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Multi-phase development of the faults and joints in the Súľov Conglomerates (Súľovské vrchy Mts., Slovakia): Implications for paleostress history

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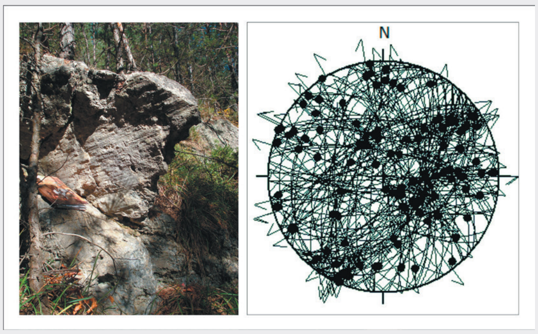
Abstract: Detailed field research of meso-scale brittle structures of the Súľov Conglomerates revealed the record of multi-phase Oligocene-Pliocene deformation in this area. The first detected tectonic event was the Oligocene to Middle Miocene transpression with compressional stress axis oriented in NW-SE to NNW-SSE direction. During the Middle-Late Miocene the transpressional tectonic regime was changed to transtension. The compression stress axis was oriented in N-S to NE-SW direction. The Pliocene tectonic regime is characterized by the change of transtension to extension, being oriented generally in the N-S direction.

Key words: Súľovské vrchy Mts., Súľov Conglomerates paleostress analysis, faults, joints

Graphical abstract



Highlights

- Paleostress analysis is based on measurements of 140 faults and 64 joints in the coarse-grained Súľov Conglomerates;
- Paleostress regime has changed from the Oligocene-Middle Miocene transpression, Middle-Late Miocene transtension to Pliocene extension;
- Paleostress field changes were caused by the interaction between the North European Platform and the ALCAPA lithospheric plate.

Introduction and geological setting

The Súľovské vrchy Mts. belong to the Central Western Carpathians. They are situated in the Middle Váh Valley in the north-western part of Slovakia (Fig. 1). The Middle Váh Valley region is composed mainly of sedimentary formations of the Paleogene age (Paleogene sediments of the Hričov-Žilina belt and Súľov-Domaniža Basin). The complicated geological structure of the area is caused by the frontal thrust stacking of the Central Carpathian nappes, gravitational collapse of orogenic wedge, formation of Later Cretaceous and Paleogene Basin and transpression and transtension during Early Miocene (Figs.1 and 2; Mello et al., 2011).

The Súľovské vrchy Mts. are built of the Súľov Conglomerates, representing the coarse grained lithosomes in the Žilina Basin and Domaniža Basin, as well. Especially, in the Pružina part of the Domaniža Basin, they form the main mass of sediments in the edge of this basin. The research of the Súľov Conglomerates is performed for more than 150 years, but in the past it consisted mainly of sedimentological study (e.g. Marschalko & Samuel, 1993; Marschalko & Kysela, 1980; Salaj, 1993; Salaj, 2001; Mello et al., 2011). The coarse-grained conglomerates and breccia were described for the first time by Štúr (1860) as the Súľov Formation. Thickness of the sequence of Súľov Conglomerates in the Middle Váh Valley area is 750–1200 m (Marschalko & Kysela, 1980; Marschalko & Samuel, 1993).

The Súľov Conglomerates belong to the Súľov Fm. of the Myjava-Hričov Group (Danian-Middle Lutetian). Evolution of the Súľov Formation started by transgression in the Late Paleocene (Mello et al., 2011). It is represented by conglomerates and dolomitic sandstones with occasional breccias accumulated along scarps of synorogenic basin. The bed of Súľov Conglomerates is divided to western and eastern part by the NNE–SSW trending fault (the Prečín–Súľov fault, *sensu* Marschalko & Samuel 1993; Fig. 1), and separated by the Cretaceous formations of the Krížna and Manín Units, cropping out in the Súľov erosional window (Marschalko & Kysela, 1980; Marschalko & Samuel, 1993; Rakús & Hók, 2003). The age of the Súľov Conglomerates was assumed accounting their stratigraphic position (Andrusov, 1965) as well as large and planktonic foraminifers from overlying and underlying formations (Samuel & Salaj, 1968; Samuel et al., 1972). They are lying above the flysch sediments with blocks of biohermal limestones of the Hričovské Podhradie Formation (Paleocene – Early Eocene), as well as above the limestones and carbonatic sandstones of the Jablonové Formation (Thanetian – Ypresian; Mello et al., 2011). The bed of Súľov Conglomerates has developed from the Jablonové Fm. and it was overlapped by flysch sediments of the Domaniža Fm. (Early – Middle Lutetian; Fig. 2; Samuel et al., 1972). This is the reason why the Súľov Conglomerates were considered as the Early Eocene in age. According to later research (Soták et al., 2017; Pulišová, 2018), the age of Súľov Conglomerates is Ypressian-Early Lutetian.

In the area of the Súľov Mts. the conglomerates are lying discordantly on the Cretaceous sediments of the Manín Unit. A paleogeographic position of the Mesozoic units, especially of the Manín Unit, was an object of discussion for a long time (e.g., Andrusov, 1938; Maheľ, 1978; Kysela et al., 1982; Rakús & Hók, 2005). The Ma-

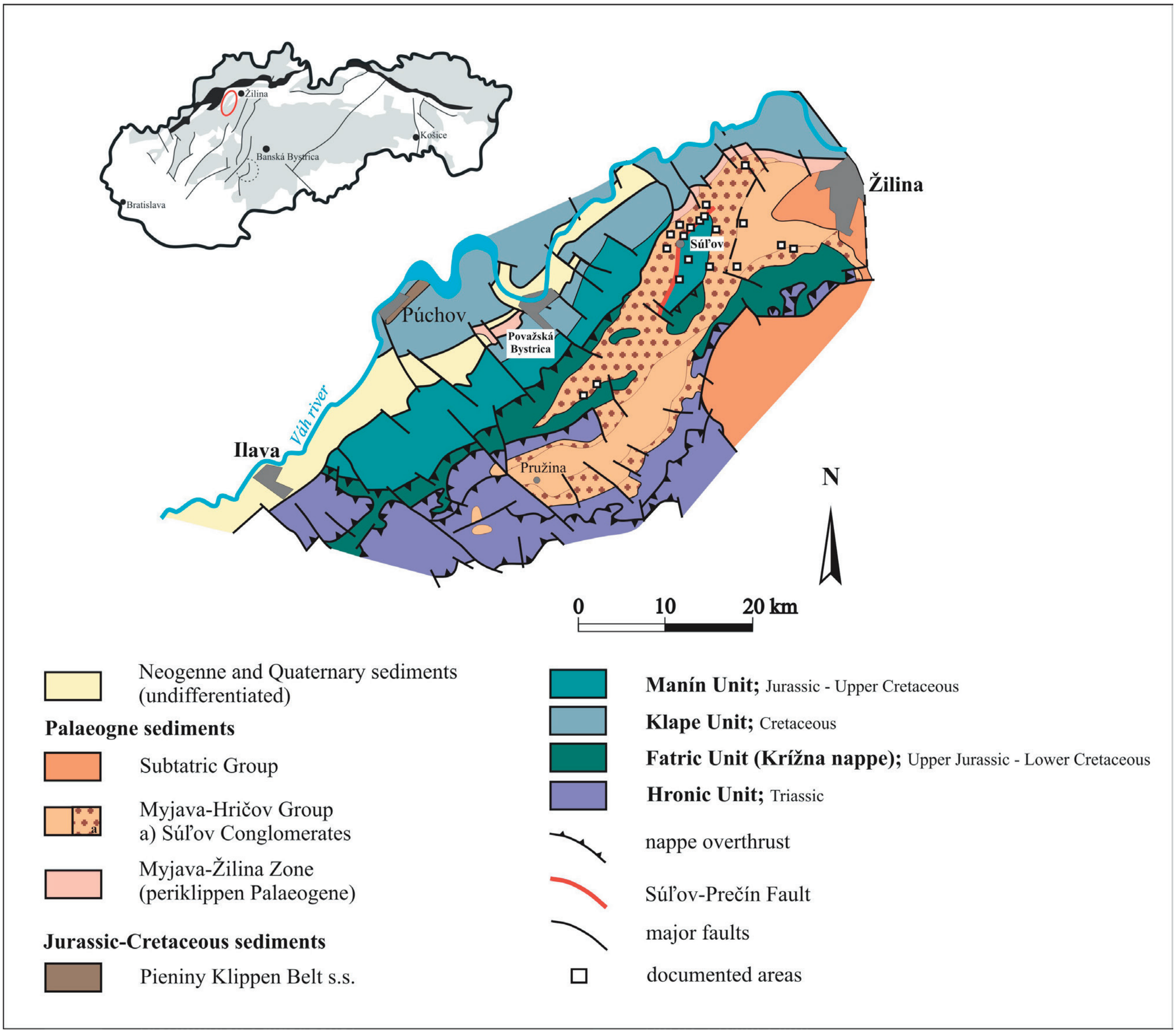


Fig. 1. Simplified geological map of the Middle Váh Valley with positions of the important study areas (white squares; modified after Mello et al., 2005).

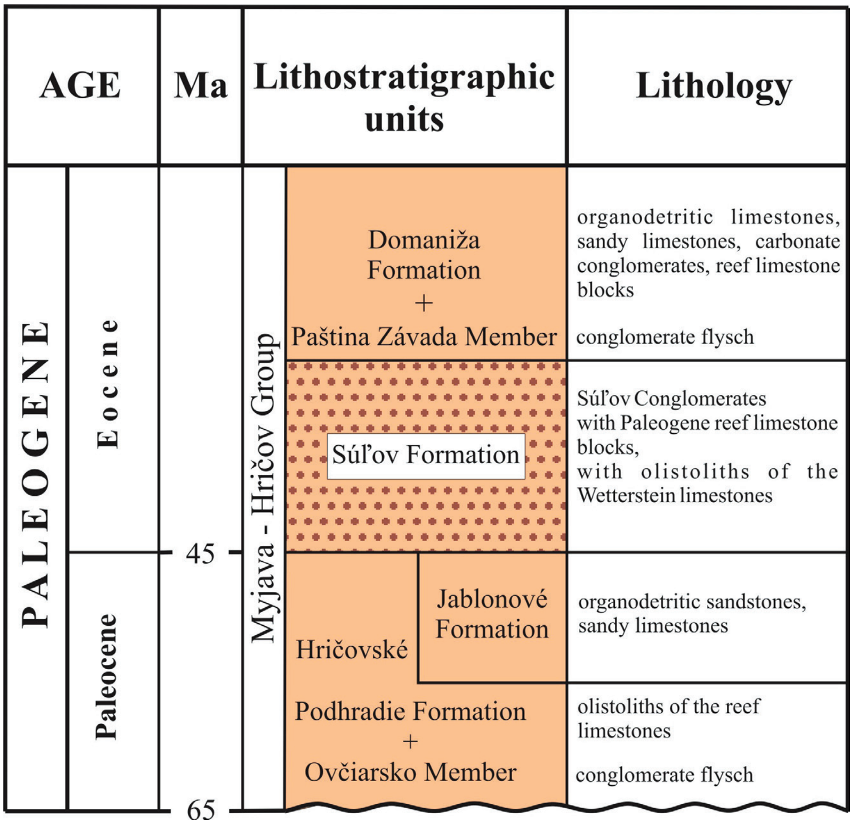


Fig. 2. Paleogene lithostratigraphy of the post-nappe formations of the study area (Mello et al. 2011, modified after Soták et al. 2017).

nín Unit in the Súľov area (Súľov erosional window) is represented by the Praznov Formation (Cenomanian), composed of thin rhythmical flysch. A detailed description of the lithology and tectonic evolution of the Paleogene and Cretaceous formations in the study area is presented by several authors (e.g., Marschalko & Kysela, 1980; Kysela et al., 1982; Salaj, 1995a, b, c; Rakús & Hók, 2005; Plašienka & Soták, 2015).

The aim of this work is a paleostress analysis of deformation structures (faults, extensional joints) of mesoscopic sizes in the Súľovské vrchy Mts., which was based on fault geometry investigations. The paleostress analyses of brittle fault structures in the Súľov Conglomerates follows up on the works, which were made in the surrounding areas (western part of the Pieniny Klippen Belt and Peri-Klippen zones) during last years (e.g. Bučová, 2013; Šimonová, 2013; Šimonová & Plašienka, 2011; 2017).

These findings are the first attempt at paleostress reconstruction in this area, as well.

Methods

The field investigation has been focused on structural records of tectonic deformation of the Súľov Conglomerates in the Súľov Mts. area. The research reported in this paper was carried out at 25 localities in the Súľov Conglomerates (Fig. 1). In the localities we have registered 140 faults and 64 tensional joints (Figs. 3 and 4). Except these, we have measured structural parameters of joints, faults, and bedding in two localities in the Súľov area, where sediments of the Manín Unit crop out on the surface. An emphasis was given on determining the sense of movement on fault planes applying the kinematic indicators (especially fault striae and Riedel's shears in the Súľov Conglomerate and accretionary mineral steps in sediments of the Praznov Fm.; Fig. 5; e.g. Petit, 1987; Marko, 1993; Twiss & Moores, 2007).

The obtained field data reveal several successive deformation events. In order to rank deformation phases, it is necessary to execute the paleostress analysis in rocks of different ages. In the study area, the range of ages of the Súľov Conglomerates and the Praznov Fm. is from Cenomanian (Praznov Fm.) to Paleogene (Cuisian – Lower Lutetian; Súľov Conglomerates). There was rarely possible to identify successive deformational phases from the intersection of movement indicators observed on the slickensides, mainly in sediments of the Praznov Fm. This is the reason, why our brittle tectonics data have been compared and combined with previous works of other authors (e.g. Kováč & Hók, 1996; Šimonová & Plašienka, 2011; Šimonová, 2013; Bučová, 2013), who conducted research in neighbouring areas.

For paleostress analysis the Inverse Rotational Optimization method implemented in the software package TENSOR was used (Delvaux, 1993; Delvaux & Sperner, 2003). The basis of the inverse method (Rotational Optimization) is the assumption that the fault movement is generated in the direction of maximum shearing stress (Bott, 1959). The fault data were used to compute the four parameters of paleostress tensor (Angelier, 1994): σ_1 (principal maximum stress axis), σ_2 (principal intermediate stress axis), σ_3 (principal minimum stress axis) and the stress ratio, which is computed by formula $R = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$. The stress ratio together with the orientation of the principal stress axes defines the tectonic regime.

For calculations of single paleostress phases, homogeneous populations of faults were separated. As a criterion for separation of faults to homogeneous populations was used the slip deviation between theoretical and measured orientation of striae (an α-angle). The stress regime is defined on the base of the orientation of stress axes and the

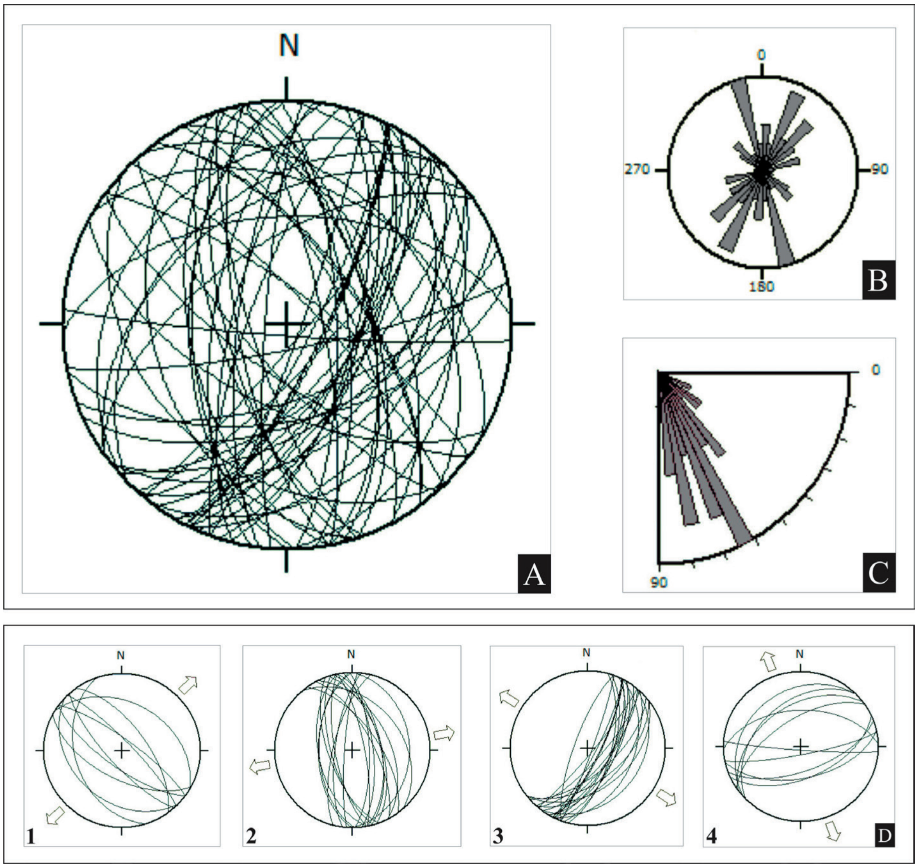


Fig. 3. Extensional joints (64 measurements), which were found out in the Súľov Conglomerates: A) stereogram of joints; B) the most common direction of joints; C) the most common dip of joints; D) extensional joints separated to homogeneous groups (the white arrows represent direction of tension during evolution of joints).

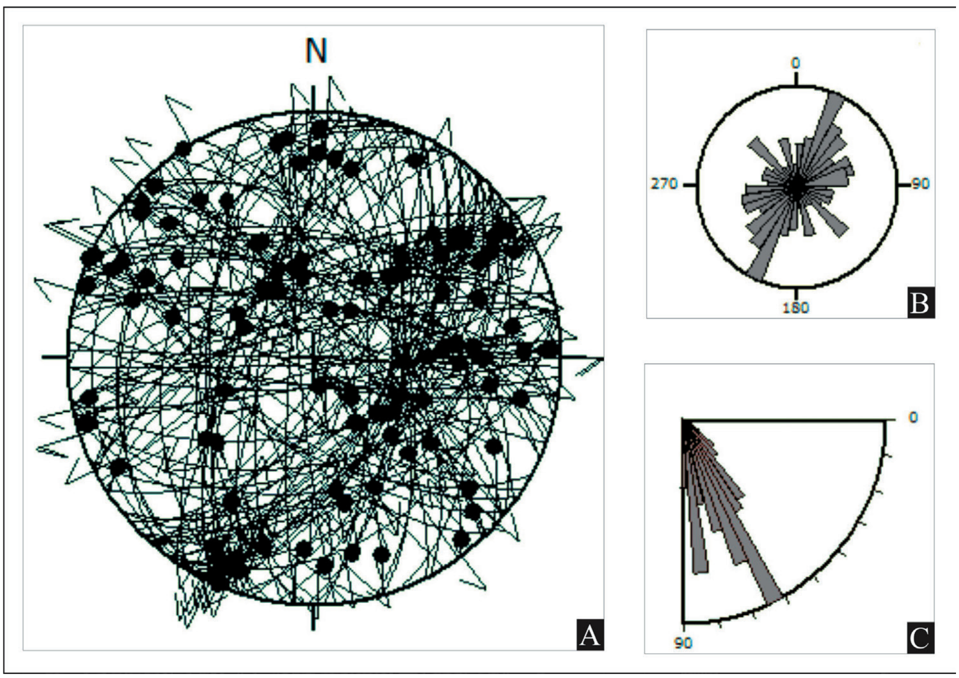


Fig. 4. Faults (140 measurements), which were observed and measured in the Súľov Conglomerates: A) stereogram of all faults; B) strike of faults; C) dip of faults.

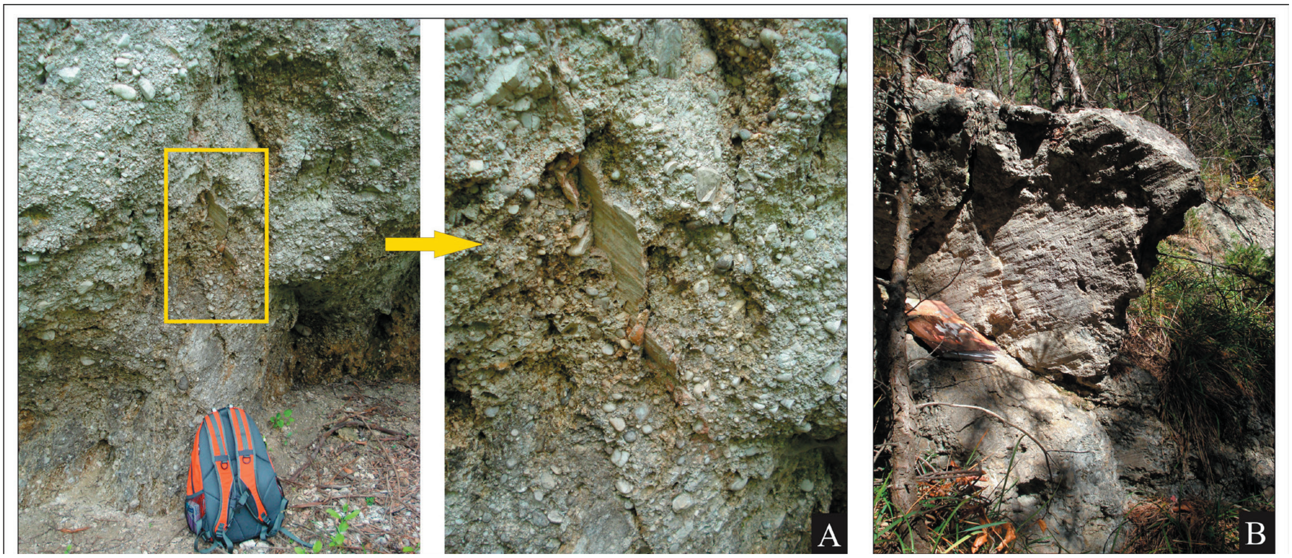


Fig. 5. Examples of the most common kinematic indicators observed in the Súľov Conglomerates: **A)** clearly observable striae in the PZ 1 site (N 49, 21661°; E 18, 62747°); **B)** Riedel's shearing in the ZZ 2 site (N 49, 06011°; E 18, 50065°).

magnitude of the parameter R' ranging from 0 to 3 (R' = 0 – 1 for the extensional tectonic regime, R' = 1 – 2 for the strike-slip tectonic regime, R' = 2 – 3 for the compressional tectonic regime; Delvaux et al., 1997).

The obtained data and results of paleostress analysis

The Súľov Conglomerates are formed by relatively homogeneous and monotonous facies. These is the reason, why identification of their bedding planes is relatively difficult, with an exception of the fine-grained conglomerates, where they are relatively well-defined. The identifying the bedding planes in homogeneous coarse-grained conglomerates was possible only at the presence of claystone intraclasts, which were eroded from basement by highly concentrated turbidite current (Rip-up mudstone clasts; Zavala & Arcuri, 2016). The common bedding dips are from 50° to 85° in the western belt and from 10° to 25° in the eastern belt of the Súľov Conglomerates (Fig. 6). Difference between the dip of bed of the western and eastern part of the belt can be due to the higher tectonic deformation of the western belt of the Súľov Conglomerates.

The deformation history of the Súľov area is characterized by the polyphase brittle faulting. The interbeds of conglomerates are cut mainly by NNE–SSW oriented

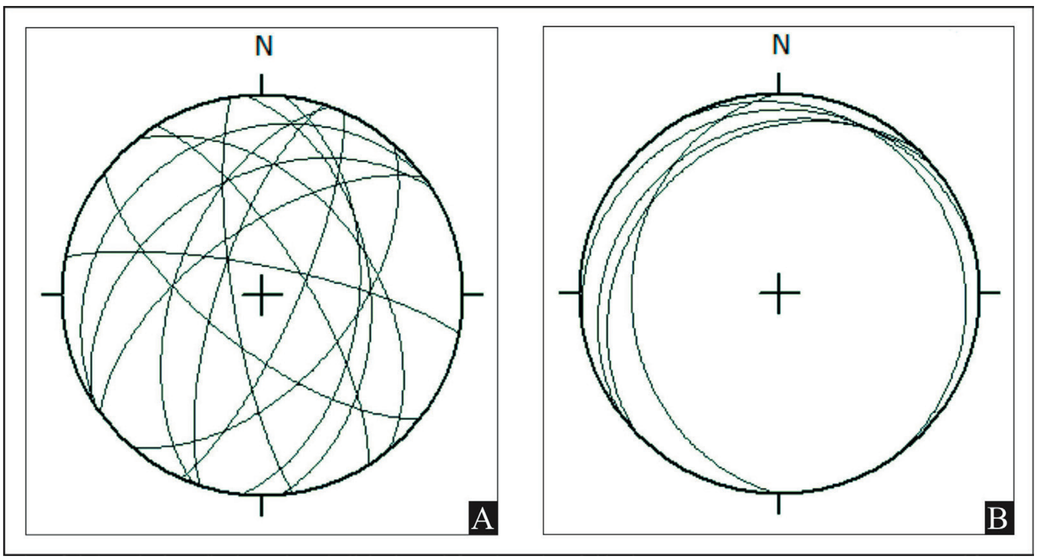


Fig. 6. Stereograms of bedding planes of the Súľov Conglomerates: A) western part; B) eastern part (20 measurements).

faults with ca. 65° dip (Fig. 4). The detected faults have been divided to homogeneous groups (D1–D5; Fig. 7, Tab. 1). Number 1 is indicating the oldest and number 5 the youngest tectonic event. The symbols *a – c* are indicating individual homogeneous groups. The research conducted in the study area showed the presence of a large joint network, as well. This regional joint network consists of four sets of tension joints. Each set has been assigned to the individual deformation phase. The morphologies of joints is very simple, with surfaces usually flat and smooth without slickensides. The joints are oriented generally in NNW–SSE to NNE–SSW direction. The most common dip is 65° (Fig. 3).

WNW-ESE compression – NNE-SSW tension (D1 deformation phase, Oligocene – Early Miocene)

The earliest tectonic phase, which was detected in the Súľovské vrchy Mts., started by transpressional tectonic regime, represented by strike-slip faults, whereas numerous reverse faults were generated in compressional tectonic regime. The fault system generated under a compressional to transpressional tectonic regime is characterized by the WNW–ESE oriented principal compressive stress axis (σ_1) and NNE-SSW oriented minimum principal stress axis (σ_3). For this deformational phase is typical especially a great number of conjugate strike-slip faults (general NNW-SSE oriented sinistral strike-slip and ENE-WSW oriented dextral strike-slip faults; Fig. 7A, D1a homogeneous group, Tab. 1). The reverse faults are predominantly trending NE-SW (Fig. 7A, D1b homogeneous group, Tab. 1). On the base of regional considerations and after comparing of the findings with other authors, this complex of fault system was likely formed during the Oligocene to Early Miocene (e.g. Marko et al., 1990, 1995; Fodor, 1995; Kováč & Hók, 1996; Fodor et al., 1999; Pešková et al., 2009; Vojtko et al., 2010). The faults of this phase are well-preserved at all localities, except for two localities in sediments of the Praznov Fm. It can be caused by bad uncovering Mesozoic background in this area, because this event should by recorded also in older sediments (e.g. Šimonová & Plašienka, 2011, 2017)

NNW-SSE compression – ENE-WSW tension (D2 deformation phase, Otnangian – Early Badenian)

The second deformation phase is represented by faults, which are generated by transpressional tectonic regime. The main compressive stress axes (σ_1) is oriented in NNW-SSE direction, the main minimum stress axis (σ_3) is oriented ENE-WSW (Fig. 7B). The structural elements are predominantly NNE-SSW-trending sinistral strike-slip faults, which are predominating over the WNW-ESE-trending dextral strike-slip faults (Fig. 7B, D2a homogeneous group, Tab. 1). There are also NE-SW-trending reverse faults in this deformation phase (Fig. 7B, D2b homogeneous group, Tab. 1).

The system of joints and veins, included in the deformation phase D2, has been identified in the Súľov Conglomerates, as well. The tension joints are oriented in the direction of the compression (NW-SE – NNW-SSE) and perpendicular to the above-mentioned reverse faults (Fig. 3D, group 1, Fig. 7B). The tension is characterized by the presence of the smooth joint surfaces.

The systems of faults and joints controlled by the NNW–SSE oriented compressional stress axis was formed probably during the Ottnangian–Lower Badenian (Marko et al, 1995; Fodor, 1995; Fodor et al., 1999; Kováč & Hók, 1996; Šimonová & Plašienka, 2011, 2017).

NNE-SSW compression – WNW-ESE tension (D3 deformation phase, Middle – Upper Badenian)

The next deformation phase is characterized by the presence of conjugate faults formed under approximately N-S directed principal compressive stress axis (σ_1) and perpendicular the W-E directed minimum principal stress axis (σ_3). Except these, the reorientation of the paleostress axis caused the origin of several of normal faults and extensional joints (Fig . 7C), being oriented generally in the N-S direction. On the base of outcrop in the Súľov Conglomerates it was not possible to determine, whether normal faults are younger or older than conjugate fault system. However, with respect to their slightly chaotic layout in the stereogram, we can suppose that they originated during the whole deformation phase D3. The faults and joints system generated under a transtensional regime with the resolved paleostress field characterized by a maximum horizontal stress axis mentioned above, being dated as the Middle Miocene (Middle – Late Badenian; Marko et al., 1995; Fodor et al., 1999; Šimonová & Plašienka, 2011, 2017).

NNW-SSE tension – ENE-WSW compression (D4 deformation phase, Sarmatian – Panonian)

The fourth deformation phase is characterized by sinistral transtension (D4). During the Sarmatian to Pannonian, the main compression axis turned clockwise from the N–S to NE–SW direction (e.g. Csontos et al., 1991; Marko et al., 1995; Hók et al., 1995). Especially sinistral strike-slip faults in the WNW–ESE direction and the NE–SW directed normal faults were formed as a result of this deformation phase (Fig. 7D, D4b homogeneous group; Tab. 1). We were able to measure twelve sinistral strike-slip faults (D4a) and nine E-dipping normal faults (D4b) in the studied area. This event was accompanied by the formation of a large set of joints with NNE-SSW orientation (Fig. 4D, group 3). The joints are oriented parallel to the normal faults and perpendicular to the extensional stress axis. Tension joints (locally hybrid) have rough surfaces with areas

Tab. 1
Homogeneous groups of faults from the study area. Explanations: n – number of fault-slip data; σ_1, σ_2, σ_3 – principal stress axes in azimuth/plunge format (in degrees); R – stress ratio $(\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$; R´- tensor type; F5 (α) – mean slip deviation (angle between observed and computed slip directions, in degrees); Q (QRw) – World Stress Map project quality ranking as defined in Sperner et al. (2003) – from A – best to E – worst.

Tensor name	n	σ_1	σ_2	σ_3	R	R′	F5 (α)	Q (QRw)	Stress regime
D1a	30	120/03	002/83	210/06	0,43	1,57	15,73	E	pure strike-slip
D1b	12	117/04	026/05	246/84	0,53	2,53	13,05	E	pure compression
D2a	28	159/05	296/83	069/05	0,45	1,55	11,4	E	pure strike-slip
D2b	6	159/02	249/05	046/84	0,5	2,5	5,6	E	pure compression
D3a	20	194/01	080/88	284/02	0,66	1,34	11,3	E	pure strike-slip
D3c	10	145/80	353/09	262/05	0,67	0,67	17,37	E	extension
D4a	11	060/04	286/84	150/04	0,5	1,5	12,62	E	pure strike-slip
D4b	9	213/85	034/05	304/00	0,5	0,5	4,66	E	extension
D5	11	164/74	265/03	356/16	0,53	0,53	16,39	E	extension

containing kinematic indicators (small accretionary mineral steps, synthetic Riedel's shear). These joints have been identified as precursors to faults. The change of orientation of the compressional paleostress axis indicates clockwise rotation of the paleostress field around a vertical axis.

N-S tension (Pliocene)

The last deformation phase, which was find out from the faults slip data, was affected of approximately N-S oriented extension during the Pliocene (Fig. 7E; Tab. 1). The most present structural elements of this deformational phase are normal faults trending generally E-W (Fig. 7E, D5 homogeneous faults group). The timing of this tectonic phase, the change of transtensional tectonic regime to pure extensional tectonic regime and rotation of extensional stress axes into the NNW–SSE to N–S direction is constrained by the results of structural investigations in neighbouring areas, where similar homogeneous groups of faults were described by other authors (e.g. Vojtko et al., 2008, 2010; Pešková et al., 2009; Králiková et al., 2010; Šimonová & Plašienka, 2011, 2017). Many tension joints were generated during extension regime. Tension joints with NE-SW-orientation are perpendicular to the extensional stress axis (Fig. 4D, group 4).

Discussion

Evolution of the Súľov Conglomerates is connected with extensional collapse of the orogenic wedge in front of the edge of the Western Carpathian in the time from the Late Ypresian to Lutetian. During the late Ypresian to Earliest Lutetian, the rear of this wedge was affected by input of huge masses of carbonatic scarp breccias (Súľov Conglomerates), which were derived from the uplifted zone of the Central Western Carpathians (Plašienka & Soták, 2015; Kováč et al., 2016; Soták et al., 2017).

The reconstruction of the paleostress field of the Súľov area carried out by structural measurements of fault slip data, revealed changes of the paleostress field during the Oligocene to Pliocene. However, any paleostress reconstruction is complicated by the Miocene block rotation of the whole Western Carpathians. The changes of the paleostress orientation in the area were likely caused by a combination of the clockwise rotation of the paleostress field and the counterclockwise rotation of the ALCAPA microplate (e.g. Fodor, 1995; Márton et al., 2016).

The first deformation phase, which was detected in the Súľovské vrchy Mts., is characterized by the formation of conjugate strike-slip faults and numbers of reverse faults. It is corresponding with the compressional to transpressional tectonic regime (e.g. Marko et al., 1995; Fodor, 1995; Fodor et al., 1999; Pešková et al., 2009; Vojtko et al., 2010; Šimonová & Plašienka, 2011, 2017), which is characterized by WNW-ESE trending main horizontal compression axis (Fig. 7, D1). This phase is dated from the Late Oligocene to the Early Miocene (e.g. Marko et al., 1995; Kováč & Hók, 1996). During this time, the collision of the Western Carpathians and the North European Platform culminated (Kováč, 2000; Kováč et al., 2016). As a consequence, the Paleogene sediments of the Peri-Klippen zone, the Rajec Basin and Turiec Basin were deformed (Hók et al., 1998; Rakús & Hók, 2003), correspondingly with the reverse faults related to thrusting of Fatric Unit (Aptian) on the Paleogene sediments in Veľká Fatra Mts. (Pulišová et al., 2014).

During the Late Eocene to Earliest Miocene the orogenic wedge collapsed again and Central Carpathian Paleogene Basin could partly communicated with piggyback basins (Myjava-Hričov Group) located above the accretionary wedge, as well (Plašienka & Soták, 2015; Kováč et al., 2016).

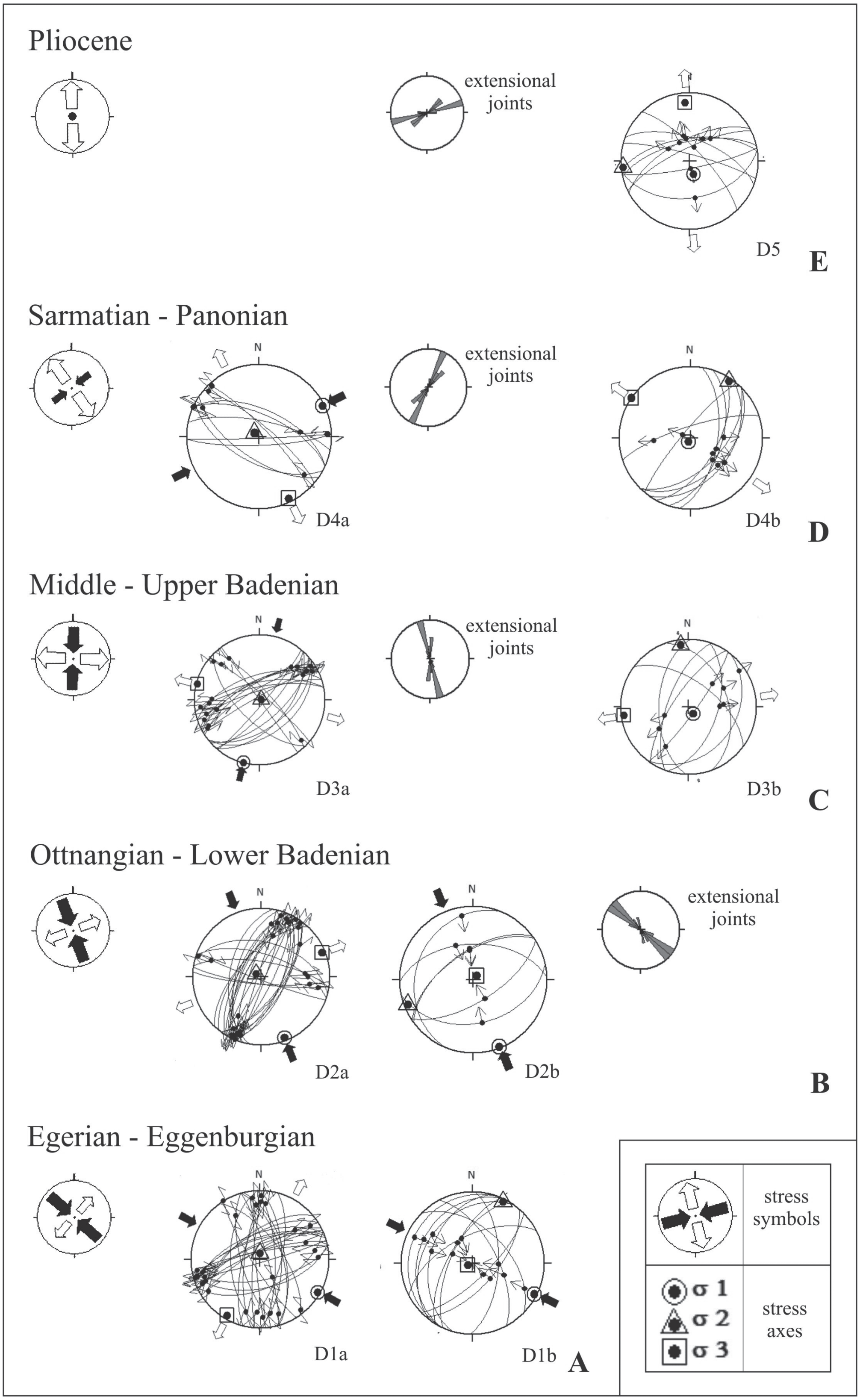


Fig. 7. Diagrams of fault orientation and their paleostress interpretation for (A) the first deformation phase, (B) the second deformation phase, (C) the third deformation phase, (D) the fourth deformation phase, (E) the fifth deformation phase. Note: the fault planes are plotted as great circles with observed slip lines and slip senses using stereograph projection-Schmidt net, lower hemisphere.

The second deformation phase (Fig. 7, D2) is a continuation of transpressional tectonic regime. The compressional stress axis was rotated from the WNW–ESE to NNW–SSE direction. In the same direction there was an influence of maximal compression axis SHmax in the Western Carpathians during Ottnangian-Early Badenian (Marko et al., 1995; Kováč & Hók, 1996; Fodor et al., 1999; Šimonová & Plašienka, 2011, 2017; Bučová, 2013).

During the operation of transpresional tectonic regime (since Early Miocene) in the western part of the Pieniny Klippen Belt a sinistral shear zone has formed (Kováč & Hók, 1996) as a result of gradual anti-clockwise rotation of the Western Carpathian domain about 50°-60° (e.g. Kováč & Túnyi, 1995; Márton et al., 2016). It follows that, the older deformation structures should also have rotated. The extensional joints generated in this phase can by a harbinger of the change of transpressional tectonic regime to trantensional one. They were generated probably at the end of the phase D2.

The next deformation phase (Fig. 7, D3) is characterized by the change of the transpressional tectonic regime to transtensional and by rotation of the compression stress axis from NNW-SSE to N-S – NNE-SSW direction during the Middle Badenian to Late Badenian (e.g. Csontos et al., 1991; Marko et al., 1995; Kováč & Hók, 1996). During this time usually conjugate faults were activated. Except this, several normal faults were found in the study area. A similar influence of paleostress axis was recorded e.g. by Pešková (2009), Šimonová & Plašienka, (2011, 2017), Bučová (2013), as well. Paleostress axis changed its direction simultaneously with the block rotation. A sinistral shear zone with SW-NE direction has originated. During the Middle Miocene this zone accommodated translation of the Western Carpatians in the NE direction, which resulted in a change from transpression to transtension (e.g. Marko et al., 1995; Kováč et al., 2016; Fodor et al., 1999).

The transtensional tectonic regime with gradual rotation of the maximum principal stress axis (σ_1) from NNE-SSW to ENE-WSW during the Sarmatian to Panonian represents the next deformation phase (D4; Fig. 7D; Tab. 1). This change indicates clockwise rotation of the paleostress field after ending of the block rotation. The change of orientation of the paleostress field was probably caused by the eastward movement of an active subduction process along the outer margin of the Carpathian arc (Kováč, 2000; Kováč et al., 2016). The sinistral transtensional tectonic regime and formation of small pull-apart basins along the Pieniny Klippen Belt are indicative for this phase, as well. The similarly oriented of paleostress axis was detected by other authors in the nearby areas (e.g. Pešková et al., 2009; Bučová, 2013, Šimonová & Plašienka, 2011, 2017).

The youngest deformation phase is characterized by a change of tectonic regime from transtensional to extensional during the Pliocene (Fig.7, D5). The extension stress axis was oriented approximately in the N-S direction. During this deformation phase only normal faults trending approximately W-E were generated. The normal faults and extensional joints originated probably due to the relaxation of compressive stress in the study area.

Conclusion

The tectonic structures measured in the Súľovské vrchy Mts. revealed changes in the paleostress field during the Oligocene to Pliocene. The changes in the paleostress field were controlled by the interaction between the North European Platform and the ALCAPA lithospheric plate.

The oldest deformation phase (D1; Egerian-Eggenburgian) is characterized by NW-SE trending main horizontal compression axis, which later rotated to NNW-SSE direction (D2 phase; Ottnangian-Lower Badenian). During this time (Oligocene-Middle Miocene) mostly reverse faults and sinistral strike-slip faults were created and compressional tectonic regime was predominant in the study area. In the next period tectonic regime was changed from compressional to transtensional (D3 and D4 phases; Middle-Late Miocene). The compressional stress axis later rotated from NNW-SSE direction to N-S, or NNE-SSW direction. Generally, normal faults and sinistral strike-slip faults were created.

The latest deformation phase (D5; Pliocene) is characterized by extensional tectonic regime with extensional component of the stress field oriented to NNW-SSE direction and a number of normal faults as a result of extensional tectonic regime.

The identified changes in the orientation of paleostress field in the Súľovské vrchy Mts. correspond with changes identified in neighbouring areas.

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Viacstupňový vývoj zlomov a puklín v súľovských zlepencoch (Súľovské vrchy, Slovensko): dôsledky pre paleonapäťovú históriu

Súľovské zlepence patriace do súľovského súvrstvia myjavsko-hričovskej skupiny sa nachádzajú na území Stredného Považia. Tvoria hlavnú výplň Žilinskej kotliny a Domanižskej kotliny (obr. 1 a 2). Výskum súľovských zlepencov bol doteraz sústredený predovšetkým na sedimentologické štúdie (napr. Samuel et al., 1972; Marschalko a Samuel, 1993; Marschalko a Kysela, 1980; Salaj, 1993; Salaj, 2001). Tektonické štruktúry zistené v súľovských zlepencoch odhalili zmeny v orientácii napäťového poľa počas oligocénu až pliocénu. Prvou zistenou deformačnou udalosťou (D1) bolo pôsobenie kompresnej paleonapäťovej osi v smere ZSZ – VJV počas oligocénu až spodného miocénu (obr. 7A). Na území Stredného Považia panoval v tomto období transpresný tektonický režim. Ďalšou deformačnou udalosťou (D2; obr. 7B) bolo pokračovanie transpresného tektonického režimu a rotácia kompresnej paleonapäťovej osi zo smeru ZSZ – VJV do smeru SSZ – JJV v období otnangu až spodného bádenu. Vznik extenzných puklín pravdepodobne na konci tejto etapy mohol byť predzvesťou zmeny tektonického režimu z transpresného na transtenzný, ktorý pôsobil na skúmanom území počas stredného až vrchného bádenu (D3; obr. 7C). V tomto období začala prevládať extenzná zložka paleonapätia pôsobiaca v smere ZSZ – VJV, kompresia bola na ňu kolmá. Počas sarmatu až panónu pokračovalo pôsobenie transtenzného tektonického režimu (deformačná fáza D4;

obr. 7D), vzniklo viac poklesových zlomov a extenzných puklín. Prevládajúca tenzia pôsobila v smere SSZ – JJV, kompresia bola na ňu kolmá. Poslednou deformačnou udalosťou bola zmena transtenzného režimu na extenzný a pôsobenie extenznej paleonapäťovej osi približne v smere S – J. Podobné údaje zistili aj iní autori z okolitých oblastí (napr. Pešková, 2009; Vojtko et al., 2008, 2010; Bučová, 2013; Šimonová a Plašienka, 2011, 2017; Soták et al., 2018). Paleonapäťová analýza je skomplikovaná rotáciou bloku Západných Karpát proti smeru hodinových ručičiek o 50 až 60° a rotáciou paleonapäťových osí v smere hodinových ručičiek (Márton et al., 2016).

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