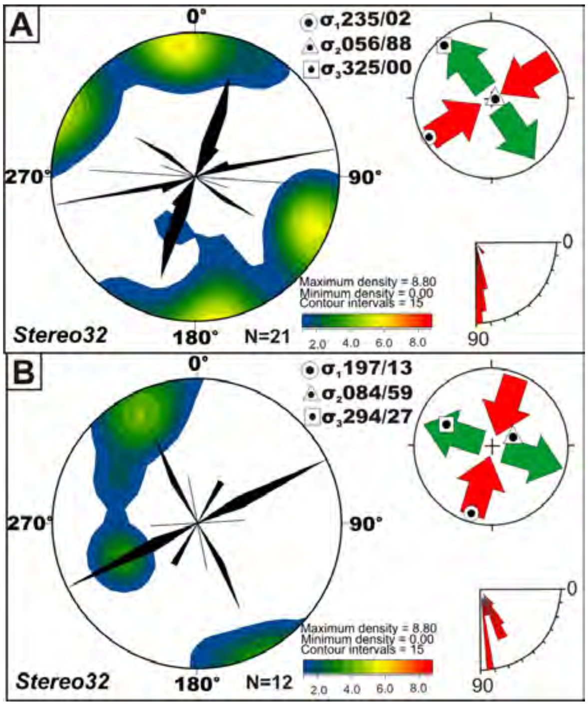

Fig. 8. Calcite veins in flysch deposits of the Dukla nappe: A) stereogram of pole in isolines, strike and dip angle rose diagrams of calcite veins and the main parameters of paleostress fields capable to cause joints formation (OP 8); B) stereogram of pole in isolines, strike and dip angle rose diagrams of calcite veins and the main parameters of paleostress fields capable to cause joints formation (OP 6)

Originality

Using the above data, we reconstructed tectonic paleostress fields evolution of the southeastern part of the Ukrainian Carpathians during the Cenozoic. Analysis of stress-strain pattern in the study area was performed on the basis of data represented in tables 1, 2 and Fig. 9.

Figure 9 shows generalized paleostress fields determined by slickensides and sliding grooves data by using kinematic method. Slickensides and sliding grooves are formed during intensive tectonic deformation. That is why it is possible to identify regional paleostress fields being active during folding-faulting and post folding-faulting stage, and local paleostress fields, which are closely related with fault zone formation.

The earliest joints were formed at the end of the Early- and Late Cretaceous sedimentation. Per these joints two strike-slip paleostress fields were reconstructed. The first paleostress field axis of maximum compression σ_1 is directed NS, axis of maximum extension σ_3 – EW and the second paleostress field: σ_1 – EW and σ_3 – NS.

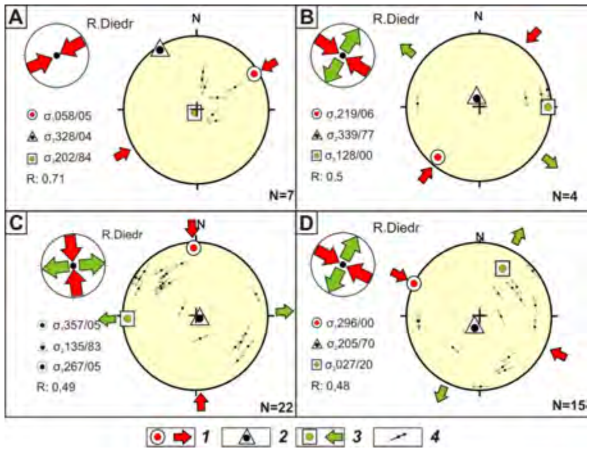

Fig. 9. Reconstruction of paleostress fields per the results of slickensides and sliding grooves (kinematic analysis) in flysch deposits in the Chorna Tysa river valley (1 – compression axis σ_1, 2 –intermediate axis σ_2; 3 – tension axis σ_3; 4 – fault slip vector). Paleostress fields: A – pure compression; B – strike-slip of typical Carpathian compression axis direction; C – strike-slip, which is associated with the Rakhiv-Tysa fault zone activity; D – strike-slip of typical Carpathian stretch axis direction)

It is complicated to define succession of these two paleostress fields. But, they undoubtedly were active at horizontal bedded rocks after litithication.

Next active strike-slip paleostress field has main compression axis directed NE-SW (the Carpathian direction perpendicular to the Ukrainian Carpathian strike). This paleostress field is confirmed by joints in the Early and Late Cretaceous deposits at studied nappes. Such strike-slip paleostress field could originate due to the Marmarosh crystalline massif thrusting at the end of the formation of the Internal Carpathians in the Early Cretaceous (Austrian phase). This paleostress field (compression axis σ_1 – 233, 078) was reconstructed per the joints in the Rakhiv formation deposits.

Most likely such paleostress fields, studied within other nappes (the Porkulets, the Dukla, and the Chornohora) also indicate the beginning of compression directed northeast-southwest. These paleostress fields were active in the Early Cretaceous and continued in the Paleogene.

Thrusting started with pure compression deformation regime determined by slickensides (σ_1 – 058/05° (compression in the Carpathian direction), σ_3 – 202/84°;

R = 0.71 (see Fig. 9). Within the study area this deformation regime is represented by reverse faults. It represents the regional paleostress field, which is affected throughout the Outer Ukrainian Carpathians during intensive compression It is testified by the compression (pure compression deformation regime) directed NE-SW. Similar pure compression paleostress field (σ_1 – 047/05° per kinematic data and σ_1 – 235/11° per joints data) was identified by Gintov et. al. [Gintov et al., 2011]. Other data [Matenco et al., 1997] show that in the Eastern Carpathians in Romanian territory σ_1 is directed 241/15±15° .

The next strike-slip paleostress field with a compression axis σ_1 of 219/06° and tension axis σ_3 of 128/00°, and R = 0,5 (see Fig. 9) was reconstructed using slickensides data (per dextral strike-slip). Such field with similar directions of normal stress axes is determined, using structural-paragenetic method, in the Cretaceous deposits within all studied nappes as well (see table 1, 2). These strike-slip paleostress field with compression axis ranging from 192 to 266 possibly was active during folding-faulting stage at all examined nappes.

At the post folding-faulting stage in southeastern part of the Ukrainian Carpathians plenty of paleostress fields were active. These paleostress fields are determined by using structural-paragenetic and kinematic method (see Table 1, 2, 3). The most representative is strike-slip paleostress field with compression axis σ_1 directed NS – 357/05°, tension axis σ_3 – 267/05°, R = 0,49 reconstructed per sinistral strike-slip slickensides. Other paleostress field is characterized by a large number of slickensides of SW-NE directed tension axis. The main axes of this strike-slip paleostress field with main axes are directed as follows: σ_1 – 296/00°, σ_3 – 027/20° and R = 0,48 (see Fig.9, D). The most active tectonic movements, deformation and carbonate veins formation (see Fig. 4–8) are related to these two late paleostress fields. Naturally, joints were reactivated simultaneously with the subsequent tension regime. These strike-slip paleostress fields are the youngest, and tension axes are directed NE-SW and NW-SE (see. Table 1, 2).

The said strike-slip and tension paleostress fields are probably related to the Rakhiv-Tysa fault zone which was active at neotectonic stage in the Tysa and Chorna Tysa river valleys. There are large number of slickensides, sinistral strike-slip with large displacement (1–1.5 m) and joints associated with these paleostress fields, as well as numerous veins. All this indicates significant tectonic activity within the Rakhiv-Tysa fault zone at post folding-faulting stage.

Veins formation is related to the mechanism of fracture and joints formation, as most of them are formed by filling the newly formed fracture free space with minerals. Mineral aggregates and veins morphology depend on fracture formation. Veins filled different joints but we identified some features of veins direction in all deposits (Fig. 10).

Calcite filled shear joints associated with different deformation regimes. The number of calcite veins within the Duklya and Porkulets nappes is much greater than within the Chornohora and Rakhiv nappes. Per the morphological features calcite veins can be divided into 2 groups: 1) thick calcite veins (0.3–2 cm) filled with blocky calcite and having clear-cut boundary with the host rocks; 2) thin calcite veins (1–2 mm), sometimes there is a awavy boundary with the host rocks.

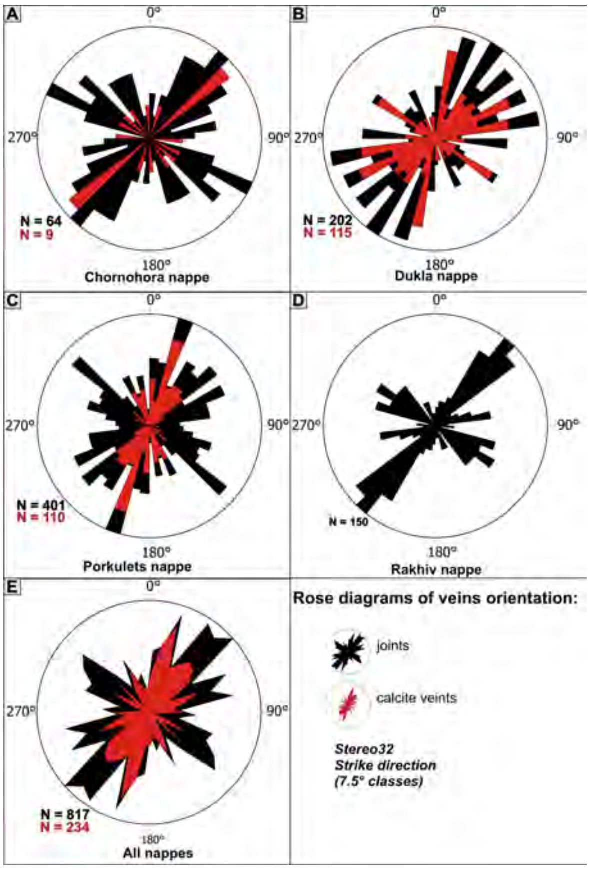

Fig. 10. Rose diagrams of the veins and joints direction in: A) the Chornogora nappe, B) the Dukla nappe, C) the Porkulets nappe, D) the Rakhiv nappe, E) All nappes

At first sight, calcite filled joints irregularly. But, on the rose diagram we can see, that almost all veins strike in north-west direction (see Fig. 10).

Fluids actively migrate along numerical neoformed fractures, connected to the subsequent reverse regime and ancient fractures, and precipitate mainly carbonate minerals. Obviously, fracture reactivation is associated with the subsequent tension regime.

Świerczewska *et al.* (2000) for the first time in detail described fracture mineralization in the Polish segment of the Outer Carpathians. Our results are comparable to these materials. According to Świerczewska *et al.* (2000) the majority of calcite in veins in the Tetiary sandstones (the Magura nappe) were filled with calcite or calcite and quartz more than once [Świerczewska et al, 2000].

Practical significance and conclusions

Using structural-paragenetic and kinematic analysis we reconstructed ancient and modern paleostress fields in the Rakhiv, Porkulets, Chornogora and Dukla nappes deposits during the Cenozoic. We investigated vein structural properties, joints, and slickenslides in the Cretaceous sandstones. Joints and slickensides data processing results supplement each other.

Palaeostress fields show changes in deformation regimes within the Dukla, Chornogora, Porkulets and Rakhiv nappes from the end of the sedimentation of the Lower and Upper Cretaceous deposits to completion of thrusting accompanied by the formation of the Ukrainian Carpathians Orogen, as well as during post folding-faulting stage.

Paleostress fields at the end of folding-faulting stage represent strike-slip deformation regime that was changed due to tension in two directions (tension axes directed SE and SW). This tension regime was identified per the modern vertical joints. The most intensive strike-slip paleostress field is determined per joints and sinistral strike-slip faults and its compression axis are of NS direction and tension axes are of EW direction. This deformation regime probably is associated with the Rakhiv-Tysa fault zone activity.

Veins formation is connected to the tectonic processes in the Rakhiv-Tysa fault zone and main stages of tectonic evolution of the Ukrainian Carpathians. The detailed study of veins showed that their formation is a result of newly formed and reactivated joints filling occurred due to the younger mechanical deformations. Analysis of direction of joints systems (see rose diagrams) filled with carbonates showed that within the Rakhiv-Tysa fault zone they filled tensional and shear fracture. Calcite filled shear and tension joints formed as result of different deformation regimes, starting from the folding-faulting stage. Great number of fractures in rocks at the Rakhiv-Tysa fault causes the increasing of permeability and determines the structural features of veins. Intensive filling of joints with carbonate minerals took place at several phases, most likely at the end of folding-faulting stage (calcite filled crossed and displaced joints). Also, in some calcite veins solid hydrocarbons and quartz (“marmarosh diamonds”) were found. We can conclude that at the end of folding-faulting stage of the Ukrainian Carpathian tectonic evolution the intensive migration of fluids, including hydrocarbons fluids, took place.

References

Angelier J. *Tectonic analysis of fault slip data sets.* 1984. J. Geophys. Res. No. 8 (B7). p. 5835–5848.

Bratus M., Lomov S. *Umovy mineraloutvorennya ta izotopna pryroda komponentiv flyuyidiv u zhylakh sered osadovykh porid Skladchastykh Karpat* [Mineral formation and isotopic nature of fluid components of veins in sedimentary rocks in the Folded Carpathians]. *Geolohiya i Geokhimiya goryuchykh kopalyn* [Geology and Geochemistry of Combustible Minerals], 1996, Vol. 1–2, pp. 94–95.

Ciulavu D., Dinu C., Szakacs A., Dordea D. *Neogene kinematics of the Transylvanian basin (Romania).* 2000. American Association of Petroleum Geologists. Vol. 84(10). p. 1589–1615.

Gintov O. B. *Polevaya tektonofizika i ee primenenie pri izuchenii deformatsiy zemnoy kory Ukrainy* [Field Tectonophysics and Its Application in Studies of the Earth’s Crust Deformation in Ukraine]. Phenix, Kiev, 2005, 572 p.

Gintov O. B., Bubniak I. M., Vikhot Yu. M., Murovskaya A. V., Nakapelyukh M. V. *Evolyutsiya napryazhenno-deformirovannogo sostoyaniya i dinamika Skibovogo pokrova Ukrainskikh Karpat* [Strain-deformed state and dynamics of the Skyba nappe of the Ukrainian Carpathians]. *Geofizicheskij zhurnal* [Geophysical Journal], 2011, issue 33 (5), pp. 17–34.

Gintov O. B., Bubniak I. M., Bubniak A. M., Vikhot Yu. M., Mychak S. V., Nakapelyukh M. V. *Naprjazhenno-deformirovannoe sostojanie i dinamika allohtonnoj chasti Predkarpatskogo progiba v svjazi s neftegazonosnost'ju (po tektonofizicheskim dannym)* [The stress-strain state and the dynamics of allochthon part of the Ukrainian Carpathian foredeep in connection with oil and gas content (by tectonophysical data)] *Geofizicheskij zhurnal* [Geophysical Journal]. 2013, issue 35 (1), pp. 75–87.

Guschenko O. I. *Metod kinematicheskogo analiza struktur razrusheniya pri rekonstruktsii poley tektonicheskikh napryazheniy* [Method of kinematic analysis of fracture structures in the reconstruction of tectonic stress fields]. *Polya napryazheniy i deformatsiy v litosfere* [Stress and strain fields in the lithosphere], 1979, pp. 7–25.

Fodor L., Csontos L., Bada G., Györfi I., Benkovics L. *Tertiary tectonic evolution of the Pannonian basin system and neighbouring orogens: a new synthesis of paleostress data.* 1999. Geological Society. Special Publication. London. Vol. 156. p. 295–334.

Faulkner D. R., Jackson C. A. L., Lunn R. J., Schlische R. W., Shipton Z. K., Wibberley C. A. J., Withjack M. O. *A review of recent developments concerning the structure, mechanics and fluid flow properties of fault zones.* 2010. Journal of Structural Geology. Vol. 32. p. 1557–1575.

Fedoryn Ya. *Vulkano-tektonicheskie struktury severo-zapadnoy chasti Marmaroshskogo massiva.* Avtoreferat Diss. [Volcanic and tectonic structures of the Northwestern part of the Maramorosh massif. Author's abstract.]. Kyiv, 1981, 27 p.

Konon A. *Tectonics of the Beskid Wyspowy Mountains (Outer Carpathians, Poland).* 2001. Geological Quaterly. Vol. 45(2). p. 179–204.

Matenco L., Bertotti G., Dinu C., Cloetingh S. *Tertiary tectonic evolution of the external South Carpathians and the adjacent Moesian platform (Romania).* 1997. Tectonics. Vol. 16(6). p. 896–911.

Matenco L., Bertotti G. *Tertiary tectonic evolution of the external East Carpathians (Romania)*. 2000. Tectonophysics. Vol. 316(3–4). p. 255–286.

Matskiv B., Pukach B., Pastukhanova S., Vorobkanych V. *Heolohichna karta dochetvertynnykh utvoren' masshtabu 1:200 000 arkushiv M-35-XXXI (Nadvirna) ta L-35-I (Visheu-de-Sus)* [Geological map of the Prequaternary formation, scale 1:200 000 sheets M-35-XXXI (Nadvirna) and L-35-I (Visheu-de-Sus).] *Derzhavne pidpryyemstvo "Zakhidukrheolohiya"* [Government Enterprises "Westukrgeology"]. Lviv, 2006.

Matviyenko O., Naumko I., Bubniak A., Bubniak I., Popivniak I., Sakhno B., Tsikhon S. *Flyuyidnyy rezhym formuvannya zhyl'nykh utvoren' u riznovikovykh vidkladakh ukrayins'koyi chastyny Skladchastykh Karpat* [Fluid regime of veins formation in different age sediments of the Ukrainian part of the Carpathians]. *Visnyk L'vivs'koho universytetu. Seriya geolohichna* [Proceeding of the Lviv University. Geological Series]. 2004, Vol. 18, pp. 239–246.

Minissale A. *Origin, transport and discharge of CO_2 in central Italy*. 2004. Earth-Science Reviews. Vol. 66. p. 89–141.

Molli G., Cortecci G., Vaselli L., Ottria G., Cortopassi A., Dinelli E., Mussi M., Barbieri M. *Fault zone structure and fluid–rock interaction of a high angle normal fault in Carrara marble (NW Tuscany, Italy)*. 2010. Journal of Structural Geology. Vol. 32. p. 1334-1348.

Nemcok M. *Transition from convergence to escape: field evidence from the West Carpathians*. 1993. Tectonophysics. Vol. 217(1–2). p. 117–142.

Nemcok M., Hok J., Kovac P., Marko F., Coward M.P., Madaras J., Houghton J., Bezak V. *Tertiary extension development and extension/compression interplay in the West Carpathians mountain belt*. 1998. Tectonophysics. Vol. 290(1–2). p. 137–167.

Nemcok M., Pogácsás G., Pospišil L. *Activity timing of the main tectonic systems in the Carpathian–Pannonian region in relation to the rollback destruction of the lithosphere*. In: Golonka J., Picha F.J. (Eds.), The Carpathians and their foreland: geology and hydrocarbon resources. 2006. The AAPG, Tulsa, Oklahoma, USA. p. 743–766.

Ratschbacher L., Frisch W., Linzer H.G., Sperner B., Meschede M., Decker K., Nemcok M., Nemcok J., Grygar R. *The Pieniny Klippen Belt in the Western Carpathians of northeastern Slovakia: structural evidence for transpression*. 1993a Tectonophysics. Vol. 226(1–4). p. 471–483.

Ratschbacher L., Linzer H. G., Moser F., Strusievicz R.O., Bedelean H., Har N., Mogos P.A. *Cretaceous to Miocene thrusting and wrenching along the central South Carpathians due to a corner effect during collision and orocline formation*. 1993b. Tectonics. Vol. 12(4). p. 855–873.

Roure F., Roca E., Sassi W. *The Neogene evolution of the Outer Carpathian flysch units (Poland, Ukraine and Romania): kinematics of a foreland / fold and thrust belt system*. 1993. Sedimentary Geology. Vol. 86(1–2). p. 177–201.

Ślączka A., Kruglov S., Golonka J., Oszczypko N., Popadyuk I. *Geology and hydrocarbon resources of the Outer Carpathians, Poland, Slovakia, and Ukraine: general geology*. 2006. AAPG Mem., 84. p. 221–258.

Shlapinskyy V. E. *Some aspects of the Ukrainian Carpathian tectonics*. 2012. Proceedings of the Shevchenko Scientific Society. Geological Collection XXX. p. 48–67.

Świerczewska, A., Tokarski, A. K. & Hurai, V. *Joints and veins during structural evolution: case study from the Outer Carpathians (Poland)*. 2000. Geological Quarterly. Vol. 44(3). p. 333–339.

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ЭВОЛЮЦИЯ ПОЛЕЙ ПАЛЕОНАПРЯЖЕНИЙ И ФОРМИРОВАНИЕ КАЛЬЦИТОВЫХ ЖИЛ В ЮГО-ВОСТОЧНОЙ ЧАСТИ УКРАИНСКИХ КАРПАТ В КАЙНОЗОЙСКОЕ ВРЕМЯ

Цель. Основной целью данной работы является исследование тектонической эволюции полей палеонапряжения и ее влияние на формирование кальцитовых жил и флюидный поток в юго-восточной части Украинских Карпат в кайнозойское время. Объекты нашего исследования – парагенезисы трещин, зеркала скольжения и жилы в меловых песчаниках в Черногорском, Дуклянском, Поркулецком и Раховском покровах в юго-восточной части Украинских Карпат. **Методика.** Для реконструкции напряженно-деформированного состояния применяли структурно-парагенетический и кинематический методы. Для обработки данных и определения главных осей полей палеонапряжений (σ_1, σ_2, σ_3) использовали программы Fabric 8, StereoNett 2.46, Tensor. Данные по зеркалам скольжения были обработаны с использованием кинематического метода с некоторыми современными изменениями для Карпатского региона. Особое внимание было уделено жилам во вмещающих породах. **Результаты.** В изучаемом регионе исследовано 16 естественных обнажений, более 850 трещин, 300 жил и 50 зеркал скольжения. Структурные особенности жил и поля палеонапряжений, которые могли бы инициировать образование трещин, были описаны. Не во всех обнажениях были найдены кальцитовые жилы. Только в нескольких точках наблюдения обнаружено статистически достоверное количество карбонатных жил. Жилы сложнее объекты для исследования. Очень важно исследовать не только жилы, но и структурные особенности, минералогию, морфологию, кристаллические микродефекты, жидкие включения в них. **Научная новизна.** Используя данные об ориентации жил и зеркал скольжения было реконструировано эволюцию полей тектонических палеонапряжений в юго-восточной части Украинских Карпат в течение кайнозоя. Наиболее активные тектонические движения, деформаций и образование карбонатных жил связаны со сдвиговыми полями палеонапряжений. Сдвиговие поля палеонапряжений являются одним из самых молодых, и его оси растяжения ориентированы в северно-восточном – юго-западном и северо-западном – юго-восточном направлении. Количество кальцитовых жил в отложениях Дуклянского и Поркулецкого покровов гораздо больше, чем в Черногорском и Раховском покровах. Почти все жилы простираются в северо-западном направлении. Конечно, древние трещины могли быть реактивированы и заполнены кальцитом под воздействием последующих режимов растяжения. **Практическая значимость.** Поля палеонапряжений в конце складчасто-надвигового этапа представляют сдвиговый деформационный режим, который был изменен растяжением в двух направлениях (ориентация осей напряженности в SE и SW направлениях). Подробное изучение жил показало, что их формирование является результатом заполнения вольного пространства новообразованных и реактивированных, во время воздействия более поздних деформационных режимов, трещин. Кальцит заполнял сколовые и тенсионные трещины, которые были сформированы в результате действия различных деформационных режимов, начиная со складчато-надвигового этапа. Результаты исследования позволяют сделать вывод, что интенсивная миграция флюидов, в том числе углеводородов, была в конце складчато-надвигового этапа тектонической эволюции Украинских Карпат.

Ключевые слова: трещины, зеркала скольжения, поля палеонапряжений, кальцитовые жилы, миграция флюидов, Раховский покров, Поркулецкий покров, Черногорский покров, Дуклянский покров.

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ЕВОЛЮЦІЯ ПОЛІВ ПАЛЕОНАПРУЖЕНЬ І ФОРМУВАННЯ КАЛЬЦИТОВИХ ЖИЛ У ПІВДЕННО-СХІДНІЙ ЧАСТИНІ УКРАЇНСЬКИХ КАРПАТ У КАЙНОЗОЙСЬКИЙ ЧАС

Мета. Основною метою цієї роботи є дослідження тектонічної еволюції полів палеонапружень і її вплив на формування кальцитових жил і флюїдний потік у південно-східній частині Українських Карпат у кайнозойський час. Об’єкти дослідження – парагенезиси тріщин, дзеркала ковзання і жили в крейдових пісковиках у Чорногірському, Дуклянському, Поркулецькому і Рахівському покривах у південно-східній частині Українських Карпат. **Методика.** Для реконструкції напружено-деформованого стану використано структурно-парагенетичний і кінематичний методи. Для обробки даних і визначення головних осей полів палеонапружень (σ_1, σ_2, σ_3) використано програми Fabric 8, StereoNett 2.46, Tensor. Дані по дзеркалах ковзання опрацьовано зі застосуванням кінематичного методу з деякими особливостями для Карпатського регіону. Особливу увагу акцентовано на вивченні жил у вмісних породах. **Результати.** У досліджуваному регіоні ми детально описали і дослідили 16 природних відслонень, понад 850 тріщин, 300 жил і 50 дзеркал ковзання. Детально описано структурні особливості жил і поля палеонапружень, які могли спричинити формування тріщин, що заповнені кальцитом. Не в усіх відслоненнях були виявлені кальцитові жили. Тільки в декількох точках спостереження заміряно статистично достовірну кількість карбонатних жил. Жили складні об’єкти для дослідження. Дуже важливо досліджувати не тільки жили, а й структурні особливості, мінералогію, морфологію, кристалічні мікродефекти, флюїдні включення в мінералах. **Наукова новизна.** Використовуючи дані про орієнтацію жил і дзеркал ковзання, реконструйовано еволюцію полів палеонапружень у південно-східній частині Українських Карпат протягом кайнозойського часу. Найактивніші тектонічні рухи, деформації і утворення карбонатних жил пов’язані зі зсувними полями палеонапружень. Це зсувні поля палеонапружень є одними з наймолодших, і їхні осі розтягнення орієнтовані в північно-східному – південно-західному і північно-західному – південно-східному напрямках. Кількість кальцитових жил у товщах Дуклянського і Поркулецького покривів набагато більша, ніж у Чорногірському і Рахівському покривах. Майже всі жили простягаються в північно-західному напрямку. Звичайно, давніші тріщини ймовірно були реактивовані та заповнені кальцитом під час активації пізніших режимів розтягнення. **Практична цінність**. Поля палеонапружень у кінці складчасто-насувного етапу представлені зсувним деформаційним режимом, який був змінений розтягуванням у двох напрямках (орієнтація осей напруження в південно-східному та південно-західному напрямку). Докладне вивчення жил показало, що їх формування є результатом заповнення вільного простору новоутворених і реактивованих, під впливом пізніших деформаційних режимів, тріщин. Кальцит заповнював сколові та тенсійні тріщини, які були сформовані в результаті дії різних деформаційних режимів, починаючи від складчасто-насувного етапу. Результати дослідження дають змогу зробити висновок, що інтенсивна міграція флюїдів, зокрема вуглеводнів, відбувалася вкінці складчасто-насувного етапу тектонічної еволюції Українських Карпат.

Ключові слова: тріщини, дзеркала ковзання, поля палеонапружень, кальцитові жили, міграція флюїдів, Рахівський покрив, Поркулецький покрив, Чорногірський покрив, Дуклянський покрив.

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