Cenozoic deformation and stress field evolution of the Kozie chrbty Mountains and the western part of Hornád Depression (Central Western Carpathians)

Ľubica Sůkalová[1], Rastislav Vojtko[1] & Ivana Pešková[2]

[1]Department of Geology and Palaeontology, Faculty of Natural Sciences, Comenius University, Mlynská dolina G, 842 15 Bratislava, Slovakia; sukalova@fns.uniba.sk, vojtko@fns.uniba.sk
[2]Dionýz Štúr State Institute of Geology, Mlynská dolina 1, 817 01 Bratislava, Slovakia; ivana.peskova@geology.sk

AGEOS

Kenozoická deformácia a vývoj napäťových polí v oblasti Kozích chrbtov a západnej časti Hornádskej kotliny (Centrálne Západné Karpaty)

Abstract: Reconstruction of the Cenozoic palaeostress fields in the western part of Hornád Depression, south of Poprad town, was the main goal of the research. This was done on the basis of analysis of fault-slips. The most important was the detailed study of fault-slip kinematics. The deformation structures were measured and recorded in the Permian volcano-sedimentary sequence of the Malužiná Formation (Hronic Unit), and in the sequences of the Borové Formation, which is a basal part of the Central Carpathian Palaeogene Basin. The youngest measured rocks were the Lower Pleistocene travertines at the locality of Hranovnické pleso. An observed chronology of deformation phases can be divided into the seven different palaeostress fields. The oldest tectonic event (*D1*) was generated in terms of strike-slip tectonic regime with the W–E compression. This was recorded only in the Malužiná Formation, together with the second deformation stage. This performs strike-slip tectonic regime with the WNW–ESE compression (*D2*). Both deformations were conditionally included in the age between the Lower Palaeocene to Oligocene. The next, very distinct deformation event (*D3*) is represented by the NW–SE oriented compression in the strike-slip tectonic regime. This event includes the subset, which performs pure NE–SW tension (*D3a*) tenuously dated at the Early–Middle Miocene, because this phase also affected the Palaeogene sediments. The fourth generation of faults (*D4*) were activated during the Middle Miocene under strike-slip tectonic regime with N–S compression, in general. The age was determined relatively, because the deformation structures (*D4*) are cut by fault of the *D5* stage. The fifth phase of deformation (*D5*) originated in strike-slip tectonic regime with the NE–SW direction of compression. The age of the deformation is considered to be the Late Miocene. The sixth deformation stage (*D6*) is characterized by the pure W–E extension. The stage was originated in the Quaternary age, because it was identified only in the Lower Pleistocene travertines, the same as the last, youngest tectonic phase. This phase consisted of NNW–SSE oriented tension (*D7*).

Key words: Western Carpathians, Kozie Chrbty Mts., Hornád Depression, fault-slip analysis, palaeostress reconstruction, faults

1. INTRODUCTION

The territory of the western part of Hornád Depression and adjacent areas of the Kozie chrbty Mts. are located in the northern Slovakia; south of Poprad town. The study area is bounded by the Poprad Depression from the north, by the Nízke Tatry Mts. from the south, by the Slovenský raj Mts. from the south-east and by the central part of Hornád Depression from the east. The territory of the Hornád Depression and southern slopes of the Kozie chrbty Mts. is drained by the Hornád and Poprad rivers (Fig. 1).

According to the geomorphological division, the whole investigated area belongs to the Tatra-Fatra geomorphological area. It included the following geomorphological units: the Hornádska kotlina Basin – Vikartovská priekopa Depression subunit as well as the Kozie chrbty Mts. – Dúbrava Massif subunit (Mazúr & Lukniš, 1980). In the regional-geological division, the Kozie chrbty Mts. represents the Veporic Unit otherwise the western part of the Hornád Depression is an integral part of the Inner Carpathian Palaeogene (Central Carpathian Palaeogene Basin – CCPB) (Vass et al., 1988).

The Kozie chrbty Mts. are elongated morphotectonic structure with the E–W direction that is substantially limited by the Poprad Depression in the north and by the Hornád Depression in the south. However, the mountains submerge below the Hornád Depression in the east (Fig. 1). The Vikartovská priekopa is the western part of the Hornádska kotlina Basin and extends in the direction of the E–W with slightly to moderately undulating topography. This depression originated in the neotectonic period by a subsidence along the E–W oriented Vikartovce fault. The landforms and structure of this depression is a result of erosion-accumulation processes of the Hornád River and its tributaries (Biely et al., 1997) but also of active tectonics (Vojtko et al., 2011).

The aim of this paper is the reconstruction of the Cenozoic evolution of the palaeostress fields in the study area. The palae-

Manuscript received 6 October 2011
Revised version accepted 9 February 2012

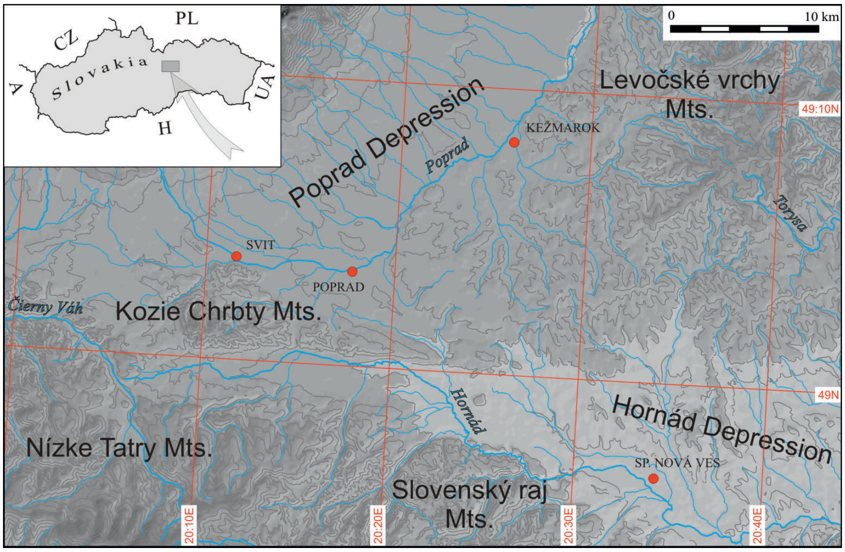

Fig. 1. Simplified digital terrain model of the study area shown by rectangle on the map of Slovakia.
Obr. 1. Zjednodušený digitálny terénny model študovanej oblasti znázornenej na mapke Slovenska obdĺžnikom.

ostress reconstruction was based on systematic data collecting of fault-slips, joints and tensional veins at the 15 localities. The measured data have been used to determine palaeostress field orientation and evolution of the study area.

2. GEOLOGICAL SETTING

The western part of Hornád Depression belongs to the CCPB and it is formed by the Lutetian to Oligocene predominantly siliciclastic sediments. It is bounded on the north by the Vikartovce fault. Along the Vikartovce fault, the Kozie chrbty Mts. were uplifted during the Late Miocene, Pliocene and Quaternary. On the south and south-east, the Nízke Tatry Mts. and Slovenský raj Mts. are located and they are composed of the palaeo-Alpine nappe structures such as Hronic, Silicic, Veporic, and Gemeric units (Fig. 2).

The Hronic Unit in the study area is represented by the Boca and Betlanovce nappes. The Betlanovce nappe forms only the NE–SW oriented narrow zone of the Triassic rocks near the Betlanovce village (Mello et al., 2000[a], 2000[b]). The Boca nappe, with the stratigraphic range from Permian to Triassic, forms the Kozie chrbty Mts. and also includes the Triassic sequence near Svit town on the NW part of study area.

The Kozie chrbty Mts. are horst stucture steep dipping to the south and they are strictly limited by the W–E Vikartovce fault from the south. The mountains are mostly composed of the Permian Malužiná Fm. (Ipoltica Group). The Malužiná Formation is also outcropped in the NE slopes of the Nízke Tatry Mts. from Vernár village to Hranovnica and Spišské Bystré villages. The formation represents a volcanosedimentary complex, consisting of polycyclic sequences from small to large sedimentary cycles (Vozárová & Vozár, 1981, 1988).

The SE part of the study area is composed of the Vernár and Stratená nappes belonging to the Silic Unit (Slovenský raj Mts.) and also the Upper Cretaceous "Gossau" Group. The Upper Cretaceous sediments overlay dolomites of Vernár nappe (e.g., Mello et al., 2000[a]).

The Hornád Depression is composed of the Palaeogene sediments of the CCPB. The CCPB is interpreted as a forearc basin located behind the Outer Carpathians accretionary wedge (Royden & Báldi, 1988; Tari et al., 1993; Kázmer et al., 2003). The CCPB lies within the West Carpathian Mountain chain and is located south of the Pieniny Klippen Belt. The sedimentary sequences of the PKB lie discordantly on the palaeo-Alpine nappe structure. The basin is filled by several hundred up to thousand meters thick of deep-marine siliciclastic sediments (Soták et al. 2001).

The sedimentary deposition of the CCPB in the Hornád Depression is divided into the litostratigraphic formations of the Subtatric Group (Gross et al., 1984): Borové, Huty, Zuberec, and Biely potok formations. The stratigraphic span of the basin fill ranges from the Late Eocene to Oligocene (Soták et. al., 1996; Janočko & Kováč, 2003). For further detailed information on sedimentological investigation of the CCPB formations in the Hornád Depression see Filo & Siráňová (1996, 1998).

The Quaternary deposits are located mainly on the Palaeogene formations of the Central Carpathian Palaeogene Basin. The spatial distribution and sediment thickness of the Quaternary deposits is highly variable, due to landforms and local variability of sedimentary processes during Late Pleistocene to Holocene. The most common Quaternary deposits are lithologically undivided slope sediments (Biely et al., 1992, 1997; Gross et al., 1999[a], 1999[b]; Mello et al. 2000[b]). Late Pleistocene and Holocene fluvial deposits are located mainly along the Hornád River. Pleistocene to Holocene travertine is predominantly located near Poprad town and the Hranovnica village (Fig. 2).

3. METHODS

Structural research was focussed on investigation of the brittle structures (faults, veins, joints). The field structural research included measurement and collection of the structural data and the kinematic analysis of faults, based on the evaluation of the faults surfaces. The sense of movement on the fault surfaces can be determined using the kinematic indicators (e.g., Hancock, 1985; Petit, 1987; Marko, 1993[a]; Angelier, 1994).

The obtained data were registered into the NeotAct database and were pre-processed using the LoCon software developed at the Department of Geology and Palaeontology, Comenius University by Rastislav Vojtko.

The basic principle of palaeostress analysis is that meso-scale structures can by related to larger regional structures. Both scales reflect the same dynamics and kinematics (Angelier, 1994). For palaeostress analysis the inverse Rotational Optimisation and the Right Dihedra methods implemented in the WinTensor software were used (Delvaux & Sperner, 2003).

The Right Dihedra method (Angelier & Mechler, 1977) provides a determination of the four parameters of the reduced stress tensor and also allows a preliminary separation of the fault population into a homogeneous set, broadly compatible with the computed stress tensor (cf. Delvaux & Sperner, 2003).

The inverse method (Rotational Optimisation) is based on the assumption of Bott (1959) that slip on a plane occurs in the direction of the maximum resolved shear stress. Fault data were inverted to obtain the four parameters of the reduced stress tensor (Angelier, 1994): σ_1 (principal maximum stress axis), σ_2 (principal intermediate stress axis), and σ_3 (principal minimum stress axis). The stress ratio is computed by formula $\Phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$ and together with the orientation of the principal stress axes defines the tectonic regime. Homogeneous populations of fault-slips for computations of single palaeostress events were separated. As a discrimination criterium for separation of fault-slips to homogeneous populations was used an α angle – slip deviation between theorethical and measured orientation of striae. The average stress regime index R' (R' = 0–1 for extensional regime, 1–2 for strike-slip regime, and 2–3 for compressive regimes) is fully defined by Delvaux et al. (1997).

These methods (especially the inversion method) have some limitations which were the subject of criticism and its results were under discussion in specific situations. The basic point of stress computation by the inversion method is that regional stress tensor is spatially and temporally homogeneous in the whole-rock mass. These computations are influenced generally by the three effects which can occur in palaeostress analysis: 1) effect of ratio between the width and length of a fault; 2) effect of the Earth's surface (topoeffect); 3) effect of interaction between two or more faults (cf. Dupin et al., 1993; Pollard et al., 1993; Nieto-Samaniego & Alaniz-Alvarez, 1996; Twiss & Unruh, 1998; Maerten, 2000; Roberts & Ganas, 2000). These effects can misinterpret results of the paleostress analysis, but their influence is in most cases slight (Angelier, 1994; Vojtko, 2003).

4. FAULT-SLIP ANALYSIS AND PALAEOSTRESS RECONSTRUCTION

The area of the western part of Hornád Depression and adjacent part of Kozie chrbty Mts. are characterized by the polyphase brittle faulting during the Cenozoic era. Data were collected at the 15 localities (Permian Malužiná Fm., Palaeogene sequences of Subtatric Group and Lower Pleistocene travertines; Fig. 3;

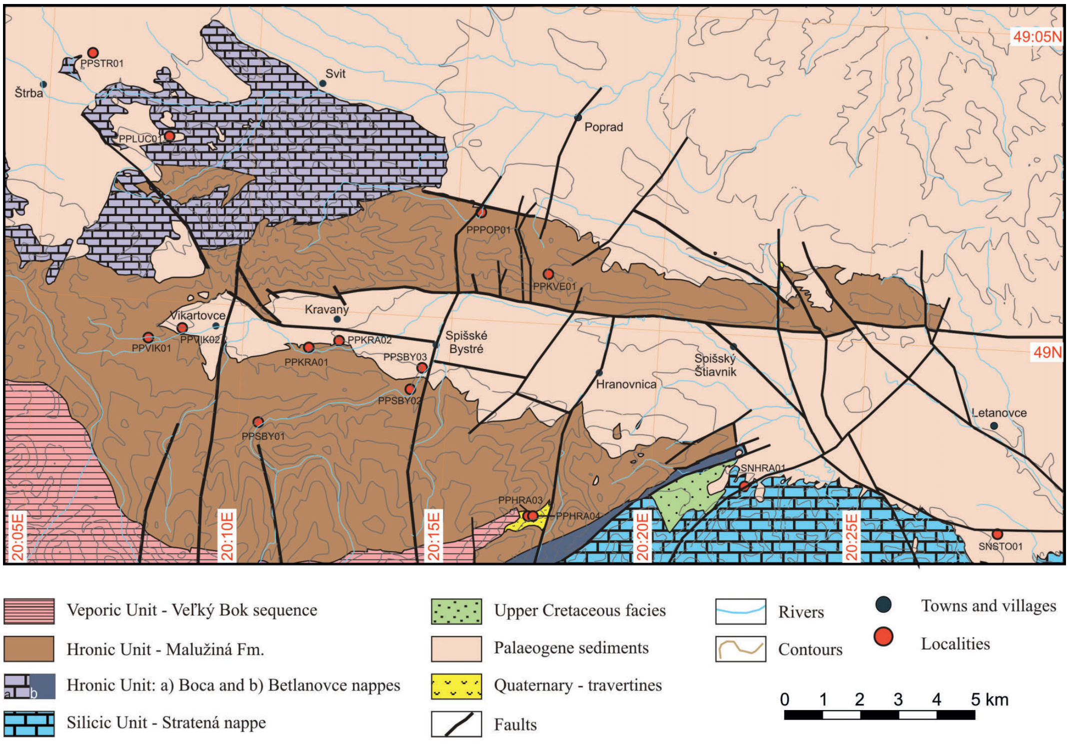

Fig. 2. Simplified geological map of the Hornád Depression and the Kozie chrbty Mts. with main fault structures (according to Biely et al., 1992, Mello et al., 2000[a], modified).

Obr. 2. Zjednodušená geologická mapa Hornádskej kotliny a Kozích chrbtov s hlavnými zlomovými štruktúrami (podľa Biely et al., 1992, Mello et al., 2000[a], modifikované).

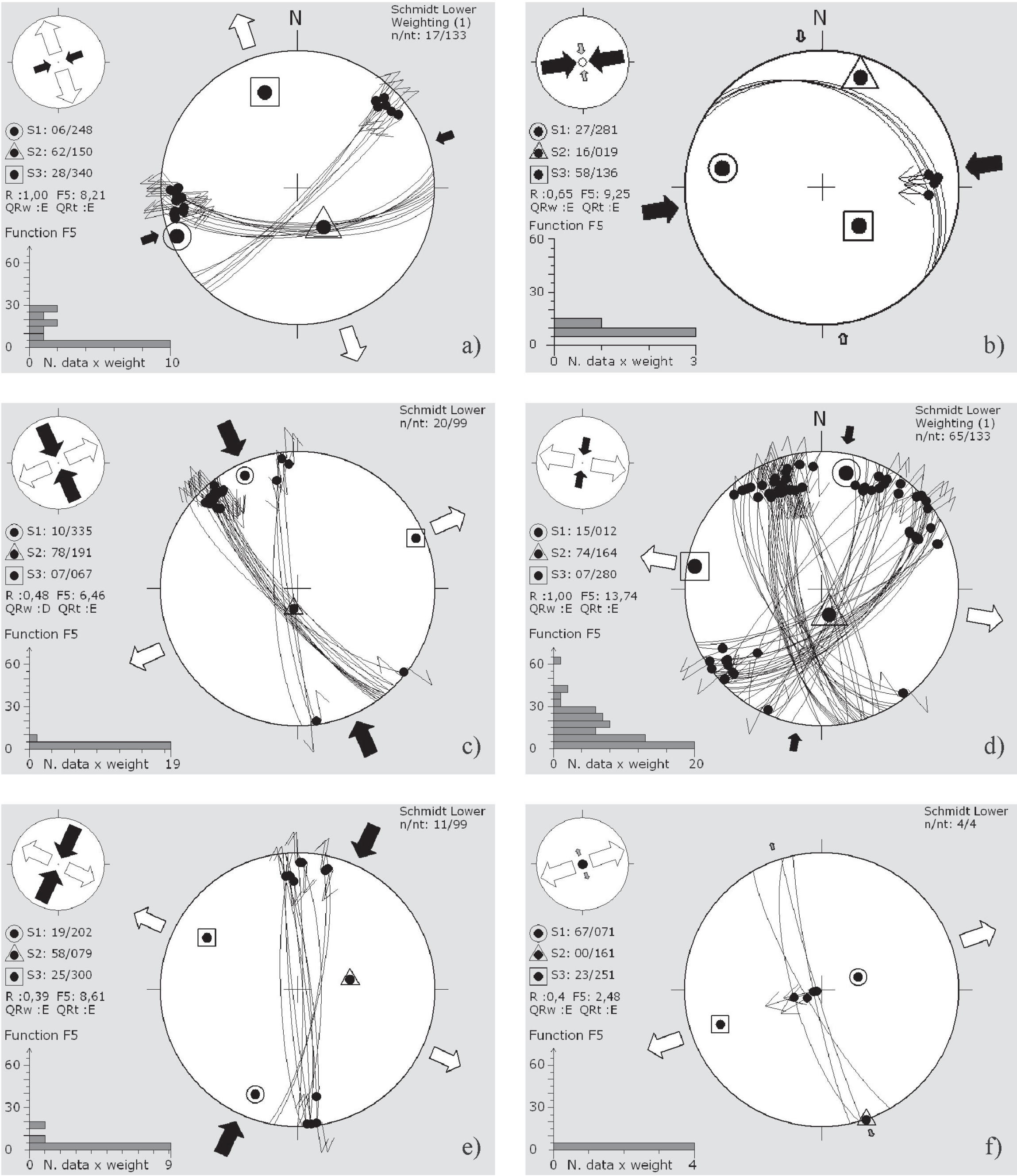

Fig. 3. Examples of paleostress reconstructions. a – Palaeocene to Oligocene phase recorded at the Bystrá locality (site code PPSBY02); b – Palaeocene to Oligocene phase; the Kvetnica locality (site code PPKVE01); c – Early Miocene phase; the Spišské Tomášovce locality (site code SNSTO01); d – Middle Miocene phase; Bystrá locality (site code PPSBY02); e – Late Miocene phase; the Spišské Tomášovce locality (site code SNSTO01); f – Quaternary phase; the Hranovnické pleso locality (site code PPHRA04). Explanation: Stereogram (Lambert's net, lower hemisphere) with traces of fault planes, observed slip lines and slip senses, histogram of observed slip-theoretical shear deviations for each fault plane and stress map symbols. S1 =σ_1, S2=σ_2 and S3=σ_3 – azimuth and plunge of principal stress axes; R =Φ

Obr. 3. Príklady paleonapäťových rekonštrukcií. a – palaocénna až oligocénna fáza zaznamenaná na lokalite Bystrá (kód lokality PPSBY02); b – Palaeocene to Oligocene phase; the Kvetnica locality (kód lokality PPKVE01); c – ranno miocénna fáza; lokalita Spišské Tomášovce (kód lokality SNSTO01); d – stredno miocénna fáza; lokalita Bystrá (kód lokality PPSBY02); e – neskoro miocénna fáza; lokalita Spišské Tomášovce (kód lokality SNSTO01); f – kvartérna fáza; lokalita Hranovnické pleso (kód lokality PPHRA04). Vysvetlivky: Stereogram (Lambertova sieť, spodná hemisféra) s priebehom zlomových plôch, pozorovaných striácií so zmyslom pohybu, histogramom pozorovaných a teoretických sklzových strihov a ich rozdielu pre každú zlomovú plochu a mapové napäťové symboly. S1 =σ_1, S2=σ_2 a S3=σ_3 – azimut and sklon hlavných napäťových osí; R =Φ

Tab. 1, 2). More than 630 fault-slips were used for palaeostress analysis to determine the orientation of principal palaeostress axes (σ_1, σ_2, σ_3) and to define the parameter Φ. Chronology of competed and determined seven deformation stages was compared with the same tectonic events in different areas of the Central Western Carpathians (e.g., Vojtko, 2003; Pešková et al., 2009; Vojtko et al., 2010). The results of the chronology are presented herein from the oldest to the youngest.

4.1. Tectonic regimes before sedimentation of the CCPB sedimentary sequence (Palaeocene–Oligocene)

The evolution of the study area during the Palaeocene to Oligocene is characterized by two different orientation of the palaoestress field (Figs. 3a,b; 4). The faults activated during these stages are older than the deposition of the Borové Fm., because of the measured fault-slips cut only the Permian Malužiná Fm. and did not continue into the basal formation of the CCPB. During time span, the NE–SW-trending dextral strike-slip and NW–SE-trending sinistral strike-slip faults were activated. The oblique reverse faults were partly observed and the normal faults were generally oriented W–E with azimuth of striae on the SE. Most of the measured fault slip data were interpreted as neoformed fault structures on the basis of their plane symmetry (conjugate faults). *The earliest deformational stage (D1)* is characterized by the W–E compression and N–S tension. *The second deformational phase (D2)*, the WNW–ESE compression and the NNE–SSW tension, also affected only the Malužiná Fm. This phase is most probably younger than previous one, but older than the deposition of CCPB sequence.

4.2. Tectonic regimes after sedimentation of the CCPB sedimentary sequence (Early Miocene – Late Miocene)

In the Upper Eocene to Oligocene sedimentary sequence of the CCPB, the brittle structures belonging into the three main deformational phases were recorded. These are predominantly characterized by a strike-slip tectonic regime with different orientation of the principal palaeostress axes.

The distinct deformational stage is represented by the strike-slip tectonic regime with *the NW–SE compression and NE–SW tension (D3)*. Dip-slip faults were mostly observed in the Malužiná Fm. In the Palaeogene sequence, predominantly the N–S sinistral and WNW–ESE dextral faults were found. Brittle deformation of this strike-slip tectonic regime is well-preserved in the Palaeogene sediments from the locality of Ďurkovec quarry (Figs. 3c, 5). This tectonic stage also includes the substage *(D3a)* which performs the pure NE–SW tension with the measured NW–SE normal faults.

The homogeneous fault population of *the N–S compression (D4)* was activated under the strike-slip tectonic regime with the N–S compression and W–E oriented tension (Figs. 3d, 6). The dominant structures are prevailing NW–SE dextral and NE–SW sinistral trending strike-slips at many localities (e.g., Bystrý potok Valley, Ďurkovec quarry, etc.).

NE–SW compression and NW–SE tension (D5) was generated in a strike-slip tectonic regime (Figs. 3e, 7). During this NE–SW compression and perpendicular tension, the N–S dextral and E–W sinistral strike-slip faults were predominantly activated on weakness planes. Some normal and reverse faults were found at the locality of Spišské Bystré in the Malužiná Fm.

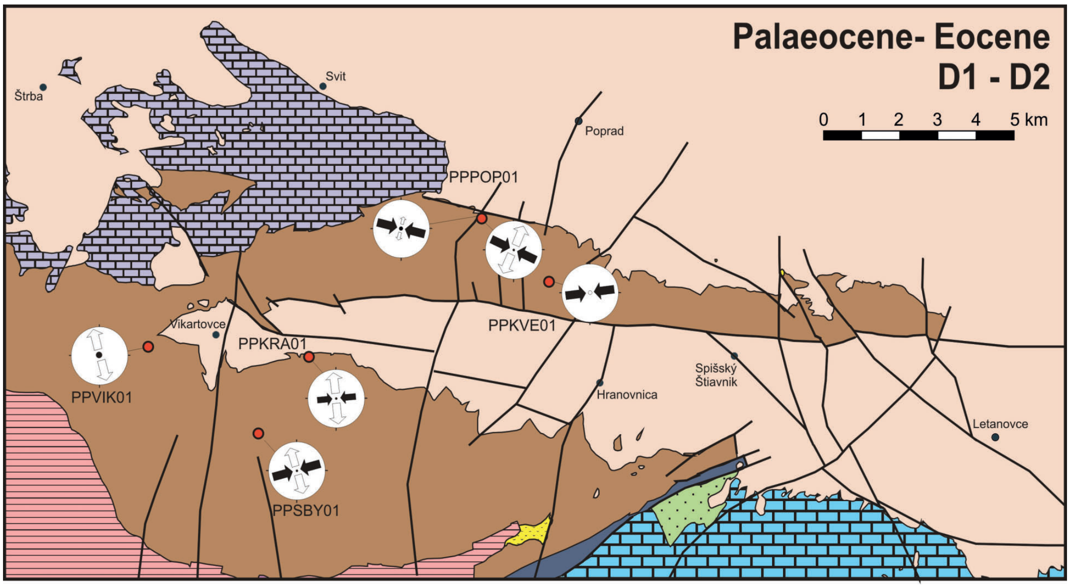

Fig. 4. Simplified tectonic map with orientation of palaeostress symbols of the E–W compression and N–S tension of *D1* and *D2* deformation stages (Palaeocene to Oligocene).

Obr. 4. Zjednodušená tektonická mapa s orientáciou paleonapäťových symbolov pre V–Z kompresiu a N–J tenziu *D1* a *D2* deformačného štádia (paleocén až oligocén).

Tab. 1. General information and location of sites with measured structures.
Tab. 1. Základné informácie o lokalitách a ich lokalizácia s meranými štruktúrami.

Number	Locality	Code	Latitude	Longitude	Formation
1	Hranovnické pleso 03	PPHRA03	48° 56´ 54´´N	20° 17´ 03´´E	Pleistocene travertine
2	Hranovnické pleso 04	PPHRA04	48° 56´ 42´´N	20° 16´ 39´´E	Pleistocene travertine
3	Kravany sandpit - Kravany pieskovňa	PPKRA02	48° 59´ 29´´N	20° 12´ 14´´E	Borové Formation
4	Lučivná	PPLUC01	49° 02´ 36´´N	20° 08´ 54´´E	Borové Formation
5	Spišské Bystré	PPSBY03	48° 59´ 08´´N	20° 14´ 16´´E	Borové Formation
6	Štrba - railways - Štrba - železnica	PPSTR01	49° 03´ 48´´N	20° 05´ 54´´E	Borové Formation
7	Vikartovce	PPVIK02	48° 59´ 32´´N	20° 08´ 27´´E	Borové Formation
8	Hrabušice quarry - Lom Hrabušice	SNHRA01	48° 54´ 42´´N	20° 17´ 16´´E	Borové Formation
9	Ďurkovec quarry - Lom Ďurkovec	SNSTO01	48° 57´ 02´´N	20° 28´ 18´´E	Borové Formation
10	Kravany quarry - Lom Kravany	PPKRA01	48° 59´ 21´´N	20° 11´ 31´´E	Malužiná Formation
11	Zámčisko - Kvetnica quarry - Zámčisko - lom Kvetnica	PPKVE01	49° 00´ 44´´N	20° 17´ 10´´E	Malužiná Formation
12	Vysová quarry - Lom Vysová	PPPOP01	49° 01´ 39´´N	20° 15´ 28´´E	Malužiná Formation
13	Spiš. Bystré Bystrá	PPSBY01	48° 58´ 07´´N	20° 10´ 25´´E	Malužiná Formation
14	Spišské Bystré quarry - Lom Spišské Bystré	PPSBY02	48° 58´ 47´´N	20° 14´ 01´´E	Malužiná Formation
15	Vikartovce	PPVIK01	48° 59´ 21´´N	20° 07´ 39´´E	Malužiná Formation

Tab. 2. Palaeostress tensors from fault-slip data. Explanations: Site – Code of locality; n – number of fault used for stress tensor determination; n_t – total number of fault data measured; $S_1 = \sigma_1$, $S_2 = \sigma_2$ and $S_3 = \sigma_3$ –azimuth and plunge of principal stress axes; R = Φ –stress ratio; α–mean slip deviation (in °); Q – quality ranking scheme according to the World Stress Map Project (Sperner et al., 2003); R′ – tensor type index as defined in the text.
***Tab. 2.* Paleonapäťové tenzory zo zlomových sklzov. Vysvetlivky: Site – kód lokality; n – počet zlomov použitých na určenie napäťového tenzora; n_t – celkový počet zlomov nameraných na lokalite; $S_1 = \sigma_1$, $S_2 = \sigma_2$ and $S_3 = \sigma_3$ –azimut a sklon hlavných napäťových osí; R = Φ – napäťový pomer; α – štandardná odchýlka (v °); Q – kvalitatívna schéma podľa projektu World Stress Map Project (Sperner et al., 2003); R‘ – index tenzorového typu ako je definovaný v texte.**

Site	n	nt	σ_1	σ_2	σ_3	Φ	α	Q	R′
PPHRA03	2	2	124/67	24/4	292/23	0.50	3.65	E	0.50
PPHRA04	4	4	71/67	161/0	251/23	0.40	2.48	E	0.40
PPKRA02A	3	24	162/60	257/3	349/30	1.00	4.87	E	1.00
PPKRA02B	4	24	32/83	126/0	216/7	0.40	2.90	E	0.40
PPKRA02C	9	24	346/13	238/52	85/36	0.61	1.06	D	1.39
PPKRA02D	6	24	305/14	170/71	38/13	0.60	11.85	E	1.40
PPKRA02E	2	24	2/61	268/2	177/29	0.50	0.65	E	0.50
PPLUC01A	1	2	352/38	171/52	261/0	0.50	0.00	E	1.50
PPLUC01B	1	2	227/75	131/2	41/15	0.50	0.00	E	0.50
PPSBY03A	4	6	156/81	309/9	39/3	0.43	4.65	E	0.43
PPSBY03B	2	6	284/89	199/0	109/1	0.50	0.65	E	0.50
PPSTR01A	21	29	332/10	222/63	68/25	0.26	10.16	B	1.74
PPSTR01B	5	29	11/33	223/50	111/15	0.36	5.12	E	1.64
PPVIK02A	1	10	333/29	137/60	239/7	0.40	0.00	E	1.60
PPVIK02B	3	10	293/74	136/15	44/6	0.80	14.20	E	0.80
PPVIK02C	5	10	215/11	23/79	124/2	0.32	0.74	E	1.68

SNHRA01A	14	25	42/00	119/88	312/2	0.25	6.52	D	1.75
SNHRA01B	4	25	73/75	234/14	325/5	0.40	8.18	E	0.40
SNSTO01A	7	99	321/14	169/73	56/7	0.41	9.64	E	1.59
SNSTO01B	20	99	335/10	191/78	67/7	0.48	6.64	D	1.52
SNSTO01C	48	99	4/11	192/79	95/2	0.43	5.59	B	1.57
SNSTO01D	5	99	159/73	353/17	261/4	0.53	5.84	E	0.53
SNSTO01E	11	99	202/19	79/58	300/25	0.39	8.61	E	1.61
SNSTO01F	7	99	95/68	323/15	227/16	0.36	7.46	E	0.36
PPKRA01A	4	173	15/50	227/36	125/16	0.39	0.77	E	0.77
PPKRA01B	54	173	52/30	217/60	317/6	0.22	12.22	C	1.78
PPKRA01C	15	173	349/3	258/31	84/58	0.39	9.43	E	2.39
PPKRA01D	13	173	154/0	245/38	64/52	0.53	8.65	E	2.53
PPKRA01E	45	173	53/78	245/12	155/2	0.46	4.89	D	0.46
PPKRA01F	22	173	350/28	213/53	91/21	0.61	4.79	E	1.39
PPKRA01G	11	173	265/1	170/68	356/21	0.83	7.14	E	1.17
PPKVE01A	8	91	136/68	338/18	245/7	0.36	16.29	E	0.36
PPKVE01B	15	91	337/86	112/3	203/3	0.31	7.95	D	0.31
PPKVE01C	4	91	281/27	19/16	135/57	0.65	18.75	E	2.65
PPKVE01D	6	91	118/7	229/70	25/18	0.42	8.90	E	1.58
PPKVE01E	14	91	233/4	108/85	323/3	0.38	10.56	D	1.62
PPKVE01F	23	91	349/6	225/80	80/8	0.35	8.25	D	1.65
PPPOP01A	19	62	27/4	127/61	294/28	0.28	10.89	C	1.72
PPPOP01B	9	62	310/21	216/9	106/67	0.21	11.37	E	2.21
PPPOP01C	4	62	282/7	188/29	21/61	0.18	13.35	E	2.18
PPPOP01D	10	62	223/6	313/12	109/76	0.32	13.15	D	2.32
PPPOP01E	3	62	295/56	145/30	47/14	0.40	4.23	E	0.40
PPPOP01F	7	62	2/74	102/3	192/15	0.80	13.81	E	0.80
PPSBY01A	5	133	311/42	209/13	106/45	0.00	3.52	E	0.00
PPSBY01B	65	133	12/15	164/74	280/7	0.39	8.65	B	1.61
PPSBY01C	17	133	248/6	150/62	340/28	0.31	2.76	E	1.69
PPSBY01D	11	133	5/51	244/23	140/30	0.27	10.97	E	0.27
PPSBY01E	12	133	37/87	189/3	278/2	0.48	3.62	E	0.48
PPSBY01F	7	133	320/11	52/11	190/74	0.43	1.91	E	2.43
PPSBY01G	12	133	208/81	83/5	353/7	0.44	2.33	E	0.44
PPSBY02A	4	22	210/9	303/15	90/74	0.31	11.60	E	2.31
PPSBY02B	5	22	231/68	41/23	133/4	0.61	1.34	E	0.61
PPSBY02C	1	22	29/1	127/82	299/7	0.15	0.00	E	1.85
PPSBY02D	1	22	318/2	208/84	48/6	0.25	0.00	E	1.75
PPSBY02E	6	22	8/8	142/79	277/8	0.39	3.15	D	1.61
PPVIK01A	4	10	76/72	253/18	163/1	0.28	3.92	E	0.28
PPVIK01B	2	10	211/14	66/73	303/9	0.40	13.60	E	1.60
PPVIK01C	3	10	134/5	247/78	43/11	0.67	18.33	E	1.33

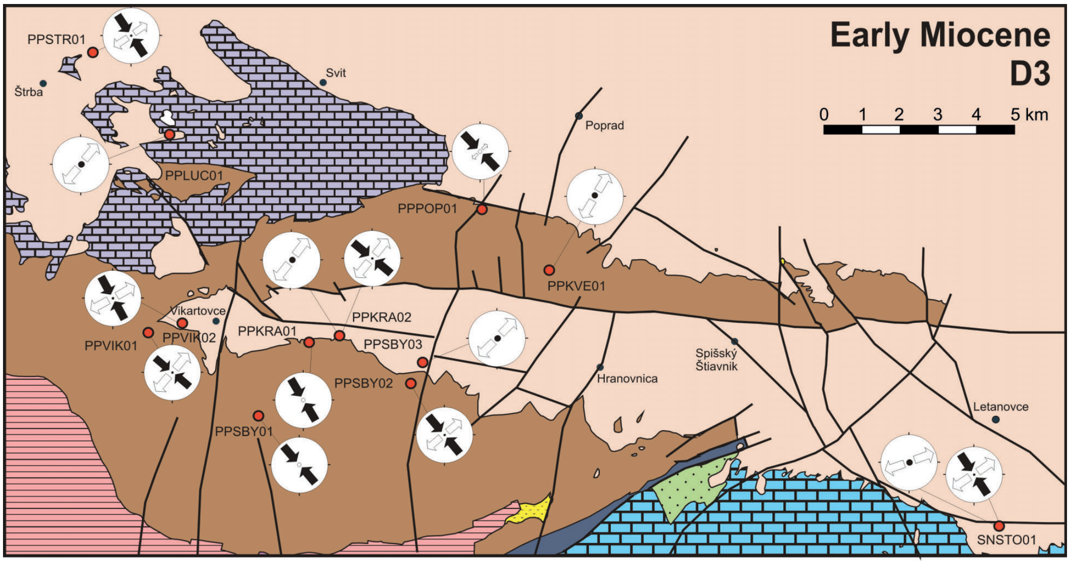

Fig. 5. Simplified tectonic map with orientation of palaeostress symbols of the NW–SE compression and NE–SW tension of *D3* deformation stage (Early Miocene).

Obr. 5. Zjednodušená tektonická mapa s orientáciou paleonapäťových symbolov pre SZ–JV kompresiu a NV–JZ tenziu *D3* deformačného štádia (ranný miocén).

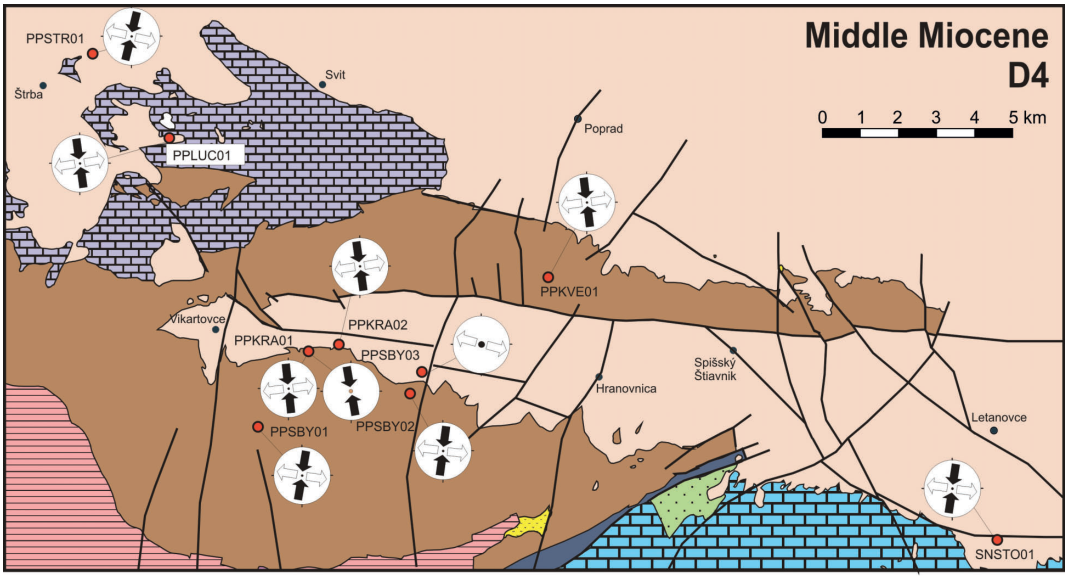

Fig. 6. Simplified tectonic map with orientation of palaeostress symbols of the N–S compression and E–W tension of *D4* deformation stage (Middle Miocene).

Obr. 6. Zjednodušená tektonická mapa s orientáciou paleonapäťových symbolov pre S–J kompresiu a V–Z tenziu *D4* deformačného štádia (stredný miocén).

4.3. Tectonic regimes during neotectonic era

Neotectonic period is defined by two different orientation of the σ_3 axis. The first one is *tectonic stage (D6)* which can be characterized by pure W–E oriented tension and it is considered to be the Quaternary in age (Figs. 3f, 8). This deformational stage controlled the young tectonic evolution of the area. Normal fault planes were recorded in the Lower Pleistocene travertines at the locality of Hranovnické pleso in two localities.

The N–S trending normal structures of the probably youngest *tectonic stage (D7)* were measured in the Palaeogene sediments near Kravany village. The kinematics of faults was determined on the basis of sedimentary marker offset. The youngest observed structures are parallel with the Vikartovce fault which is considered to be Quaternary in age (Vojtko et al., 2011). However, this orientation of the stress tensor was not identified in the previously mentioned travertines.

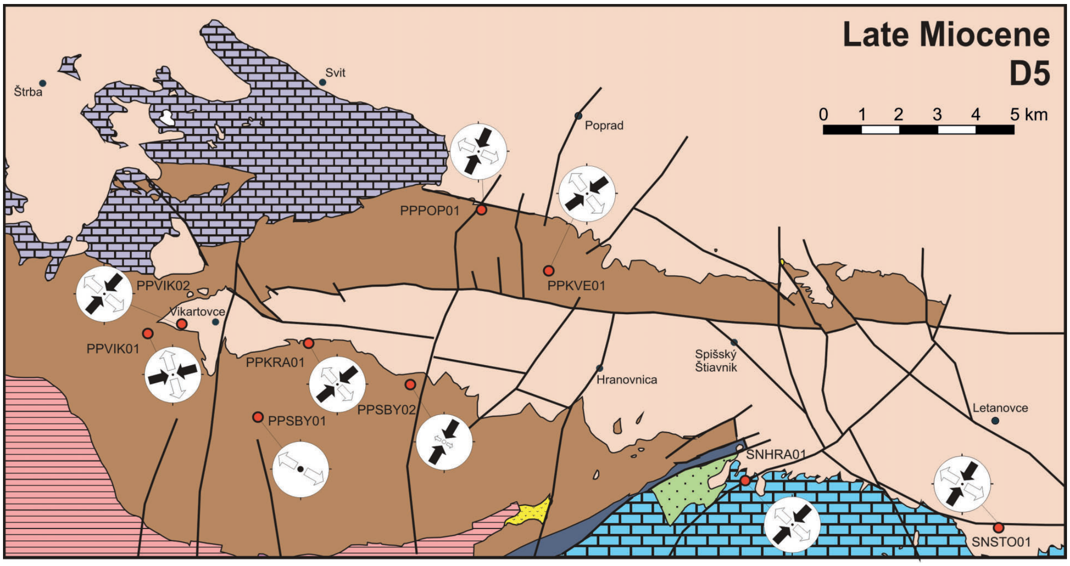

Fig. 7. Simplified tectonic map with orientation of palaeostress symbols of the NE–SW compression and NW–SE tension of *D5* deformation stage (Late Miocene).

Obr. 7. Zjednodušená tektonická mapa s orientáciou paleonapäťových symbolov pre SV–JZ kompresiu a SZ–JV tenziu *D5* deformačného štádia (neskorý miocén).

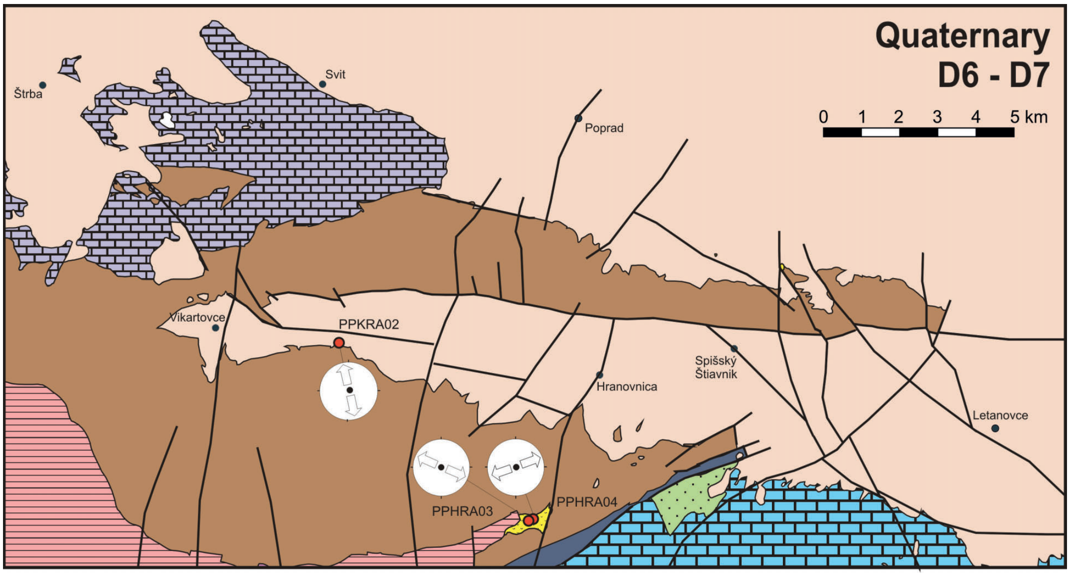

Fig. 8. Simplified tectonic map with orientation of palaeostress symbols of the E–W to NNW–SSE tension of *D6* and *D7* deformation stages (Quaternary).

Obr. 8. Zjednodušená tektonická mapa s orientáciou paleonapäťových symbolov pre V–Z až SSZ–JJV tenziu *D6* a *D7* deformačného štádia (kvartér).

5. INTERPRETATION AND CHRONOLOGY

The earliest deformational stage (*D1* – Palaeocene to Oligocene) is characterized by the W–E compression and N–S tension (Fig. 9). The faults activated during this stage are older than the deposition of the Borové Fm., because of the measured fault-slips cut only the Permian Malužiná Fm. and do not continue into the basal formation of the CCPB. The second deformational phase (*D2*), the WNW–ESE compression and the NNE–SSW tension, also affected only the Malužiná Fm. This phase is most probably younger than the previous one, but older than the deposition of CCPB sequence. Similar deformational phases were determined for example from the Orava, Spišská Magura, Podhale, and Slovenský raj Mts. (Marko, 1993[b]; Vojtko, 2003; Petráš, 2008; Pešková et al., 2009; Vojtko et al., 2010).

The distinct deformational stage (*D3*) is represented by the strike-slip tectonic regime and it is considered to be Early Miocene in age. Reverse or normal faults were mostly observed in

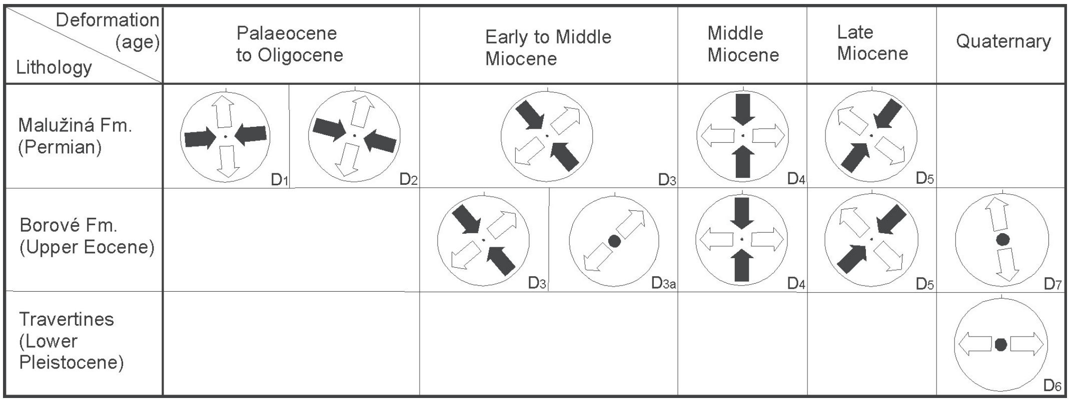

Fig. 9. Synthetic scheme of chronology for Palaeocene to Quaternary regional stress fields in the Kozie chrbty Mts. and the Hornád Depression western part.

Obr. 9. Syntetická schéma chronológie paleocénnych až kvartérnych regionálnych napäťových polí v Kozích chrbtoch a v západnej časti Hornádskej kotliny.

the Malužiná Fm. In the Palaeogene sequence, predominantly the N–S sinistral and WNW–ESE dextral faults were found. Deformation of the palaeogene sediments in the localities of Ďurkovec and Štrba quarrys is very good example of this strike-slip tectonic regime. This stage also includes the substage (*D3a*) which performs the pure NE–SW tension with measured NW–SE normal faults. The age was determined on the basis of study by Petráš (2008); Pešková et al., (2009) and Vojtko et al. (2010).

The homogeneous fault population (*D4*) was activated during the Middle Miocene under the strike-slip tectonic regime with the N–S compression and W–E oriented tension. The prevailing NW–SE dextral and NE–SW sinistral trending strike-slips are dominant structures at many localities (e.g., the Bystrý potok Valley, Ďurkovec quarry, etc.). Normal faults are also often observed at many localities. Oblique faults were measured at the locality of Kravany pri Hornáde. The age of the *D4* deformation was determined relatively, based on the cross-cutting relations between the deformation structures *D4* and *D5* stages and on the basis of study by Pešková et al. (2009) and Vojtko et al. (2010).

The deformational stage (*D5*) was generated in a strike-slip tectonic regime and it is considered to be Late Miocene in age. During this NE–SW compression and perpendicular tension, the N–S dextral and E–W sinistral strike-slip faults were activated on weakness planes. Some normal and reverse faults were found at the locality of Spišské Bystré in the Malužiná Fm. The same tectonic regime was also observed in the area of Orava region (Pešková et al., 2009); Slovenské rudohorie Mts. (Vojtko, 2003) and Spišská Magura (Vojtko et al., 2010).

The young tectonic stage (*D6*) is characterized by pure W–E oriented tension and it is considered to be the Quaternary in age. This deformational stage controlled the young tectonic evolution of the area. Normal fault planes were recorded in the Lower Pleistocene travertines at the locality of Hranovnické pleso. The same W–E extension was also determined in the Orava-Nowy Targ Basin (Pešková et al., 2009).

The N–S trending normal faults belong most probably to youngest tectonic stage (*D7*) were measured in the Palaeogene sediments near Kravany village. The kinematics of faults was determined on the basis of sedimentary marker offset. The youngest observed structures are parallel with the Vikartovce fault which is considered to be Quaternary in age (Vojtko et al., 2011). Practically the same orientation of tension in the area of the Muráň fault was also reconstructed by Marko (1993[b]).

6. CONCLUSIONS

The study area is composed by the palaeo-Alpine tectonic units (Hronic and Silicic units) and by post-nappe cover formations which are represented by sedimentary succession of the Late Cretaceous and the Central Carpathian Palaeogene Basin (CCPB).

Structural measurements were carried out predominantly in abandoned quarries, outcrops along the roads and railways. At those sites, the Hronic, Silicic or CCPB rock sequence were occurred. Moreover, the structural data of brittle deformation were also collected from the outcrops located in the Lower Pleistocene travertine mounds in the Hranovnické pleso.

Based on the fault-slip analysis, the strike-slip kinematics is dominant in the study area. The determined heterogeneous deformation can be chronologically divided into seven independent homogeneous deformational stages (Fig. 9): 1) the youngest Quaternary tectonic phase is characterized by the NNW–SSE oriented tension; 2) the second deformation stage is defined by pure E–W tension which also originated during the Quaternary period because it was recorded in Pleistocene travertines; 3) third deformational phase arose in the strike-slip tectonic regime with the NE–SW direction of compression and NW–SE tension. Its estimated age is the Late Miocene; 4) fourth generation of brittle structures are assigning to the Middle Miocene in age and were developed under the strike-slip tectonic regime with the N–S compression and perpendicular tension; 5) fifth, a very significant deformation event is represented by the NW–SE compression and NE–SW tension in the strike-slip tectonic regime. This phase also includes a subset, which performs pure NE–SW tension. The age of this deformational stage was tenuously dated to Early–Middle Miocene. The third up to fifth deformation phases were recorded in sedimentary succession of the CCPB and the Hronic and Silicic units; 6) sixth deformational phase was identified only in the Permian formation of the Hronic Unit. This phase is characterized by strike-slip tectonic regime with the WNW–ESE compression and NNE–SSW tension; 7) the last oldest deformation phase recorded in the studied area was the E–W compression and perpendicular tension in the strike-slip tectonic regime. The last two deformation phase were included into the Early Palaeocene to Eocene/Oligocene boundary.

Acknowledgement: This work was supported by the Slovak Research and Development Agency under contract Nos. APVV-0158-06, ESF-EC-0006-07, and by the VEGA grant agency under the contract No. 1/0712/11.

References

Angelier J., 1994: Fault slip analysis and paleostress reconstruction. *In:* Hancock P. L. (Ed.): Continental deformation. Pergamon Press, University of Bristol (U.K.), London, 53-100.

Angelier J. & Mechler P., 1977: Sur une méthode graphigue de recherche des contraintes principles également utilisable en tectonique et en séismologie: la méthode des dièdres droits. *Bulletin de la Societe Geologique de France*, 19, 1309-1318.

Biely A., Beňuška P., Bezák V., Bujnovský A., Halouzka R., Ivanička J., Kohút M., Klinec A., Lukáčik E., Maglay J., Miko O., Pulec M., Putiš M. & Vozár J., 1992: Geologická mapa Nízkych Tatier (M 1:50 000). Štátny geologický ústav Dionýza Štúra, Bratislava.

Biely A., Bujnovský A., Vozárová A., Klinec A., Miko O., Halouzka R., Vozár J., Beňuška P., Bezák V., Hanzel V., Kubeš P., Lukáčik E., Maglay J., Molák B., Pulec M., Putiš M. & Slavkay M. 1997: Vysvetlivky ku geologickej mape Nizkych Tatier. (M 1:50 000). Štátny geologický ústav Dionýza Štúra, Bratislava, 232 p.

Bott M.H.P., 1959. The mechanics of oblique slip faulting. *Geological Magazine*, 96, 109-117.

Delvaux D. & Sperner B., 2003: New aspects of tectonic stress inversion with reference to the TENSOR program. *In*: Nieuwland D. A. (Ed.): New Insights into Structural Interpretation and Modelling. Geological Society, London, Special Publications, 212, 75-100.

Delvaux D., Moeys R., Stapel G., Petit C., Levi K., Miroshnichenko A., Ruzhich V. & San'kov V., 1997: Palaeostress reconstructions and geodynamics of the Baikal region. Central Asia. Part II: Cenozoic tectonic stress and fault kinematics. *Tectonophysics*, 282. 1-4, 1-38.

Dupin J.M., Sassi W. & Angelier J., 1993: Homogeneous stress hypothesis and actual fault slip: a distint element analysis. *Journal of Structural Geology*, 15, 8, 1033-1043.

Filo I. & Siráňová Z., 1996: Tomášovské vrstvy – nová litostratigrafická jednotka podtatranskej skupiny. Geologické Práce, Správy, Bratislava, 102, 41-49.

Filo I. & Siráňová Z., 1998: Hornádske a Chrastianske vrstvy – nové oblastné litostratigrafické jednotky podtatranskej skupiny. Geologické Práce, Správy, Bratislava, 103, 35-51.

Gross P., Köhler E. & Samuel O., 1984: Nové litostratigrafické členenie vnútrokarpatského paleogénu pri Pucove. Geologické Práce, Správy, 77, 75-86.

Gross P., Buček S., Ďurkovič T., Filo I., Karoli S., Maglay J., Nagy A., Halouzka R., Spišák Z., Žec B., Vozár J., Borza V., Lukáčik E., Mello J., Polák M. & Janočko J. 1999[a]: Geologická mapa Popradskej kotliny, Hornádskej kotliny, Levočských vrchov, Spišsko-šarišského medzihorie, Bachurne a Šarišskej vrchoviny (M 1:50 000). Ministerstvo životného prostredia, Geologická služba Slovenskej republiky, Bratislava.

Gross P., Buček S., Ďurkovič T., Filo I., Maglay J., Halouzka R., Karoli S., Nagy A., Spišák Z., Žec B., Vozár J., Borza V., Lukáčik E., Janočko J., Jetel J., Kubeš P., Kováčik M., Žáková E., Mello J., Polák M., Siráňová Z., Samuel O., Snopková P., Raková J., Zlinská A., Vozárová A. & Žecová K. 1999[b]: Vysvetlivky ku geologickej mape Popradskej kotliny, Hornádskej kotliny, Levočských vrchov, Spišsko-šarišského medzihorie, Bachurne a Šarišskej vrchoviny (M 1:50 000). Ministerstvo životného prostredia, Geologická služba Slovenskej republiky, Bratislava, 239 p.

Hancock P.L., 1985: Brittle microtectonics: principles and practice. *Journal of Structural Geology*, 7, 3/4, 437-457.

Janočko J. & Kováč M., 2003: Geotectonic background of origin of Western Carpathian sedimentary basins. *Mineralia Slovaca*, 35, 3-4, 169-180.

Kázmer M., Dunkl I., Frisch W., Kuhlemenn J. & Ozsvárt P., 2003: The Palaeogene forearc basin of the Eastern Alps and Western Carpathians: subduction erosion and basin evolution. *Journal of the Geological Society,* 160, 413-428.

Maerten L., 2000: Variation in slip on intersecting normal faults: Implications for paleostress inversion. *Journal of Geophysical Research*, 105, B11, 25553-25565.

Marko F., 1993[a]: Kinematické indikátory strižných poybov pri krehkej deformácii. *Mineralia Slovaca*, 25, 4, 285-287.

Marko F., 1993[b]: Kinematics of Muráň fault between Hrabušice and Tuhár village. In: Rakús M. & Vozár J. (Eds.): Geodynamický model a hlbinná stavba Západných Karpát. Konferencie, Sympóziá, Semináre, Štátny geologický ústav Dionýza Štúra, Bratislava, 253-261.

Mazúr E. & Lukniš M., 1980: Regionálne geomorfologické členenie (1:500 000), Geografický ústav Slovenskej akadémie vied, Bratislava.

Mello J., Filo I., Havrila M., Ivanička J., Madarás J., Németh Z., Polák M., Pristaš J., Vozár J., Koša E. & Jacko S. jun., 2000[a]: Geologická mapa Slovenského raja, Galmusu a Hornádskej kotliny (M 1:50 000). Geologický ústav Dionýza Štúra, Bratislava.

Mello J., Filo I., Havrila M., Ivan P., Ivanička J., Madarás J., Németh Z., Polák M., Pristaš J., Vozár J., Vozárová A., Liščák P., Kubeš P., Scherer S., Siráňová Z., Szalaiová V. & Žáková E., 2000[b]: Vysvetlivky ku geologickej mape Slovenského raja, Galmusu a Hornádskej kotliny (M 1:50 000). Geologický ústav Dionýza Štúra, Bratislava, 303 p.

Nieto-Samaniego A.F. & Alaniz-Alvarez S.A., 1996: Origin and tectonic interpretation of multiple fault patterns. *Tectonophysics*, 270, 197-206.

Pešková I., Vojtko R., Starek D. & Sliva Ľ., 2009: Late Eocene to Quaternary deformation and stress field evolution of the Orava region (Western Carpathians). *Acta Geologica Polonica*, 59, 1, 73-91.

Petit J.P., 1987: Criteria for the sense of movement on fault surfaces in brittle rocks. *Journal of Structural Geology*, 9, 5-6, 597-608.

Petráš M., 2008: Kinematika a dynamika Muráňskeho zlomového systému v oblasti Slovenského raja. Manuskript – Diplomová práca, Prírodovedecká fakulta, Univerzita Komenského, Bratislava, 89 p.

Pollard D.D., Saltzer S.D. & Rubin A.M., 1993: Stress inversion method: are they based on faulty assumptions? *Journal of Structural Geology*, 15, 8, 1045-1054.

Roberts G.P. & Ganas A., 2000: Fault-slip directions in central and southern Greece measured from striated and corrugated fault planes: Comparison with focal mechanism and geodetic data. *Journal of Geophysical Research*, 105, B10, 23443-23462.

Royden L.H. & Báldi T., 1988: Early Cenozoic tectonics and paleogeography of the Pannonian Basin and surrounding regions. *American Association of Petroleum Geologists Memoirs*, 45, 1-16.

Soták J., Bebej J. & Biroň A. 1996: Detrital analyse of the Paleogene flysch deposits of the Levoča Mts: evidence for sources and paleogeography. *Slovak Geological Magazine* 2, 3-4, 345-349.

Soták J., Pereszlényi M., Marschalko R., Milička J. & Starek D. 2001: Sedimentology and hydrocarbon habitat of the submarine-fan deposits of the Central Carpathian Paleogene Basin (NE Slovakia). *Marine and Petroleum Geology*, 18, 1, 87-114.

Sperner B., Müller B., Heidbach O., Delvaux D., Reinecker J. & Fuchs K., 2003. Tectonic stress of the Earth's crust: advances in the World Stress Map Project. *In:* Nieuwland D.A. (Ed.): New insights in structural interpretation and modelling. Geological Society, London, *Special Publications*, 212, 101-128.

Tari G., Báldi T. & Báldi-Beke M., 1993: Paleogene retroarc flexural basin beneath the Neogene Pannonian Basin: a geodynamic model. *Tectonophysics*, 226, 433-456.

Twiss R.J. & Unruh J.R., 1998: Analysis of fault slip inversions: Do they constrain stress or strain rate? *Journal of Geophysical Research*, 101, 8335-8361.

Vass D., Began A., Gross P., Kahan Š., Köhler E., Krystek I., Lexa J. & Nemčok J., 1988: Regionálne geologické členenie Západných Karpát a severných výbežkov Panónskej panvy na území ČSSR (M 1:500 000). Geologický ústav Dionýza Štúra, Bratislava.

Vojtko R., 2003. Štruktúrna analýza zlomov a geodynamický vývoj strednej časti Slovenského rudohoria. Manuskript – dizertačná práca, Prírodovedecká fakulta, Univerzita Komenského, Bratislava, 91 p.

Vojtko R., Tokárová E., Sliva Ľ. & Pešková I., 2010: Reconstruction of Cenozoic palaeostress fields and revised tectonic history in the northern part of the Central Western Carpathians (the Spišská Magura and Východné Tatry Mountains). *Geologica Carpathica*, 61, 3, 211-225.

Vojtko R., Marko F., Preusser F., Madarás J. & Kováčová M., 2011: Late Quaternary fault activity in the Western Carpathians – evidence from the Vikartovce Fault (northern Slovakia). *Geologica Carpathica*, 62, 6, 563-574.

Vozárová A. & Vozár J., 1981: Litostratigrafická charakteristika mladšieho paleozoika hronika. Bratislava, *Mineralia Slovaca*, 13, 5, 385-403.

Vozárová A. & Vozár J., 1988: Late Paleozoic in West Carpathians. Geologický ústav Dionýza Štúra, Bratislava, 314 p.

Resumé: Územie západnej časti Hornádskej kotliny a priľahlej oblasti Kozích chrbtov sa nachádza v severnej časti stredného Slovenska, južne od mesta Poprad. Západnú časť Hornádskej kotliny a časť Kozích chrbtov ohraničuje zo severu Popradská kotlina, zo západu a juhu Kráľovohoľské Nízke Tatry, z juhu a juhovýchodu Slovenský raj a z východu centrálna časť Hornádskej kotliny. Územie západnej časti Hornádskej kotliny, južných a severovýchodných svahov Kozích chrbtov je odvodňované riekou Hornád, ktorá patrí do úmoria Čierneho mora. Severozápadnú časť Kozích chrbtov odvodňuje rieka Poprad, ktorá patrí do úmoria Baltického mora (Obr. 1).

Podľa geomorfologického členenia patrí celé študované územie pod tatransko – fatranskú geomorfologickú oblasť, geomorfologický celok Hornádska kotlina, podcelok Vikartovská priekopa a geomorfologický celok Kozie chrbty, podcelok Dúbrava (Mazúr & Lukniš, 1980). Z hľadiska regionálno – geologického členenia patria Kozie chrbty (Vikartovský chrbát) veporiku, západná časť Hornádskej kotliny patrí vnútrokarpatskému paleogénu a Slovenský raj gemerskému pásmu (Vass et al., 1988) (Obr. 2).

Článok je zameraný na rekonštrukciu kenozoického vývoja paleonapäťového poľa v študovanej oblasti. Paleonapäťová rekonštrukcia bola realizovaná zberom a následnou štruktúrnou analýzou 690 zlomov na 15 lokalitách (Tab. 1, 2).

Na základe kinematiky zlomov na študovaných lokalitách a vzťahmi medzi vekovo odlišnými zlomami na lokalitách, bolo možné pomocou softvérových aplikácií vyseparovať týchto 7 hlavných deformačných udalostí (Obr. 9):

Najstaršia tektonická fáza (*D1*) je charakterizovaná približne Z–V kompresiou a S–J tenziou v smerne-posuvnom tektonickom režime (Obr. 3a,b; 4). Druhá deformačná etapa (*D2*) bola generovaná v smerne-posuvnom tektonickom režime. Kompresia mala smer ZSZ–VJV a na ňu kolmá tenzia mala smer SSV–JJZ. Prvé dve deformačné udalosti nezasahovali do paleogénnych sedimentov centrálno-karpatskej paleogénnej panvy, z čoho vyplýva, že deformácia prebiehala pred usadením paleogénnych sekvencií. Podľa prác publikovaných z iných oblastí (napr. Vojtko, 2003; Petráš, 2008; Pešková et al., 2009; Vojtko et al., 2010) boli deformácie zaradené do obdobia medzi vrchným paleocénom až stredným eocénom/?oligocénom. Zlomy tretej generácie (*D3*) vznikali počas smerne-posuvného tektonického režimu, ktorý má smer kompresie SZ–JV a smer tenzie SV–JZ. Podľa vzťahu s nižšie uvedenými deformačnými fázami ju považujeme za staršiu a jej vek predpokladáme za spodný miocén, čo sa zhoduje aj so staršími prácami (Obr. 3c, 5). Štvrtú orientáciu paleonapäťového poľa (*D4*) vypočítaného zo zlomových štruktúr tvorí generálne S–J kompresia a Z–V tenzia vyvíjaná počas smerne-posuvného tektonického režimu. Na základe prác (napr. Vojtko, 2003; Petráš, 2008; Pešková et al., 2009; Vojtko et al., 2010) je táto deformačná fáza zaraďovaná do stredného miocénu (Obr. 3d, 6). Piata deformačná etapa (*D5*) je aktivovaná v smerne-posuvnom tektonickom režime so SV–JZ orientovanou kompresnou zložkou a SZ–JV orientovanou tenznou zložkou. Predpokladáme, že táto deformačná etapa patrí vrchnomiocénnej tektonike (Obr. 3e, 7). Šiesta deformačná udalosť (*D6*) vznikala pravdepodobne v podmienkach čistej extenzie s generálne orientovanou tenziou v smere Z–V. Poklesové zlomy boli namerané v staropleistocénnych travertínoch Hranovnického plesa a vznikali v najmladších etapách tektonického vývoja oblasti. Orientácia tenzie v Z–V smere je veľmi dobre korelovateľná s výsledkami získanými z Oravsko-novotargskej panvy (Pešková et al., 2009) a z oblasti Spišskej Magury a Podhalia (Vojtko et al., 2010) (Obr. 3f, 8). Najmladšiu deformačnú udalosť (*D7*) predstavuje SSZ–JJV extenzia. Zlomové sklzy vznikali v pripovrchových „studených" podmienkach a sú paralelné s vikartovským zlomom, ktorý je kvartérnou zlomovou štruktúrou (Vojtko et al., 2011).

Výpočtom a štatistickým vyhodnotením údajov z nameraných zlomov bolo možné identifikovať výraznú dominanciu tektonických zrkadiel so smerne-posuvným pohybom. Na základe tohto poznatku môžeme povedať, že oblasť bola dlhodobo pod vplyvom smerne-posuvného tektonického režimu, ktorý spôsoboval krehké deformácie v predmetnom území.