Late Badenian to Quaternary palaeostress evolution of the northeastern part of the Danube Basin and the southwestern slope of the Štiavnica Stratovolcano (Slovakia)

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Abstract: The Danube Basin, located among the Eastern Alps, Western Carpathians, and Transdanubian Range, covers northwestern part of the Pannonian Basin. The basin is represented by typical finger-like morphostructures of pre-Cenozoic basement and Neogene sediments. Based on the basin-and-range structure, the area is traditionally divided into five depressions (Blatné, Rišňovce, Komjatice, Želiezovce, and Gabčíkovo-Györ depressions). From the geological point of view, the Danube Basin is infilled by the middle Miocene to Quaternary marine, lacustrine, and alluvial sedimentary sequences. The pre-Cenozoic basement is composed of the Tatric and Veporic units, except southernmost part formed by the tectonic unit of the Transdanubian Range. The eastern part of the basin was influenced by extensive volcanic activity of the Štiavnica Stratovolcano and volcanoes buried below the basin fill during the middle Miocene. Fault-slip analysis was performed in the study area to reveal and discuss the palaeostress field evolution form the Badenian onward. The structural measurements were carried out in outcrops with the following lithostratigraphy: (1) Badenian shallow sea to deltaic deposits; (2) Sarmatian deltaic to alluvial sediments; (3) upper Miocene alluvial sequence; (4) Lower Pleistocene river sediments; (5) Pleistocene loess sequences. Based on the obtained fault-slip data and palaeostress reconstruction, four main palaeostress phases can be distinguished: (1) the oldest Late Badenian to Early Sarmatian phase is characterized by strike-slip tectonic regime with the general orientation of compressional stress axis (σ_1) in the N–S direction and perpendicular tension, which dominated at the end of the stage (σ_3); (2) Sarmatian to Early Pannonian strike-slip tectonic regime is defined by the NE–SW oriented σ_1 and the NW–SE oriented σ_3; (3) the Pannonian to earliest Pliocene phase can be described by extensional tectonic regime with the orientation of σ_3 in NW–SE direction; (4) the youngest recorded extensional tectonic regime is characterized by the NE–SW to E–W orientation of the σ_3 axis. This tectonic phase can be tenuously dated at Pliocene to Quaternary age and is most probably still active.

Key words: Danube Basin, Štiavnica Stratovolcano, Miocene–Quaternary, tectonic evolution, fault-slip analysis

1. INTRODUCTION

The Danube Basin, located at the Eastern Alps, Western Carpathians, and Transdanubian Range junction, represents a northern depocentre of the Pannonian Basin system (Fig. 1). The northern part of the basin is divided into finger like depressions placed between the Western Carpathian Core Mountains, from west to east known as the Blatné, Rišňovce, and Komjatice depressions (Vass, 2002). The eastern part is formed by the Želiezovce Depression and the central part is represented by the Gabčíkovo-Györ Depression (Fig. 2).

The formation of these depressions was predominantly controlled by normal faulting (cf. Fig. 2). The Blatné Depression is bordered by the Malé Karpaty Fault in the west and by the Považie Fault in the east. The Rišňovce Depression is located in between the Považský Inovec Mts. and the Tribeč Mts. and is bounded by the Ripňany Fault on the west and the Veľké Zálužie Fault on the east. The Komjatice Depression was formed on the eastern hanging-wall of the Komjatice Fault. The faulting of the Danube basin was controlled by asymmetric subsimple shearing where the dominant faults were located in the western sides of aforementioned depressions (e.g., Bielik et al., 2002; Hók et al.

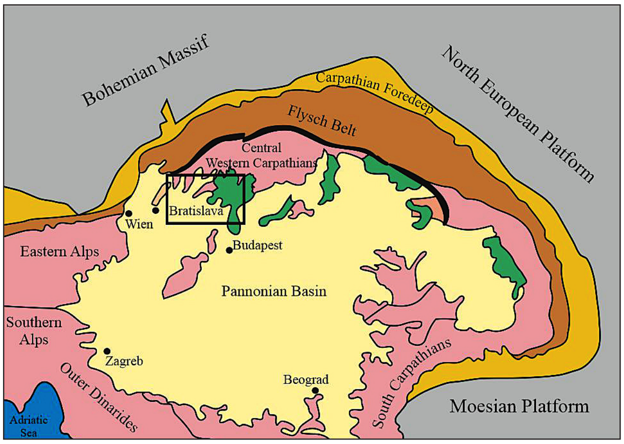

Fig. 1. Simplified tectonic sketch map of the Alpine-Carpathian-Pannonian-Dinaridic orogene system with the study area shown by black rectangle.

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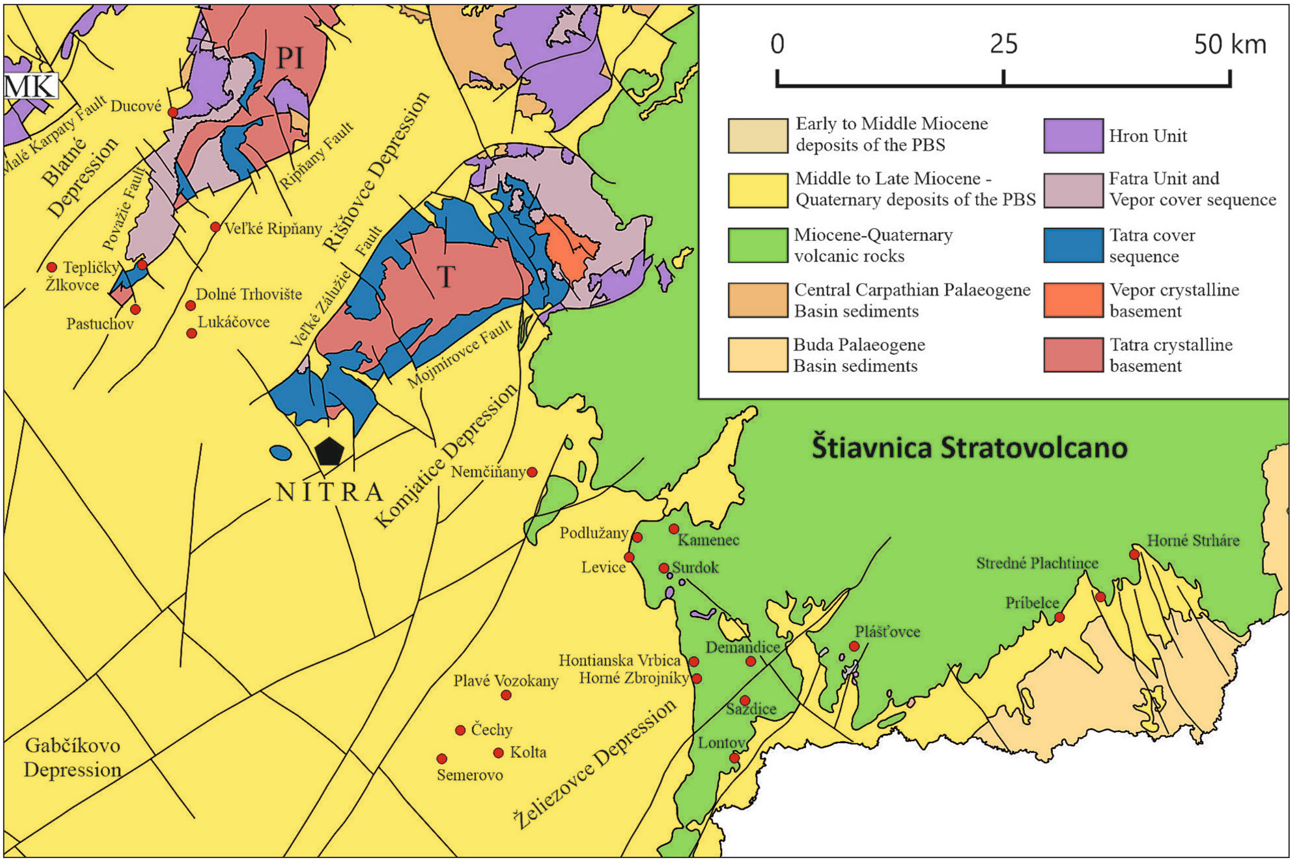

Fig. 2. Simplified tectonic map with location of the study sites (map according to Bezák et al., 2004, simplified). Explanation: MK – Malé Karpaty Mts., PI – Považský Inovec Mts., and T – Tribeč Mts.

2016). This process took place under transtension/extension tectonic regime with the principal palaeostress tensional axis in the W–E to NW–SE (Marko et al. 1991, 1995; Fodor 1995; Marko & Kováč 1996). Three main tectonic phases can be recognized in the tectonic evolution of the study area. The first two phases were linked with the simple shear model, which led to the opening of halfgrabens in the Danube Basin system. The third tectonic phase can be characterized by pure shear extension especially in the eastern part of the basin with presence of the angular disconformity between the Sarmatian and Pannonian sediments (cf. Hók et al., 2016).

The pre-Cenozoic basement of the basin is formed by the Western Carpathian Variscan crystalline fundament, their Upper Palaeozoic to Mesozoic cover sequences (Tatra and Vepor units) and locally palaeo-Alpine superficial nappes (Fatra and Hron units). The basement, south of the Hurbanovo-Diósjenö Fault, is composed of tectonic units of the Transdanubian Range with conspicuous affinity to the tectonic unit forming the Southern Alps (e.g., Haas & Budai, 2014; Klučiar et al., 2016; Kováč et al., 2016). The palaeo-Alpine nappe pile is sealed by the Palaeogene to lower Miocene strata predominantly occurring in the northernmost portion of the basin (Fusán et al., 1987; Hók et al., 2016). Deposition of the middle Miocene sedimentary fill started after the basin opening during the Badenian (Rybár et al., 2015, 2016; Kováč et al., 2017[a], 2017[b]). This process was in close relation to the asthenospheric bulging and initial rifting of the Danube Basin, which is followed by marine transgression (Lankreier et al., 1995; Kováč, 2000; Konečný et al., 2002).

The study area was subject of intensive geological mapping of the middle Miocene to Quaternary strata supplemented by a sedimentological research (e.g., Vass, 2002; Nagy et al., 1998[a], 1998[b], Pristaš et al., 2000; Maglay et al., 2006; Šujan & Rybár, 2014; Rybár et al., 2015, 2016; Šujan et al., 2016; Sztanó et al., 2016). However, fault-slip analysis and palaeostress reconstruction have never been done systematically. There are several structural works, which were oriented on some specific problems, but not especially focused on the Cenozoic tectonic evolution of the Danube Basin (e.g., Nemčok et al., 1998; Fodor, 1995; Marko et al., 1995). For this reason, the aim of this paper is the reconstruction of palaeostress field from the late Badenian to Quaternary period. We hope that this data will be important for future reconstruction of kinematics on principal fault zones in the study area and the neighbourhood.

2. LITHOSTRATIGRAPHY

The lithostratigraphic record comprises predominantly middle to upper Miocene, Pliocene, and Quaternary formations, respectively. The onset of sedimentation in the Danube Basin is characterized by the shallow to deep marine Bajtava, Špačince, and Báhoň formations during the Badenian (15.0–12.7 Ma; Fig. 3).

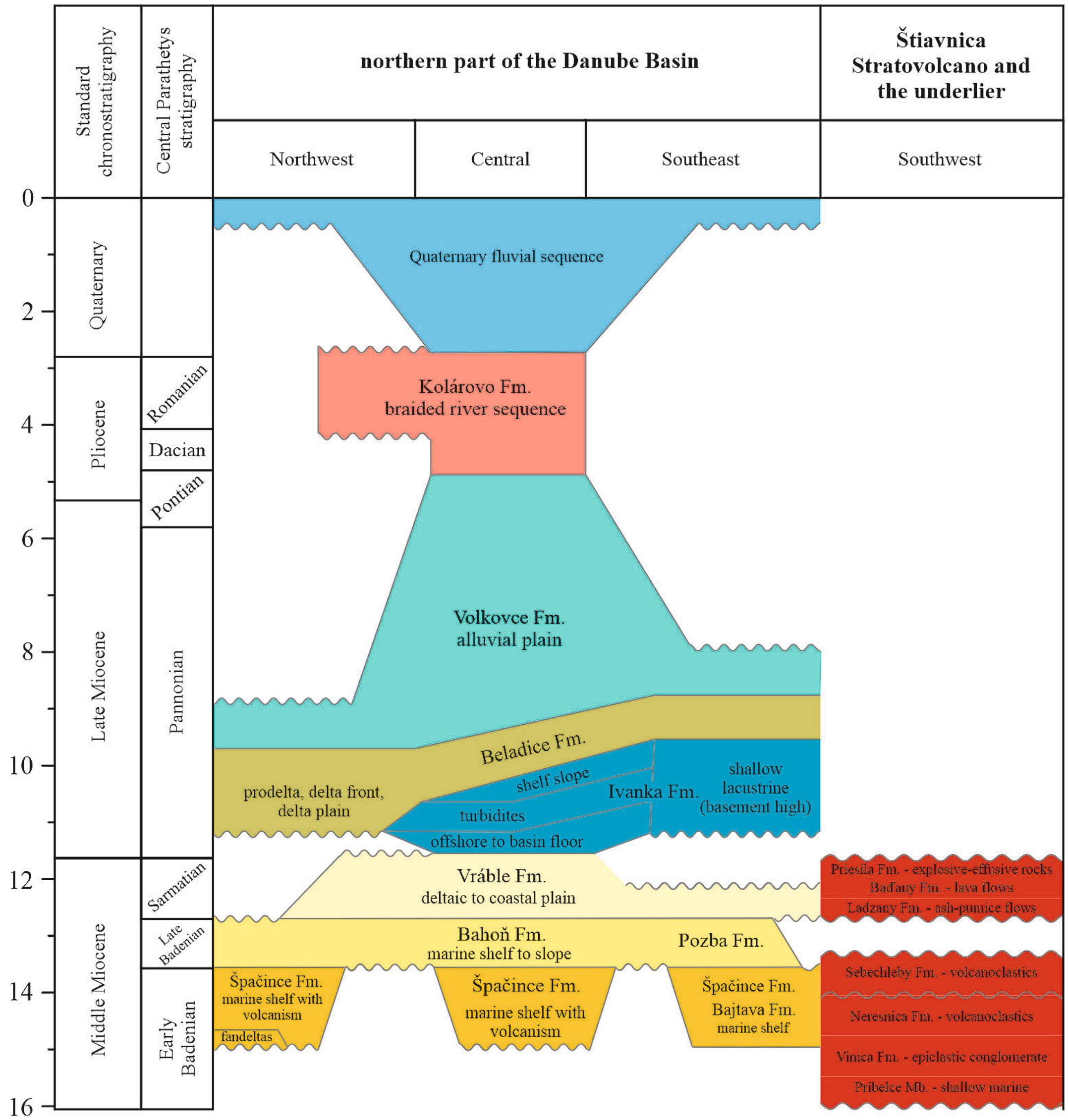

Fig. 3. Lithostratigraphic column of the Danube Basin and the Štiavnica Stratovolcano (for further information see section Lithostratigraphy).

At the eastern part of the Danube Basin and on the southwestern slope of the Štiavnica Stratovolcano, the Vinica Formation (Badenian) and Príbelce Member are present. Coarse-grained epiclastic volcanic conglomerates characterize the Vinica Formation. The Príbelce Mb. (Badenian) is a basal member of the Vinica Fm. with predomination of fine to coarse-grained sands and volcanoclastic detritus. The Vinica Fm. is covered by the Neresnica Fm. that includes products of extrusive volcanic activity of hypersthene-hornblende andesite with garnet (Konečný et al., 1998[a], 1998[b]).

A gradual sedimentary changeover in the basin to the regressive Vráble Formation occurred in the late (Sarmatian, 12.7–11.6 Ma) and alluvial, deltaic, and coastal plain environments dominated (Vass, 2002; Nagy et al., 1998[a], 1998[b]; Kováč et al., 2007).

The products of explosive eruptions of ash-pumice flows were succeeded by the effusions of mostly glassy and leucocratic pyroxenite andesite lava flows of the Baďany Formation (Sarmatian). The explosive-effusive products of volcanic activity of amphibole-pyroxene andesite of the Priesila Formation (Sarmatian) form a palaeovalley fill on the south-western slope of the Štiavnica Stratovolcano and continues into the area of eastern Danube Basin (Konečný et al., 1998[a], 1998[b]).

After basin inversion supposed during the middle–late Miocene transition (Horváth et al., 2006) a new subsidence cycle (Lankreijer et al., 1995) occurred, which led to formation of up to 300 m deep basin floor depocentre in the area of the Gabčíkovo-Györ and Komjatice depressions (Kováč et al., 2010, 2011, 2017[b]; Šujan et al., 2016; Sztanó et al., 2016). The early late Miocene is characterized with isolation of the brackish Pannonian Lake and sedimentation of the Ivanka Formation (Pannonian), which comprises continuous succession from basin floor shales and turbidites, followed by shelf slope silts and clays caped by offshore shelfal deposits. No significant surface occurrence of the Ivanka Formation was observed and therefore no structural data for this sequence were acquired in the study area. Gradual transition to deltaic environment of the Beladice Formation during 11.0–9.5 Ma was caused by progradation of deltaic systems fed by the Eastern Alpine and Western Carpathian rivers and oriented south-westward or south-eastward (Šujan et al., 2016; Sztanó et al., 2016).

Tab. 1: List of study locations with general information on position and litho- and chronostratigraphy.

No.	Site	Longitude	Latitude	Altitude [m a.s.l.]	Formation	Age	Age [Ma]
1	**Žlkovce**	17°42′44.16″E	48°27′35.34″N	160	Weichselian Fm.	Late Pleistocene	0.09–0.01
2	**Ducové**	17°52′14.90″E	48°37′24.10″N	175	Weichselian Fm.	Late Pleistocene	0.09–0.01
3	**Tepličky**	17°50′45.60″E	48°28′13.10″N	255	Weichselian Fm.	Late Pleistocene	0.09–0.01
4	**Veľké Ripňany**	17°56′57.90″E	48°30′51.10″N	195	Volkovce Fm./Lukáčovce Mb.	Pliocene/Quaternary	8.0–6.0/2.5–2.0
5	**Dolné Trhovište**	17°55′23.16″E	48°26′04.68″N	175	Volkovce Fm./Lukáčovce Mb.	Pliocene/Quaternary	8.0–6.0/2.5–2.0
6	**Lukáčovce**	17°55′42.42″E	48°24′26.58″N	190	Volkovce Fm./Lukáčovce Mb.	Pliocene/Quaternary	8.0–6.0/2.5–2.0
7	**Pastuchov**	17°50′30.65″E	48°25′33.27″N	260	Volkovce Fm.	Late Pannonian	8.0–6.0
8	**Semerovo**	18°21′08.20″E	48°00′35.20″N	135	Volkovce Fm.	Late Pannonian	8.0–6.0
9	**Čechy**	18°22′33.60″E	48°02′21.80″N	180	Volkovce Fm.	Late Pannonian	8.0–6.0
10	**Kolta**	18°26′05.16″E	48°01′17.84″N	250	Volkovce Fm.	Late Pannonian	8.0–6.0
11	**Plavé Vozokany**	18°26′20.20″E	48°04′40.70″N	175	Volkovce Fm.	Late Pannonian	8.0–6.0
12	**Nemčiňany**	18°27′18.00″E	48°18′16.81″N	235	Nemčiňany Fm.	Early Pannonian	11.6–11.0
13	**Levice**	18°36′07.24″E	48°13′20.92″N	180	Baďany/Priesil Fm.	Sarmatian	12.6–11.6
14	**Kamenec**	18°39′53.53″E	48°15′20.36″N	210	Baďany/Priesil Fm.	Sarmatian	12.6–11.6
15	**Surdok**	18°39′22.02″E	48°12′57.12″N	190	?Vráble Fm.	Sarmatian	12.6–11.6
16	**Podlužany**	18°36′45.72″E	48°14′39.85″N	200	?Vráble Fm.	Sarmatian	12.6–11.6
17	**Demandice**	18°47′42.00″E	48°07′51.00″N	165	?Vráble Fm.	Sarmatian	12.6–11.6
18	**Sazdice**	18°47′27.70″E	48°05′30.24″N	140	?Vráble Fm.	Sarmatian	12.6–11.6
19	**Hontianska Vrbica**	18°42′48.96″E	48°07′34.78″N	180	Vráble Fm.	Sarmatian	12.6–11.6
20	**Lontov**	18′46′56.20″E	48°02′03.40″N	135	Vráble Fm.	Sarmatian	12.6–11.6
21	**Horné Zbrojníky**	18°43′02.94″E	48°06′34.38″N	180	Vráble Fm.	Sarmatian	12.6–11.6
22	**Plášťovce**	18°56′48.33″E	48°09′14.72″N	170	Bajtava Fm.	Early Badenian	15.0–14.0
23	**Stredné Plachtince**	19°18′18.64″E	48°13′19.50″N	290	Bajtava Fm.	Early Badenian	15.0–14.0
24	**Horné Strháre**	19°21′06.96″E	48°15′55.43″N	350	Vinica Fm. (Príbelce Mb.)	Early Badenian	16.0–14.8
25	**Príbelce**	19°14′44.00″E	48°11′50.90″N	350	Vinica Fm. (Príbelce Mb.)	Early Badenian	16.0–14.8

A regression and onset of the alluvial sequence of the Volkovce Formation followed. Long lasting alluvial deposition, which occupied the entire basin from 8.9 Ma to at least 6.0 Ma, gave rise to deposition of up to 1500 m thick pile of mostly clayey floodplain succession with occurrence of channel belts (Kováč et al., 2010, 2011, 2017[b]; Šujan et al., 2016, 2017[a]). Pliocene basin inversion, active between 6.0 and 4.0 Ma (Horváth, 1995; Horváth et al., 2006), caused partial denudation of the Volkovce Formation apart from the Gabčíkovo-Györ Depression. The late Miocene alluvial succession could be observed in commonly appearing outcrops representing dominantly channel belt deposits in sand pits, offering structural record of variable quantity. The recent surface erosion processes are linked to the tectonic disruption of the Volkovce Fm. (Burian et al., 2017).

Early Pliocene basin inversion led to following increase of sediment supply, which is recorded in sedimentation of braided rivers representing strata of the late Pliocene Kolárovo Formation (Fig. 3). Mentioned succession was deposited on a wide pediplain and was preceding by intense planation. Pleistocene deposits are preserved in remnants of river terraces along the basin margins, related to the Quaternary uplift of the mountains, which limits the basin (Vojtko et al., 2008; Šujan et al., 2017[b], 2018). Pliocene to Pleistocene transition is recorded mainly in the north-eastern part located at the Rišňovce Depression by the Lukáčovce Member (Šarinová, 2002; Šarinová & Maglay, 2002). The Lukáčovce Member represents thin accumulation of braided river deposits placed in the uppermost levels of terrace staircases. Continual sedimentation from the late Miocene up to recent is supposed in the Gabčíkovo-Györ Depression (Kováč et al., 2010, 2011, 2017[a], 2017[b], 2018). The age of all discusses formations in this chapter is predominantly taken from the works of Sztanó et al., (2016), Šujan et al. (2016, 2017[a], 2018), Kováč et al. (2018).

3. METHODS

Systematic tectonic studies were carried out at the northern margin of the Danube Basin and the southeastern slopes of the Štiavnica Stratovolcano. Field observations consists mainly of measurements of faults, but joints were also taken into account. The structures were observed in sedimentary and volcano-sedimentary formations, which have never been deeply buried and still stayed very close to the surface. From that reason a semi-quantitative stress orientation method focussed on kinematic and geometric characteristics of fault-slip data was applied, namely, right dihedra method. The method has proven to be the most robust, although it lacks the precision of its more elegant numerical counterparts. Results obtained by its application seldom differ substantially from numerical analyses of the same data. For other, more complicated graphical analyses, the reader is referred to the papers written by Compton (1966), Arthaud (1969), and Aleksandrowski (1985). Thus, this method was used for site with small amount of data and Pliocene to Quaternary deposits, because of almost lithostatic stress-free environment, which is caused by relatively thin strata with non-significant lithostatic pressure. For more numerous and heterogeneous group of fault-slips, an inversion method was used. The inversion method is based on the assumption of Bott (1959) and Wallace (1951) that the 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: the principal axes are σ_1 (maximum compression), σ_2 (intermediate compression), σ_3 (minimum compression, tension respectively) and the ratio of the principal stress differences: $\Phi = (\sigma_2 - \sigma_3) / (\sigma_1 - \sigma_3)$. The latter defines the shape of the stress ellipsoid (cf. Angelier, 1989, 1994). All these values can be derived from the observed brittle failure pattern, because a theoretical well-known equation defines the relationship between the different types of faults and the stress fields (cf. Anderson, 1951; Bott, 1959).

The obtained fault-slip data were handled and visualized by the TectonicsFP 1.7.7 computer program coded by Franz Reiter and Peter Acs (Ortner et al., 2002). The joint measurements were processed by the Orient 3.9.0 software coded by Frederick W. Vollmer (cf. Vollmer, 2019).

4. FAULT-SLIP ANALYSIS AND PALAEOSTRESS RECONSTRUCTION

4.1. Loess deposits (Weichselian a.k.a. Vistulian; 80–11.5 ka BP)

The loess deposits form a spatially extensive Pleistocene cover. However, only several localities with observed normal faults were found (Žlkovce, Ducové quarry, and Tepličky gourge) in the Blatné and Rišňovce depressions, respectively.

The Žlkovce site consists of four small outcrops close to the village of Žlkovce (Tab. 1; Fig. 2). Fractures only were measured at the sites, but some of them may also be faults, but we do not have enough evidence for this assumption and therefore the measured structures were only included into the joint set. In the overall characteristics of the measured joints from all the localities around the village of Žlkovce, the NNW–SSE strikes appear

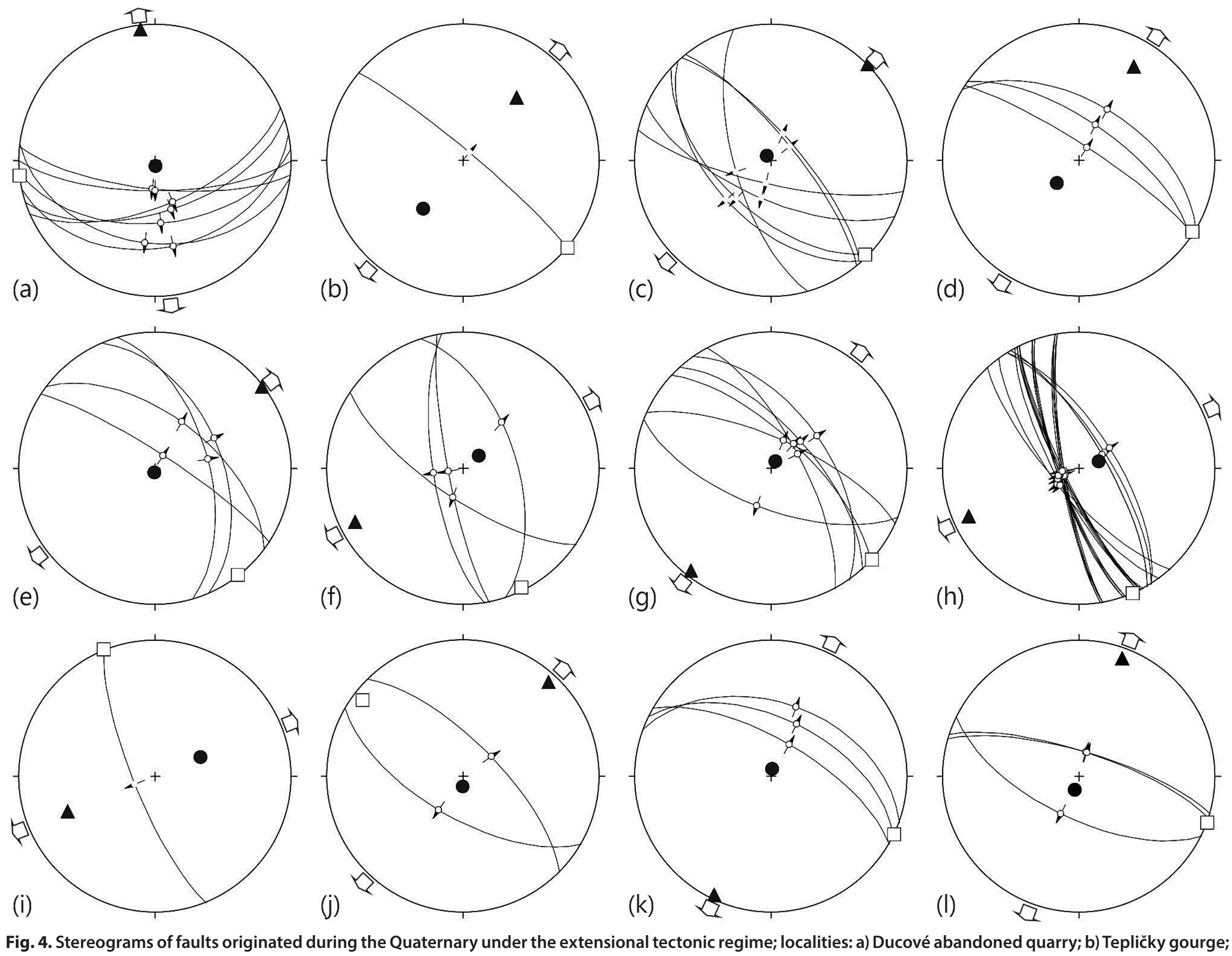

Fig. 4. Stereograms of faults originated during the Quaternary under the extensional tectonic regime; localities: a) Ducové abandoned quarry; b) Tepličky gourge; c) Veľké Ripňany abandoned sand pit; d) Dolné Trhovište abandoned sand pit; e) Lukáčovce abandoned sand pit; f) Pastuchov abandoned sand pit; g) Príbelce abandoned sand pit; h) Kolta abandoned sand pit; i) Nemčiňany sand pit; j) Kamenec abandoned sand pit; k) Sazdice site; l) Lontov abandoned sand pit.

in the direction of the valley and the relatively less frequent joints are in the N–S direction of plane strikes, which are parallel with the "Váh graben" (Váh Holocene fluvial plane).

The Ducové abandoned quarry is located approximately 350 m south of Ducové village. In the quarry, the Triassic Wetterstein dolomite of the Hron Unit is outcropped and is covered by the Vistulian loessial sediments. These sediments are cut by seven normal faults out of 13 faults (Tab. 1; Fig. 2). Based on the data processing of palaeostress analysis of fault-slips it was confirmed that these faults belong to two homogeneous groups. The first group is characterized by faults, which are sealed by the Vistulian loessial deposits. It means that these faults are older than the Vistulian. However, the lower time limit is unknown. This faulting was activated under extensional tectonic regime where the principal minimal palaeostress axis operated in the ENE–WSW direction. The second group is younger than the Vistulian and the faults were developed under the N–S principal minimal palaeostress axis (σ_3) in an extensional tectonic regime (Fig. 4a).

The Tepličky site is located in the northern part of the Rišňovce Depression 1200 m north-west of Tepličky village, in a deep gorge (Tab. 1; Fig. 2). The lower part of this site is composed of Triassic dolomite to dolomite breccia and partly also quartzite of the Tatra Unit occurs. The Triassic succession is covered by sand and gravel of the Volkovce Formation (late Pannonian) and red coloured clay of the Lukáčovce Formation (Early Pleistocene). The upper part of the gorge consists of the Vistulian loamy sediments (cf. Vojtko et al., 2008). In this site, one NW–SE normal fault with NE downthrown block was observed, which cut the loessial sediments. The offset on the fault plane is approximately 0.65 m. Based on the geometric calculation, this fault was activated during the extensional tectonic regime with the orientation of minimal stress axis (σ_3) in the NE–SW direction during the latest Pleistocene to Holocene (Fig. 4b).

4.2. Lukáčovce Member (Pleistocene; 2.5–2.0 Ma) and Volkovce Formation (late Pannonian–Pleistocene; 8.0–6.0 Ma)

The Veľké Ripňany abandoned sand pit is located approximately 2.5 km north-west of Veľké Ripňany village on the right side of the Radošina stream in the area of Vinohrady (Tab. 1, Fig. 2). This is an old abandoned sand pit where light yellow to brown cross-stratified alluvial sand and weakly consolidated sandstone (Volkovce Formation) of late Miocene age is exposed. Above the strata, the Early Pleistocene Lukáčovce Formation composed of coarse sandy to gravelly cross-beds occurs and the Vistulian loess forms the upper portion of sand pit. Twenty-five fault-slips were measured in this locality, which belong to two homogeneous groups (cf. Vojtko et al., 2008). The first group consist of almost NE–SW oriented faults (Fig. 5a), which cut the Volkovce Formation but do not continue into the overlying strata (Lukáčovce Formation). The second group is younger than the previous one and is composed of the fault with the NW–SE strike (Fig. 4c).

The Dolné Trhovište abandoned sand pit is situated southeast of Dolné Trhovište village. In this site, the Volkovce Formation, consisting of channel fill sand and locally covered by the Lukáčovce Formation, was extracted in the past (Tab. 1; Fig. 2). Two polygenetic sets of normal faults can be distinguished in to homogeneous groups. Older fault set disrupted older strata represented by the Volkovce Formation (Late Pannonian) and do not continues to Lower Pleistocene strata of the Lukáčovce Formation. This group includes 23 ENE–WSW striking conjugate normal faults, which formed a typical horst and graben pattern and indicates a vertical position of principal maximum palaeostress axis (σ_1) and consequently point to NNW–SSE-directed extension (Fig. 5b). The younger fault set cut the Lukáčovce Formation and is characterised by the NW–SE normal faults which operated under the NE–SW oriented minimal principal palaeostress axis (σ_3) (Fig. 4d).

The Lukáčovce abandoned sand pit lie roughly 1 km NNW of Lukáčovce village (Tab. 1, Fig. 2). In this sand pit, the lower portion is composed of sand of the Volkovce Formation, which is covered by the red clay with occasional pebbles of the Lukáčovce Formation in the middle portion of the uncovered wall. The Vistulian loess forms the upper part of the sand pit. The sedimentary strata in this locality are disrupted by five faults where four of them cut the Lukáčovce Formation. However, it is not possible to observe whether the fault also cut the overlying loess because where the faults occurred the loess deposits are missing at this site. The strike of these faults is roughly in a NW–SE direction with the dipping northeastwards (Fig. 4e). One ENE–WSW fault with the SSE dip is sealed by the Lukáčovce Formation and disrupts only sand of the Volkovce Formation (Fig. 5c). Based on the palaeostress reconstruction the older fault operated under the almost N–S oriented σ_3 in extensional tectonic regime. The last four faults that cut the Lukáčovce Formation were activated when the minimal stress axis (σ_3) was placed into the NE–SW direction.

The Pastuchov abandoned sand pit is located 1 km east of Hlohovec town on the western slope of the the Považský Inovec Mts. (Tab. 1; Fig. 2). The outcrop comprises channel fill deposits of cross-bedded medium sands graded to inclined heterolithic stratification and caped by overbank silts (Šujan et al., 2017[a]). In the sand pit, four fault-slip data were measured and were interpreted as normal faults based on the crosscutting relation with respect to the bedding planes. The strike of the faults is generally in the NW–SE direction with inclination on both sides (Fig. 4f). According to these geometrical criteria, it is possible to consider these faults as conjugate fault system, which was originated during the extensional tectonic regime with orientation of (σ_3) in the NE–SW direction with subvertical compressional axis (σ_1).

The Semerovo locality is in present abandoned sand pit situated in the southern margin of the village of Semerovo (Tab. 1; Fig. 2). The outcrop is composed of channel fill cross-stratified medium to fine sands, overlain by silty overbank deposits. Ten dislocations were observed on the locality. Unfortunately, it was not possible to find any slickenside lineations, because the rocks on the site are poorly outcropped and weathered. We do not exclude that some of these fractures are faults. In this case, all measured fractures were interpreted only as joints. These N–S fractures are moderately inclined eastwards and the orientation of principal minimal axis (σ_3) is in the W–E direction.

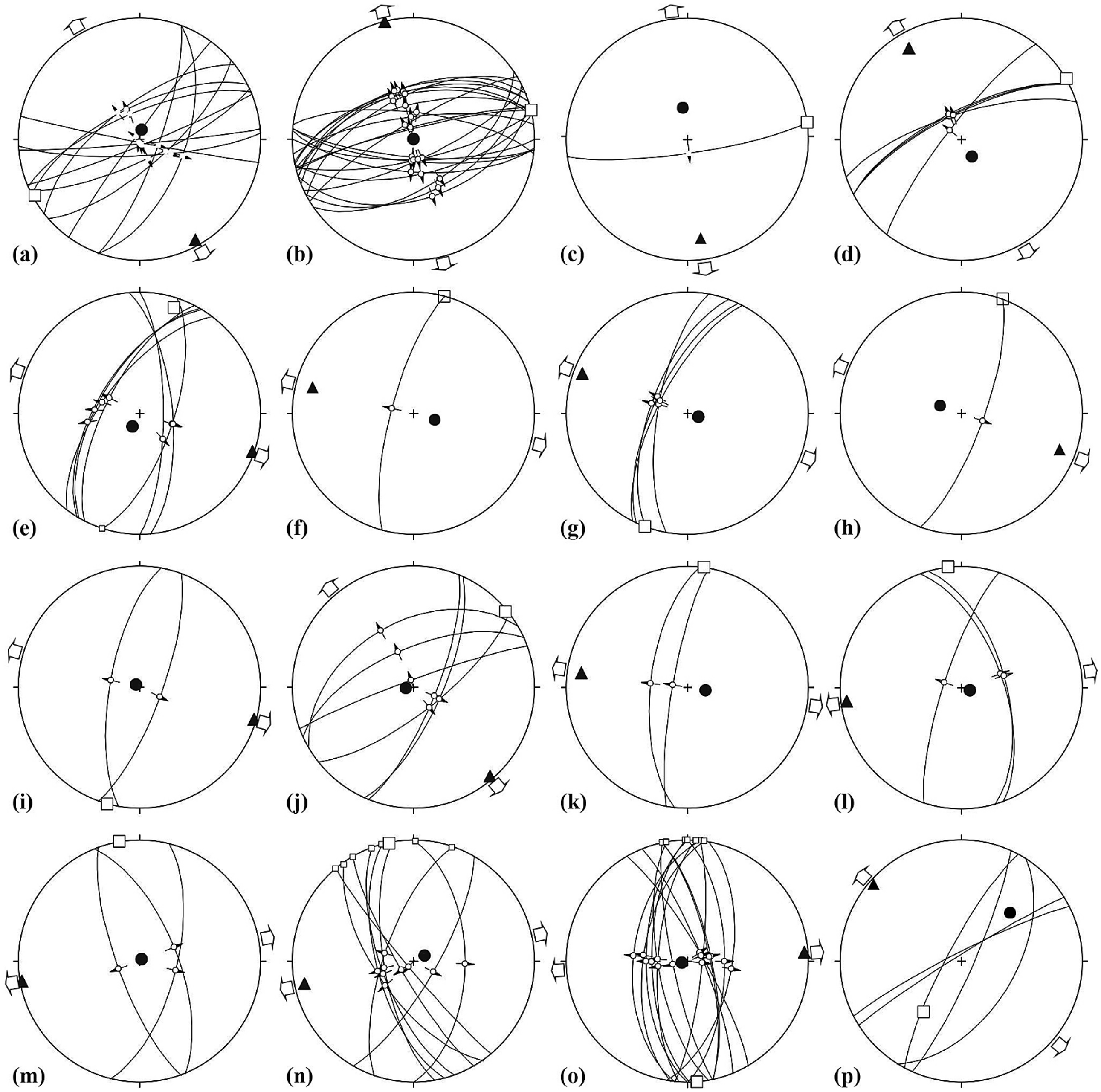

Fig. 5. **Stereograms of faults originated during Sarmatian and Pannonian/Pliocene age under the extensional tectonic regime with principal extensional axis oriented in W–E to NW–SE direction. Localities: a) Veľké Ripňany abandoned sand pit; b) Dolné Trhovište abandoned sand pit; c) Lukáčovce abandoned sand pit; d) Čechy abandoned sand pit; e) Plavé Vozokany abandoned sand pit; f) Levice site; g) Surdok site; h) Podlužany abandoned sand pit; i) Hontianska Vrbica abandoned sand pit; j) Lontov abandoned sand pit; k) Horné Zbrojníky abandoned sand pit; l) Demandice abandoned sand pit; m) Sazdice site; n) Horné Strháre abandoned sand pit; o) Príbelce abandoned sand pit; p) Plášťovce site.**

The Čechy abandoned sand pit is located approximately 250 m north of the village of Čechy in the Komjatice Depression. Fine-grained sand with occasional intercalation of silt of the Volkovce Formation are dominant lithology of the outcrop (Tab. 1; Fig. 2). The beds are disrupted by six normal faults, which most probably belongs into one homogeneous group. However, based on the stress analysis it is possible to separate the fault-slip into the two individual groups. The first fault group is represented by five fault-slips, which operated during tension with a NW–SE direction of the σ_3 stress axis (Fig. 5d). The maximal compressional stress axis was placed in subvertical position. The last fault-slip was included into the second (younger) group. Unfortunately, the only one fault do not provide a more precise data for palaeostress analysis.

The Kolta sand pit is located close to the village of Kolta and lies in the Komjatice Depression. In the abandoned sand pit, fine-grained cross-stratified sand of the Volkovce Formation was mined. In immediate overburden of the formation, the Pleistocene strata has been preserved (Tab. 1; Fig. 2, 7b). A well-visible conjugate fault system, which consists of two main faults and about fifteen small antithetic or synthetic faults (Fig. 7b), was measured only in the Volkovce Formation. Based on palaeostress analysis the measured fault-slips belong to one homogeneous group, which was active under the extensional tectonic regime characterized by the WSW–ENE minimal stress axis and subvertical maximal stress axis (Fig. 4h).

The Plavé Vozokany abandoned sand pit is approximately 2.5 km of Plavé Vozokany village between Plavé Vozokany and Hurbanovce villages close to the left bank of the Kvetnianka stream (Tab. 1; Fig. 2, 7c). The site is located in the Komjatice Depression and sandy, silty, and occasionally clayey strata belongs to the Volkovce Formation. The rocks in the sand pit are disrupted by seven faults having normal kinematics and belonging to one homogeneous group. The NNE–SSW faults operated under extensional tectonic regime with the orientation of the minimal stress axis – σ_3 in a ESE–WNW direction and the subvertical compressional axis – σ_1 (Fig. 5e).

4.3. Nemčiňany Formation (early Pannonian; 11.6–11.0 Ma)

The Nemčiňany sand pit is located 250–500 southeast of Nemčiňany village (Tab. 1; Fig. 2). Four levels of the sand pit expose coarse sandy-gravelly tabular beds of gravity flow deposits of fan delta foresets, alternated by gravelly fills of chutes. The strata on this quite extensive sand pit is practically not disrupted by faults. Only one fault was observed in the western part of the quarry with several decimetres of normal dip-slip offset (Fig. 4i). The strike of the fault is in the NNW–SSE direction with inclination south-westwards. The fault was activated during the extensional tectonic regime with the orientation of principal minimum palaeostress axis – σ_3 in approximately NW–SE direction.

4.4. Baďany and Priesila formations (Sarmatian; 12.6–11.6 Ma)

The Baďany and Priesila formations represent the volcanic to volcaniclastic products of the Štiavnica Stratovolcano. These volcanic products composed of ash-pumice flows were succeeded by the effusions of pyroxenite andesite lava flows and explosive-effusive amphibole-pyroxene andesite. Only two localities (Levice and Surdok) were studied within these formations as is presented in the following paragraphs.

The locality of Levice – Skalný Rad is situated directly inside Levice town at the street of Pavol Országh Hviezdoslav 50 m northwest of the Levice Castle (Tab. 1; Fig. 2). On the locality, epiclastic volcanic breccia with pebbles and boulders is outcropped. One normal fault only was observed in the site with the strike in NNE–SSW direction and dipping westwards (Fig. 5f). The orientation of principal minimal palaeostress axis (σ_3) is approximately in the W–E direction. However, the precise calculation of palaeostress field is impossible due to lack of any additional data.

The Surdok site is located approximately 2 km east of Levice town and 1 km west of Krškany village in the valley of Surdok (Tab. 1; Fig. 2). The locality represents occasionally exploited sand pit. Medium to coarse-grained tufitic sandstones of the Baďany Formation (Sarmatian) are cropping out in the mentioned site. At this site, four normal faults were observed with the general NNE–SSW strike direction and dipping westwards (Fig. 5g). The orientation of principal minimal palaeostress axis (σ_3) is approximately in the W–E direction, while the principal compressional axis is subvertical. The faulting was controlled by extensional tectonic regime.

4.5. Vráble Formation (Sarmatian; 12.6–11.6 Ma)

The Vráble Formation is exposed in seven visited localities (Kamenec, Podlužany, Demandice, Sazdice, Hontianska Vrbica, Lontov, and Horné Zbrojníky villages), which are predominantly located in the Želiezovce Depression.

The Kamenec site is located close to Levice town approximately 6 km in northeast direction (Tab. 1; Fig. 2). On the outcrop a cross bedding tuffite sandstones with intercalation of siltstone to claystone are preserved. The sedimentary strata are considered to be deltaic in origin with volcanic and volcaniclastic influence, respectively. Two normal NW–SE striking faults were observed and measured on the site and they are interpreted as a conjugate fault set (Fig. 4j). This fault set was activated under the extensional tectonic regime with the orientation of principal minimal palaeostress axis (σ_3) in NE–SW direction, while the principal maximal palaeostress axis (σ_1) remains subvertical.

Podlužany village is located 4 km north of Levice town (Tab. 1; Fig. 2). The sand pit is located in the SE periphery of the village. Large scale sandy to gravely trough cross-beds with erosional bases dominate the outcrop. The bottom of these beds is formed by a fine grained tuffaceous ripp-up clasts with rhizolits. Minor small-scale cross-beds with mud drapes are also present. Traction transport must have dominated and the deposits can be interpreted as a channel fills and linguoid dunes occasionally influenced by tidal processes. Altogether, the environment can be interpreted to a coarse-grained delta top. Based on its stratigraphic position, sediments of the locality are correlated with the Sarmatian (late Serravallian) Vráble Fm. (Nováková et al., 2018). One normal fault only with 10 cm offset on the fault plane was observed in the site with the strike in NNE–SSW direction and dipping eastwards (Fig. 5h). The orientation of principal minimal palaeostress axis (σ_3) is approximately in the W–E direction. Unfortunately, the fault plane is too weathered, and the slickenside lineations are not well preserved.

The next abandoned sand pit is located approximately 500 m east of *Demandice village* (Tab. 1; Fig. 2). The sand pit was established in deltaic deposits of clay and sand with intercalation of several horizons of tuff and tuffite. This site is considered as a part of the Vráble Formation. However, the Volkovce Formation cannot be definitively excluded (cf. Nagy et al., 1998[a]). Sedimentary strata at this site are cut by three generally N–S conjugate normal faults which belong to homogeneous group. The faults operated in extensional tectonic regime with the orientation of tension in ENE– WSW direction and with subvertical compressional stress axis (Fig. 5l).

The Sazdice site is located immediately in the village of the same name (Tab. 1; Fig. 2, 7e). In this site deltaic sediments (sand, silt, and clayey silt) of the Vráble Formation occur (Nagy et al., 1998[a]). Nine normal faults were observed. Based on the palaeostress reconstruction it is possible to divide them into 3 homogeneous monogenetic groups. The first group can be characterised by NNW–SSE normal faults (Fig. 5m), the second one by WNW–ESE conjugate normal faults (Fig. 4k), and last one by NNE–SSW dextral strike-slip faults (Tab. 2; Fig. 6a). Moreover, there is also distinct joint system.

The Hontianska Vrbica sand pit (Tab. 1; Fig. 2) is occupied by sandy trough cross-beds while gravelly trough-cross beds and fossiliferous tuffite beds are in the minority. Small tuffaceous ripp-up clasts are present. Similarly, to the Podlužany section, traction transport dominates and the deposits can be interpreted as channel fills and linguloid dunes of a tide influenced coarse-grained delta top environment. Only two normal faults were observed in this sand pit with the general NNE–SSW strike direction and dipping on both side (Fig. 5i). The orientation of principal minimal palaeostress axis (σ_3) is approximately in the W–E direction, while the principal compressional axis is subvertical. The faulting was controlled by extensional tectonic regime and is considered to be conjugate.

The Lontov abandoned sand pit is located in an agricultural cooperative at the vicinity of Lontov village (Tab. 1; Fig. 2; 7d). The wall of the sand pit consists of horizontally bedded sand, sandstone and tuffaceous silt. Normally graded, gravely, fossiliferous, planar cross-beds are in the minority. The sediments possibly belong to a similar deltaic system as mentioned higher (Podlužany, Hontianska Vrbica). Nine heterogeneous normal faults were measured, which belong to two homogeneous

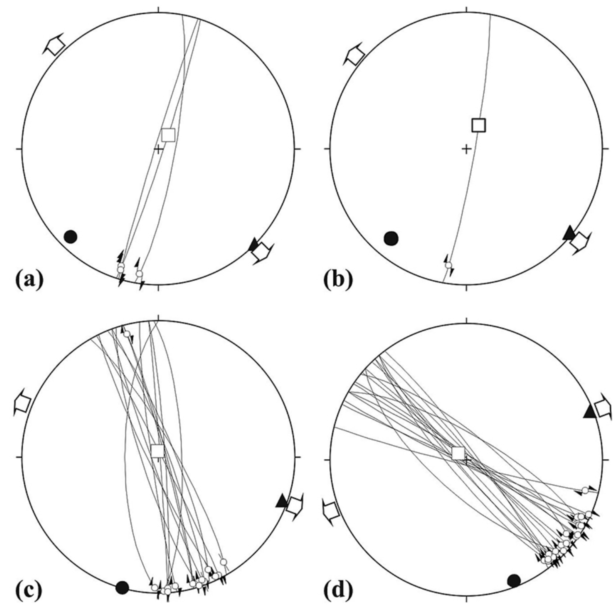

Fig. 6. Stereograms of faults originated during the Sarmatian, and Pannonian ages under the strike-slip tectonic regime. a, b, c) NE–SW principal compressional stress axis (σ_1) and perpendicular tension calculated from the Sazdice site (a), Horné Strháre abandoned sand pit (b), and Príbelce abandoned sand pit (c) sites; d) NNW–SSE principal compressional stress axis (σ_1) and ENE – WSW principal minimal stress axis (σ_3) at the locality of Príbelce abandoned sand pit.

monogenetic fault groups. The first group of six NE–SW oriented conjugate normal faults was activated under a palaeostress field, which was defined by the NW–SE minimal stress axis (σ_3) and subvertical maximal stress axis (σ_1) (Fig. 5j). The second group is characterized by extensional tectonic regime with the orientation of minimal stress axis (σ_3) in a NNE–SSW direction and vertical maximal stress axis – σ_1. During this stress state, the conjugate WNW–ESE normal faults operated (Fig. 4l).

The Horné Zbrojníky sand pit is located approximately 500 m east of the village of Zbrojníky (Tab. 1; Fig. 2,7a). In this abandoned sand pit trough, cross-bedded gravels to sands of the Vráble Formation crop out. Deltaic to alluvial origin can be considered. These sediments are overlain by Pleistocene loam. The debris to loam deposits of Pleistocene covers these sediments. Older sedimentary strata are disrupted by two N–S striking normal faults, where an extensional tectonic regime was detected (Fig. 5k).

4.6. Bajtava Formation (early Badenian, 15.0–14.0 Ma)

The site is located 1.5 km west of *Plášťovce village* close to the main state road no. 75 at the southern foot of the Babica hill (303 m asl.). The numerous outcrops are occupied by fossiliferous horizontally bedded tuffites and normally graded to massive conglomerates with erosive bases. Mass gravity transport is considered (Hyžný et al., 2015). At the site, only fractures with no movement were observed. The jointing can be divided into two homogeneous groups. The first group contains five systematic relatively moderately to steeply dipping joints with striking in the NE–SW direction. Based on these data it is possible to estimate the orientation of principal minimal palaeostress axis (σ_3) in NW–SE direction (Fig. 5p). The second group is represented by only one NW–SE oriented joint, which is not conform to previous joint set and was placed into new homogeneous generation. This joint can be activated during the extensional tectonic regime with the orientation of σ_3 in NE–SW direction.

The Stredné Plachtince site is located approximately 500 m east of the village. This site is an active quarry. The bottom of the section is composed of bidirectional, trough sandy cross-beds, with mud drapes passing into large-scale unidirectional planar cross-beds and the section ends with gravely trough cross-beds. Tidal environment with gradual passage to alluvial environment is interpreted here (Rybár et al., 2014). At a locality no faults were indicated; however, 11 joints were measured. These joints were part of one relatively homogenous group. Based on these data it is possible to calculate the orientation of principal minimal palaeostress axis (σ_3) in NE–SW direction with relatively vertical maximal palaeostress axis (σ_3).

4.7. Vinica Formation (early Badenian; 16.0–14.8 Ma)

Approximately 750 m west of *the Horné Strháre village* an abandoned, occasionally mined, sand pit could be find. The lower Badenian deposits of the Príbelce Member (Vass, 2002) cropp out there. The base of the sediments is composed of fossiliferous, large scale coarse sandy to gravelly foresets, overlain by sandy to

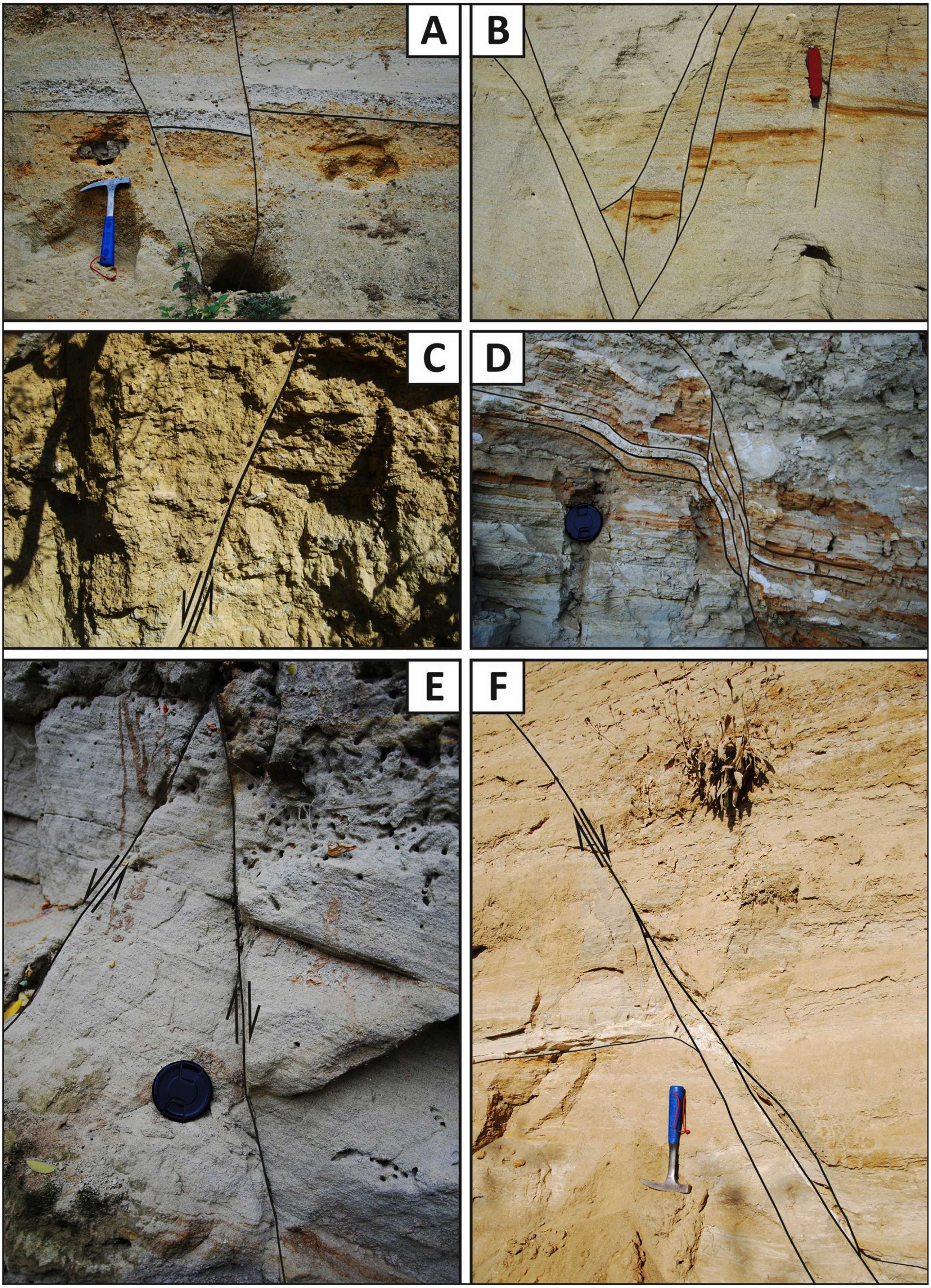

Fig. 7. Field photos of measured fault structures: a) Horné Zbojníky; b) Kolta; c) Plavé Vozokany; d) Lontov; e) Sazdice; f) Príbelce.

gravelly, unidirectional, grouped planar cross-beds, and higher above predominantly by gravely, unidirectional, planar cross-bedded. The section is topped by a mega-paraconglomerates with boulder size well rounded clasts floating in tuffaceous matrix. Deltaic, tidal to alluvial environment is interpreted here (Rybár et al., 2014). Twelve polygenetic normal and strike-slip faults were measured, which belong to two homogeneous polygenetic fault groups. The first group of nine generally NNW–SSE oriented normal faults was activated under a palaeostress field, which was defined by the NE–SW minimal stress axis (σ_3) and subvertical maximal stress axis (σ_1) (Fig. 5n). The second group is characterized by strike-slip tectonic regime with the orientation of maximal stress axis (σ_1) in a NE–SW direction and orientation of minimal palaeostress axis (σ_1) in NW-SE direction (Fig. 6b).

The Príbelce abandoned sand pit is located north-west of Horné Príbelce village (Novohrad-Nógrad Basin). At the base, the sediment consists of massive gravels with erosive bases, above covered by large-scale unidirectional cross-beds laterally passing into bidirectional medium scale cross-beds. Higher-up unidirectional large-scale cross-beds follow and are topped by ripple cross-laminated tuffaceous sands. All mentioned facies include mud drapes. Therefore, an open coast tidal channel to tidal flat environment affected by wave activity may be assumed (Rybár et al., 2014, 2017). This section is the type outcrop of the Príbelce Member of the Vinica Formation (Vass, 2002; Tab. 1; Fig. 2, 7f). Based on superposition relationships, the sand is lying on denuded Ottnagian to Karpathian deposits and beneath the Vinica Formation s.s. with typical fauna of the early Badenian (Vass et al., 1979). The deposits are disrupted by 60 polygenetic faults of normal or strike-slip kinematics. Based on the palaeostress reconstruction of fault-slips, it was possible to divide polygenetic fault set into four monogenetic fault groups. The fault group (1) is characterised by normal faults with strike in N–S direction. This fault population was activated during the pure extensional tectonic regime with the orientation of σ_3 in the W–E direction (Fig. 5o). The fault group (2) is formed by the NW–SE directed normal faults where only two have reliably determined kinematics (Fig. 4g). The faulting was activated during the extensional tectonic regime with the orientation of principal minimal palaeostress axis in NE–SW direction. The last two fault populations were generated during the strike-slip tectonic regime with evolution of predominantly dextral strike-slip faults. The fault group (3) is characterized by NW–SE striking of faults and the fault group (4) by the N–S striking of faults. Both monogenetic populations were activated when the principal minimal and maximal palaeostress axis operated in subhorizontal positions – σ_1 in NNE–SSW, NNW–SSE direction, respectively (Fig. 6c,d).

5. EVOLUTION OF STRESS FIELD SINCE BADENIAN – A DISCUSSION

The reconstruction of the Badenian to Quaternary palaeostress field of the area was carried out based on structural measurements of fault-slip and joint data. The measurements on several hundreds of faults permit reconstruction of the palaeostress field evolution in the northwest part of the Danube Basin and southern slopes of the Štiavnica Stratovolcano. The fault-slip analysis and palaeostress reconstruction allowed recognition of four structural phases during the Badenian to Quaternary interval.

The late Badenian stress field is characterized by the NNW–SSE principal compressional axis (σ_1) and ENE–WSW perpendicular principal extensional axis (σ_3) under the condition of the strike-slip tectonic regime. Both palaeostress axes were subhorizontal, while the principal intermediate axis (σ_2) was in subvertical position. This tectonic regime was well identified in the Príbelce, Horné Strháre, and Sazdice sites. The strike-slip faults are predominantly oriented in a NW–SE or NNE–SSW direction forming conjugate sets (Fig. 8). During the Sarmatian to early Pannonian age the NNW–SSE oriented (σ_1) axis progressively rotated into the NE–SW position, in general. The palaeostress relaxed on the newly formed NNW–SSE to NNE–SSW dextral strike-slip faults (Figs. 6a–c, 8). This deformation phase occurred after the deposition of Badenian sediments and before the late Pannonian Volkovce Formation. These tectonic phases are well known from the Central Western Carpathians (e.g., Marko et al., 1991, 1995; Fodor, 1995; Bada et al., 1996; Fodor et al., 1999; Marko & Vojtko, 2006; Pešková et al., 2009; Vojtko et al., 2010; Sůkalová et al., 2012). Based on the data from the Štiavnica Stratovolcano, we can assume that this strike-slip tectonic regime was only short period in between extensional tectonic regime (Fig. 8).

After the aforementioned tectonic regime, the extensional tectonics prevailed. Stress field represents tension in the NW–SE direction of the stress axis during the late Pannonian to Pliocene period. This stage is characterized by the NE–SW striking predominantly conjugate normal faults with moderate to steeply dipping fault planes and almost dip-slip directed striae (Figs. 5, 8). Similar, or practically the same data were previously published by Priechodská & Harčár (1988), Vojtko et al. (2008), Králiková et al. (2010), Hók et al. (2011). At the transition between the Pliocene and Pleistocene, the direction of extensional axis changed from NW–SE to NE–SW. This change is documented by different relationship between faults observed in the Pliocene and Pleistocene sediments. However, tectonic evolution during the Pliocene is not well known because of absence of suitable outcrops. the tectonic inversion of the Danube (Pannonian) Basin was proposed also for the study area in the Pliocene (e.g., Horváth, 1993; Bada et al., 2001, 2007), but structural measurements do not prove it yet. Based on the fault slip analysis and palaeostress reconstruction, there are only two extensional tectonic regimes in the Pannonian and Quaternary, or Plio-Quaternary age, respectively. Because the tectonic inversion of the basin is considered to be a "large scale lithospheric folding" (Bada et al., 2001) locally, the expression of this compression can be expressed by extensional tectonics close to the surface level because of the lithostatic stress-free conditions. It means that normal faulting represents this lithospheric scale compressional phase and the evolution of compressional structures is localised only in the deeper portion of sedimentary infill of the Danube Basin.

The Quaternary stress field of NE–SW tension (S_h) is oriented parallel to the Western Carpathian range. This tectonic stress field was observed at several localities (Figs. 4, 8). The recent stress field is often deduced from earthquake focal mechanisms,

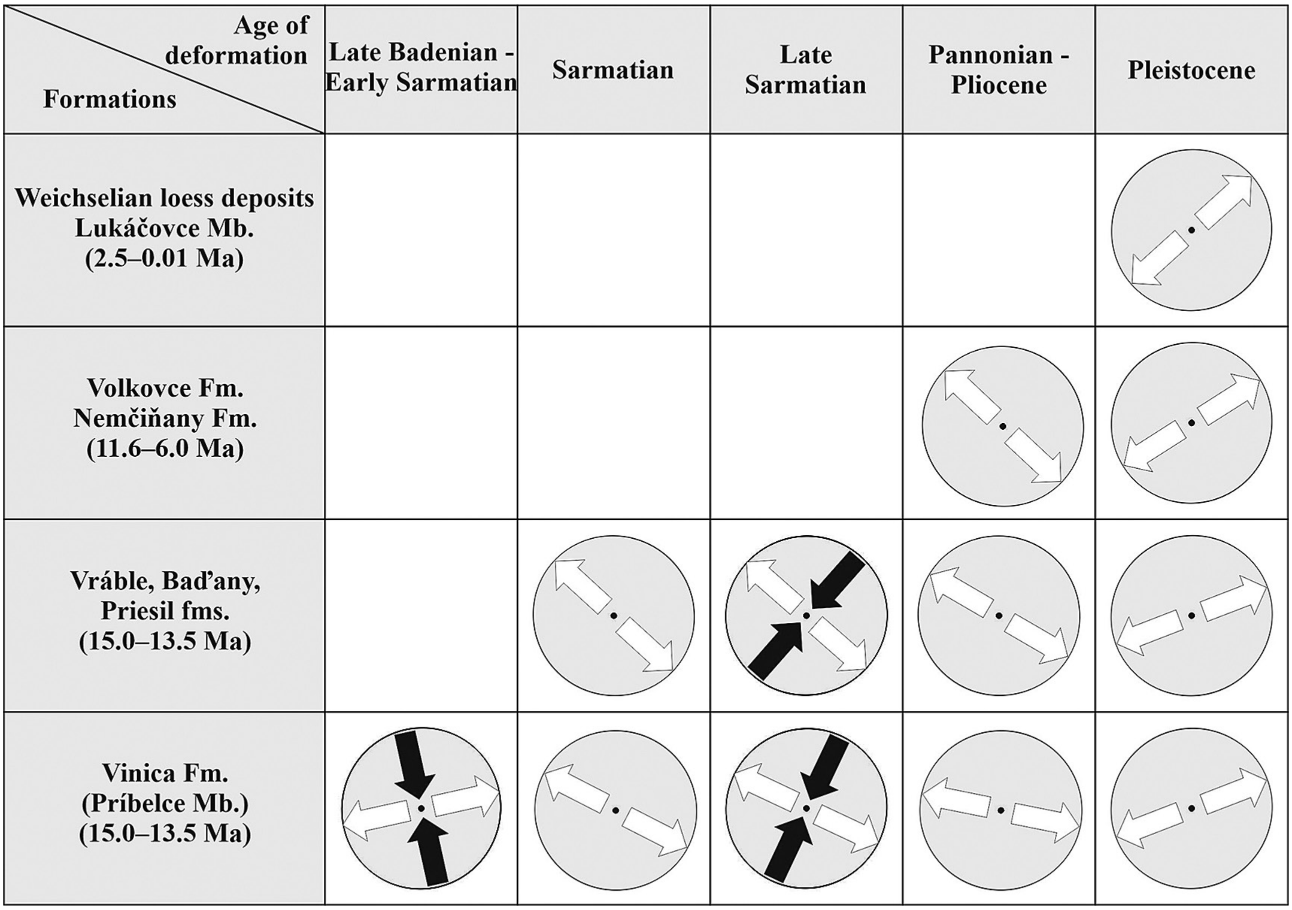

Fig. 8. Synthetic table of chronology for Badenian to Quaternary regional stress fields in the northern part of the Pannonian Basin.

borehole breakout analysis and modelling of crustal processes (Gerner, 1992; Jarosiński, 1998, 2005; Gerner et al., 1999; Bada et al., 2001). Structural measurements of fault slip data in Pliocene and Quaternary deposits, by contrast, have rarely been made (e.g., Čepek, 1938; Vojtko et al., 2008; Králiková et al., 2010; Hók et al., 2011). A similar Quaternary stress field was supposed by Marko et al. (1995) and Marko & Kováč (1996) in the Alpine–Carpathian transition zone and by (Hók et al., 1995) in the Horná Nitra Depression based on the structural measurements. Borehole breakout and earthquake focal mechanism analysis indicate NW–SE oriented S_H compression in the Bohemian Massif and in the western part of the Outer Western Carpathians (e.g., Peška, 1992; Jarosiński, 1998, 2005; Havíř & Stráník, 2003; Havíř, 2004). A compressive tectonic regime prevailed in the Outer Western Carpathians and in the adjacent Bohemian Massif. A strike-slip tectonic regime had been determined along the Pieniny Klippen Belt and the Mur-Murz-Leitha fault system (Labák et al., 1997; Reinecker & Lenhardt, 1999). The dominant extensional tectonic regime in the Central Western Carpathians can be explained as hinterland extension caused by continuing convergence of the ALCAPA with the European Platform (cf. Csontos et al., 1991; Gerner, 1992; Peška, 1992; Pospíšil et al., 1992; Fodor et al., 1999; Hók et al., 2000). The NE–SW orientation of S_H extension has been measured by extensometer station in central part of the Štiavnica stratovulkano near the village of Vyhne (Mentes, 2008) and also in the southern part of the Danube Basin and the Transdanubian Range (Gerner, 1992; Gerner et al., 1999; Fodor et al., 2005). However, published data by Fojtíková et al. (2010) are in contradiction with aforementioned measurements. In this work, the N–S to NNE–SSW compression was calculated using the focal mechanism solution in the northwestern part of the Danube Basin. Probably, these measurements are results of compressional tectonic regime in the deeper part of basin related to the basin inversion. It is considered the result of interaction between the ALCAPA and the Adria Mega-units pushing to the NNE (e.g. Bada et al., 1999; Gerner et al., 1999).

6. CONCLUSIONS

The Danube Basin and surrounding area, located among the Eastern Alps, Western Carpathians, and Transdanubian Range, covers northwestern part of the Pannonian basin system. This basin is represented by typical morphostructures on contact with Western Carpathian Mountains with finger-like character. From the geological point of view, the Danube Basin is filled by the middle Miocene to Quaternary marine, lacustrine to alluvial sedimentary sequences with intercalation of the Miocene volcanic and volcaniclastics rocks. The pre-Cenozoic basement of this basin is composed of the Tatra and Vepor units, except southernmost part formed by the tectonic unit of the

Transdanubian Range. The principal aim of this study was to understand of palaeostress field evolution since the Badenian using faults-slip analysis and palaeostress reconstruction. The structural measurements were carried out on outcrops with the following lithostratigraphy: (*i*) lower Badenian shallow sea to deltaic Príbelce Mb. of the Vinica Fm.; (*ii*) ash-pumice flows and the effusions of mostly glassy and leucocratic pyroxenite andesite lava flows of the Baďan Formation together with the volcanic products of amphibole-pyroxene andesite of the Presil Formation; (*iii*) the upsection is represented by the Vráble Fm. (Sarmatian), Nemčiňany Fm. (earliest Pannonian), and Volkovce Fm. (late Pannonian), which consist predominantly of deltaic and alluvial coarse- to fine-grained gravel to sand deposits; (*iv*) Lower Pleistocene river sediments of the Lukáčovce Member and Upper Pleistocene loessial sequences. According to extensive lithostratigraphic range of the Miocene deposits in the study area, it was easier to determine the timing of individual tectonic phases. Therefore, based on the obtained fault-slip data and palaeostress reconstruction, four palaeostress phases have been distinguished: (*i*) the youngest palaeostress phase is characterized by extensional tectonic regime, where the principal minimum σ_3 axis was oriented in NE–SW to E–W direction. This tectonic phase can be tenuously dated at Middle Pleistocene to Holocene and is most probably still active. (*ii*) the Pannonian to Pliocene phase can be described by extensional tectonic regime with the orientation of σ_3 in NW–SE direction; (*iii*) Sarmatian to early Pannonian strike-slip tectonic regime is defined by the NE–SW oriented σ_1 and the NW–SE oriented σ_3. We assume, that this tectonic regime lasted only a short period in between extensional tectonic regime with the orientation of σ_3 in NW–SE direction; and *(iv)* the oldest late Badenian to early Sarmatian tectonic phase is characterized by strike-slip tectonic regime with the general orientation of compressional stress axis (σ_1) in the NNW–SSE direction and perpendicular tension (σ_3). During this tectonic phase (~30°) rotation of crustal fragments caused the opening of the Badenian depocentres in the Danube Basin.

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