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ORIENTATIONS OF PALEOSTRESSES IN THE JURASSIC LIMESTONES ON THE FRONT OF THE WEST CARPATHIAN FLYSCH NAPPES (PAVLOV HILLS, SOUTH MORAVIA)

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Abstract: The paleostress analysis was applied at 16 sites in the Mesozoic limestones, which are tectonically incorporated into the Cretaceous and the Paleogene strata on the front of the West Carpathian flysch nappes (South Moravia, Czech Republic). 25 solutions were obtained. These solutions can be divided into two groups. The first group represents the paleostress field with predominantly NW-SE compression and NE-SW extension connected with the Early Neogene movements of the Ždánice Nappe. The azimuth of eigenvector of acceptable σ_1 axes varies from 97° up to 167°. This variability can be explained by rotation of individual tectonic slices of the Ždánice Nappe during the movement of this nappe. The different tectonic scales probably rotated in different directions (anticlockwise rotation in the case of some scales, clockwise rotation in the case of others). The second group of solutions represents the paleostress field with NE-SW compression and NW-SE extension.

Key words: Neogene, Outer Western Carpathians, Waschberg-Ždánice Belt, paleostresses.

Introduction

Tectonic movements are closely related to the orientations of the principal stress axes. The orientations of the principal stress axes can be computed by analysis of the orientations of kinematic indicators on activated brittle failures. Similarly, the character of movements along the significant tectonic structures could be determined from the known orientation of the principal stress axes.

The paleostress analysis based on the investigation of the fault striae data was carried out at 16 sites situated in the small area (about 20 km^2) of the Pavlov Hills region (South Moravia, Czech Republic). In this way, more detailed knowledge about the character of the paleostress fields affecting this part of the Outer Western Carpathians was obtained. The aim of this article is to inform about the results of this analysis and to contribute to better knowledge of structural and paleostress evolution within the outermost part of the junction area of the Western Carpathians and Eastern Alps.

Geological and structural setting

The Pavlov Hills region is situated in the outermost part of the outer units of the Carpathian flysch belt, near the front of the Waschberg-Ždánice Belt (Fig. 1). The tectonic slices of the Klentnice Formation (Oxfordian to Tithonian) and the Ernstbrunn Limestones (Late Tithonian–?Hauterivian, see Stráník et al. 1999) form the N-S to NNE-SSW orientated klippen in this region. The Upper Cretaceous sediments of the Klement Formation and the Pálava Formation were transgressively deposited on the Ernstbrunn Limestones. The imbricated tectonic slivers of the Mesozoic sediments were detached from the European Platform, tectonically transported and incorporated into the frontal zone of the Ždánice Nappe (Pícha & Stráník 1999; Stráník et al. 1999). Originally, these Mesozoic sediments were deposited on the eastern slope of the Pavlov carbonate platform, which was situated on the western margin of the Ždánice area (Eliáš & Eliášová 1986). The Lower Miocene sediments found between two tectonic slices in the borehole Pavlov Hills-1 (Stráník et al. 1962) prove the Styrian age of the origin of this imbricated structure, contemporaneous with the final stage of the overthrust of the Ždánice Nappe.

The greater part of the Ždánice Nappe is formed by the Tertiary sediments of the Němčice Formation (Middle Eocene to Lower Oligocene in the studied region), the Menilitic Formation (Oligocene) and the Ždánice-Hustopeče Formation (Egerian) (Stráník et al. 1999).

The Ždánice Unit is thrust to the NW over the Neogene sediments of the Carpathian Foredeep deposited on the SE margin of the Bohemian Massif. In the northern part of the Pavlov Hills region, the narrow tectonic slices of the Pouzdřany Unit are developed in front of the Ždánice Nappe. The eastern part of the Ždánice Unit is covered by the Neogene sediments of the Vienna Basin. In the basement of the Vienna Basin, the Ždánice Unit dips under the Magura Nappe.

The Pavlov Hills region is affected not only by oblique thrusts developed during the movements of nappes, but also by significant strike-slip shear zones and oblique-slip transverse faults. The imbricated fabric of the Ždánice Unit is disturbed by the NW-SE to E-W trending faults on the front of

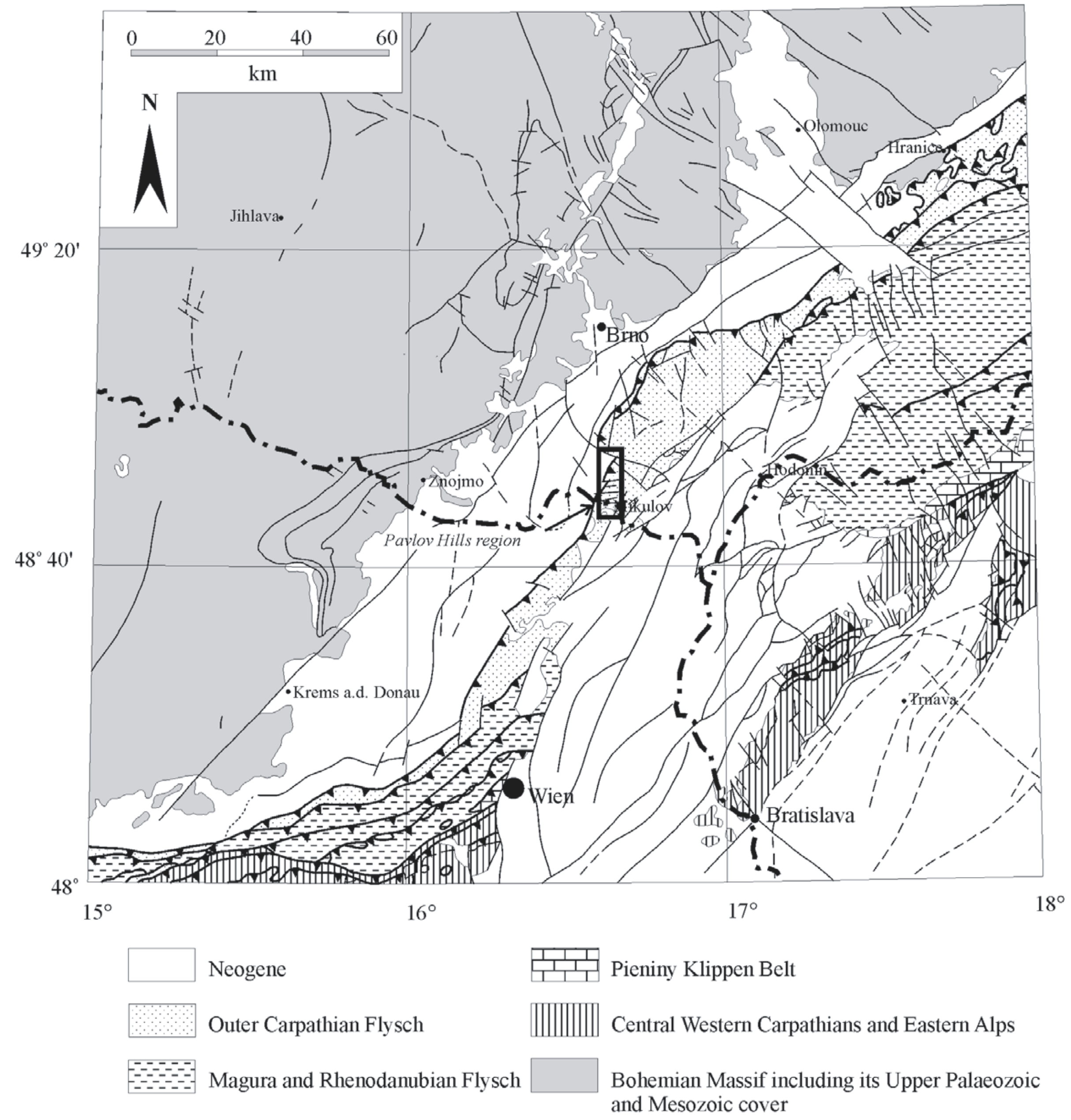

Fig. 1. Geological scheme of the junction area of the Western Carpathians and Eastern Alps with the Pavlov Hills region marked (geological map compiled and modified after Kodym et al. 1967 and Maheľ 1973).

the West Carpathian flysch nappes. Significant displacement is supposed also along the N-S oriented faults forming the eastern tectonic boundary of the klippen in the Pavlov Hills region. Sinistral NNE-SSW and NE-SW strike-slip faults, which belong to the Falkenstein-Mikulov Fault System, bound the klippen Šibeničník and Svatý kopeček in the southern part of the Pavlov Hills region (Roth 1980; Stráník et al. 1999). The huge strike-slip movements connected with the Early to Middle Miocene formation of the Vienna pull-apart basin were discussed by a number of authors (for instance Fodor 1995; Hubatka & Krejčí 1996; Roth 1980; Royden 1985). These movements were connected with the Neogene tectonic extrusion of the West Carpathian region from the Alpine domain to the NE accompanied by the counter-clockwise rotation of the extruded blocks (Decker et al. 1994; Fodor 1991; Kováč 2000).

Methods

The paleostress analysis was based on study of fault striae data. Slickolites were predominantly used as kinematic indicators, other indicators (offsets of planar structures, crystal fibres etc.) were less often observed. The program BRUTE3 (Hardcastle & Hills 1991) was used to calculate the orientations of the principal paleostresses. Only exceptionally, in the

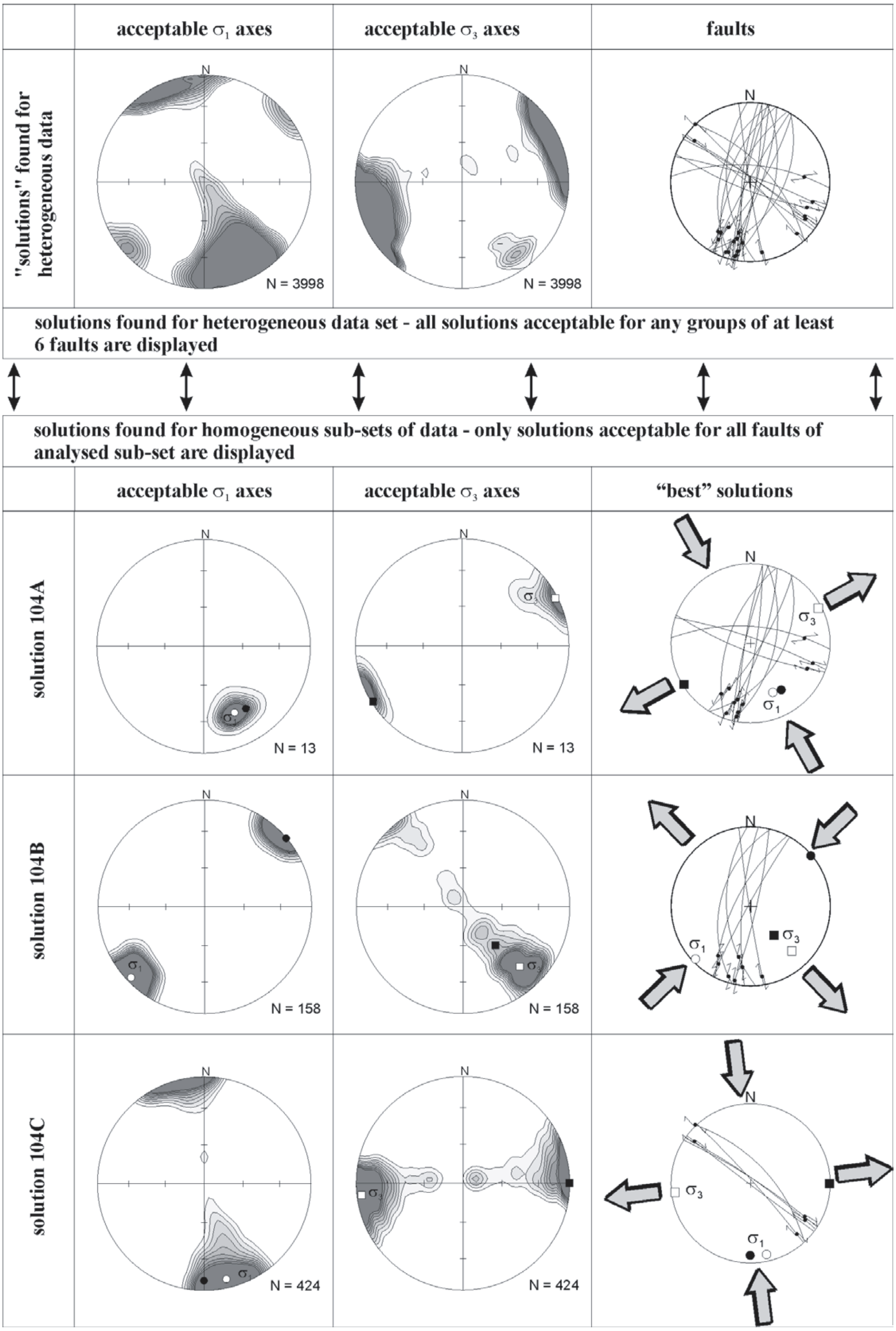

Fig. 2. Example of solutions for heterogeneous data set and for homogeneous sub-sets at the Svatý kopeček site (104) computed by program BRUTE3 (Hardcastle & Hills 1991) — contoured diagrams of acceptable orientations of the principal stresses and diagram of the "best" computed orientations of the principal stresses (Lambert projection, lower hemisphere). **White circle** — eigenvector of the all acceptable orientations of the σ_1 axis; **black circle** — best solution of the σ_1 axis; **white square** — eigenvector of all the acceptable orientations of the σ_3 axis; **black square** — best solution of the σ_3 axis; **N** — number of acceptable solutions; **great circles** — fault planes used for stress analysis; **grey arrows** — orientations of principal horizontal stresses (see text for more information).

cases of less numerous data sets, the orientations of principal stresses were estimated with the use of the graphical method of Angelier & Mechler (1977).

The program BRUTE3 tests all possible reduced tensor configurations (by selected increments) against analysed data sets and chooses the acceptable tensors, which satisfy the limits (Hardcastle & Hills 1991). The first tested factor is the maximum limit of 25° for angular difference θ between the rake of maximum shear stress and the rake of measured striations. Secondly, the value of the shear component of stress was compared with the minimum value following from the Coulomb criteria for the reactivated faults.

The reduced tensor has four degrees of freedom. Three angular variables of the acceptable reduced tensor describe the acceptable orientations of the principal stress axes. Fourth variable is the shape ratio ϕ defined by Angelier (1975) as $\phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$. The shape ratio was tested in the range from 0.1 to 0.9, program BRUTE3 does not test the limit values $\phi = 0$ and $\phi = 1$.

The orientations of the principal stress axes of acceptable tensors could be contoured to show the range of the acceptable results (Fig. 2). For each principal axis the relevant eigenvector of orientation matrix was computed as the average orientation. The mean value of the angular difference θ between the rake of maximum shear stress and the rake of measured striations was used as criteria for the selection of the "best" solution. The "best" solutions are reduced tensors with the least mean value of θ.

The contoured diagrams were also used for separation of heterogeneous data (Fig. 2). Solutions, which are acceptable for any sub-set of data, are displayed in diagram. This contoured diagram shows several groups of possible solutions. Found possible solutions were used as a criterion for separation of data by the program SELECT (Hardcastle & Hills 1991).

Computed orientations of principal paleostresses

25 solutions (see Table 1) based on the analyses of fault geometries were obtained at 16 sites in the Pavlov Hills region (Fig. 3). 21 solutions were computed by program BRUTE3. Four solutions were determined by the graphical method of Angelier & Mechler (1977). Two main groups of solutions were distinguished according to orientations of the principal axes. These groups are the following:

1. group of predominantly NW-SE compression and/or NE-SW extension;
2. group of NE-SW compression and NW-SE extension.

Predominantly NW-SE compression and/or NE-SW extension

19 solutions of the analyses carried out at 12 sites shows predominantly NW-SE compression and NE-SW extension. Most of these solutions have gently dipping σ_1 and σ_3 axes. Computed solutions are represented by sub-horizontal σ_1 axis and steep σ_3 axis only at two sites (sites 111 and 118).

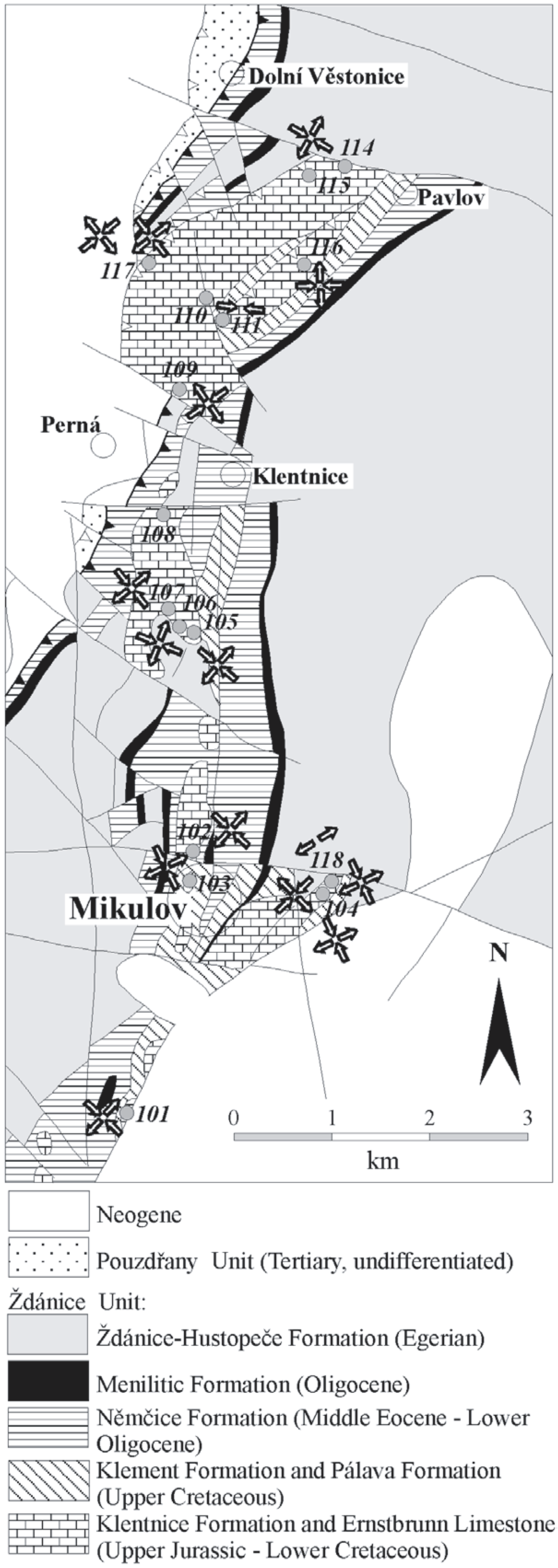

Fig. 3. Geological scheme of the Pavlov Hills region (after Stráník et al. 1999, modified and simplified) with marked studied sites (grey circles). White arrows show computed orientations of horizontal principal stresses (see text for more information).

Table 1: Solutions of paleostress analysis computed by program BRUTE3 (Hardcastle & Hills 1991) or determined by the graphical method of Angelier & Mechler (1977). EL — Ernstbrunn Limestone, KF — Klement Formation.

Site	Solution	Rock	Stress tensor best solution		eigenvectors			Method
			σ_1	σ_3	σ_1	σ_3	stress ratio	
101	101A	EL	318/20	216/28	313/23	219/8	0.3-0.7	BRUTE3
	101B	EL	180/10	294/66	161/15	251/24	0.1-0.4	BRUTE3
102	102A	EL, KF	315/50	47/2	313/47	46/2	0.1-0.3	BRUTE3
103	103A	EL	150/10	60/0	334/20	71/9	0.5-0.9	BRUTE3
104	104A	EL	146/30	238/2	155/32	63/3	0.3-0.5	BRUTE3
	104B	EL	50/0	140/51	226/5	137/24	0.1-0.4	BRUTE3
	104C	EL	180/10	90/0	167/9	263/5	?	BRUTE3
105	105A	EL	310/10	43/17	130/0	221/6	0.1-0.4	BRUTE3
106	106A	EL	110/0	200/20	292/1	198/16	0.1-0.3	BRUTE3
107	107A	EL	326/30	229/13	321/31	227/8	0.5-0.8	BRUTE3
109	109A	EL	30/50	134/11	31/57	146/13	0.7-0.9	BRUTE3
	109B	EL	210/10	110/45	203/4	108/47	0.1-0.3	BRUTE3
111	111A	EL, KF	280/10	34/66	277/3	160/74	?	BRUTE3
	111B	EL, KF	NW-SE	NE-SW				AM
114	114A	EL	280/60	75/28	276/52	74/40	?	BRUTE3
	114B	EL	293/30	54/42	300/40	60/37	?	BRUTE3
116	116A	EL	ESE-WNW	NNE-SSW				AM
117	117A	EL	42/44	157/28	34/30	142/28	?	BRUTE3
	117B	EL	NW-SE	NE-SW				AM
118	118A	EL, KF	340/10	239/47	334/10	235/54	?	BRUTE3
	118B	EL, KF	328/20	228/34	326/11	204/57	0.3-0.4	BRUTE3
	118C	EL, KF	349/30	230/40	341/23	233/36	0.2-0.6	BRUTE3
	118D	EL, KF	310/10	219/47	125/14	225/35	0.1-0.5	BRUTE3
	118E	EL, KF	154/40	267/25	157/63	240/3	0.1-0.4	BRUTE3
	118F	EL	NE-SW	NW-SE				AM

Mostly steep strike-slip or oblique-slip faults correspond to the discussed orientation of the principal stresses. The sinistral and dextral strike-slips trend NNW-SSE to NNE-SSW and NW-SE to E-W, respectively. There is significant variability in the trend of the thrusts and oblique thrusts. Predominantly, they are dipping to the E. At the Janišův vrch site (118) N-S to NNW-SSE trending oblique normal faults were also measured.

In the cases of solutions determined by program BRUTE3, the azimuth of eigenvector of acceptable σ_1 axes varies from 97° up to 167° (Fig. 4). At sites 104 and 118 on the northern margin of Svatý kopeček and at site 111 near Soutěska, the crossing of several fault structures used for the determination of discussed paleostresses was observed.

At site 111 near Soutěska, the eastwards dipping thrusts of Ernstbrunn Limestones over the sediments of the Klement Formation and the Pálava Formation were used for determination of orientation of paleostress field with E-W to WNW-ESE maximum compression. The thrusts are cut by younger WSW-ENE oriented steep oblique thrusts which were active under NW-SE compression.

At the Svatý kopeček (104) and Janišův vrch sites (118) the duplex fabric of the Ernstbrunn Limestone was observed (Fig. 5). The duplex fabric originated between larger moderately dipping faults, which were repeatedly reactivated (strike-slips, oblique thrusts). At the Janišův vrch site (118), the tectonic planes bounding individual tectonic slices trend E-W to NW-SE. Striations on these planes prove oblique-slip movements. The resulting solutions show the sub-horizontal σ_1 axis oriented NW-SE or NNW-SSE and the σ_3 axis dipping towards SE or ESE. The dip of the σ_3 axis is about 50° in the case of local field determined from duplexes (solution

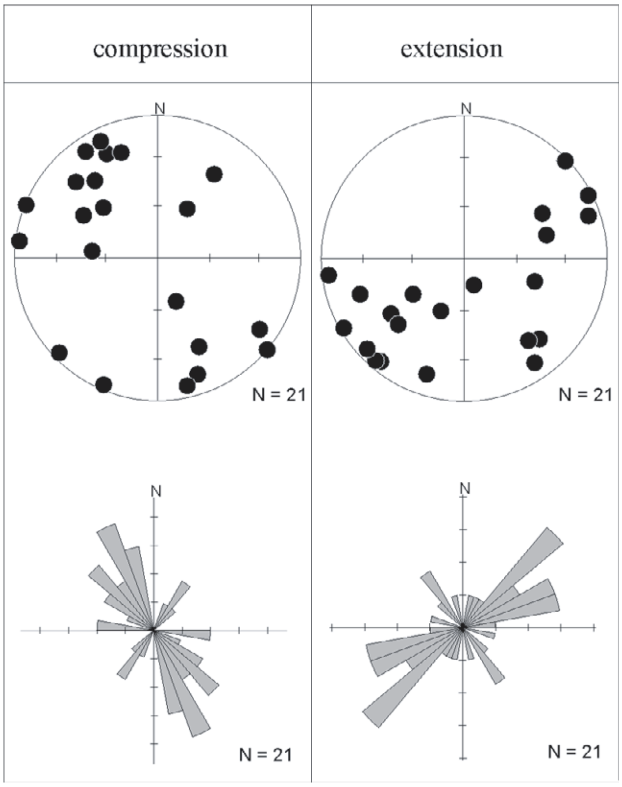

Fig. 4. Orientation of eigenvectors of the acceptable σ_1 axes (maximum compression) and σ_3 axes (maximum extension) determined by program BRUTE3. **Upper diagrams** — point diagrams of orientations of eigenvectors (Lambert projection, lower hemisphere); **lower diagrams** — histograms of strikes of eigenvectors (frequency of histograms is 10°).

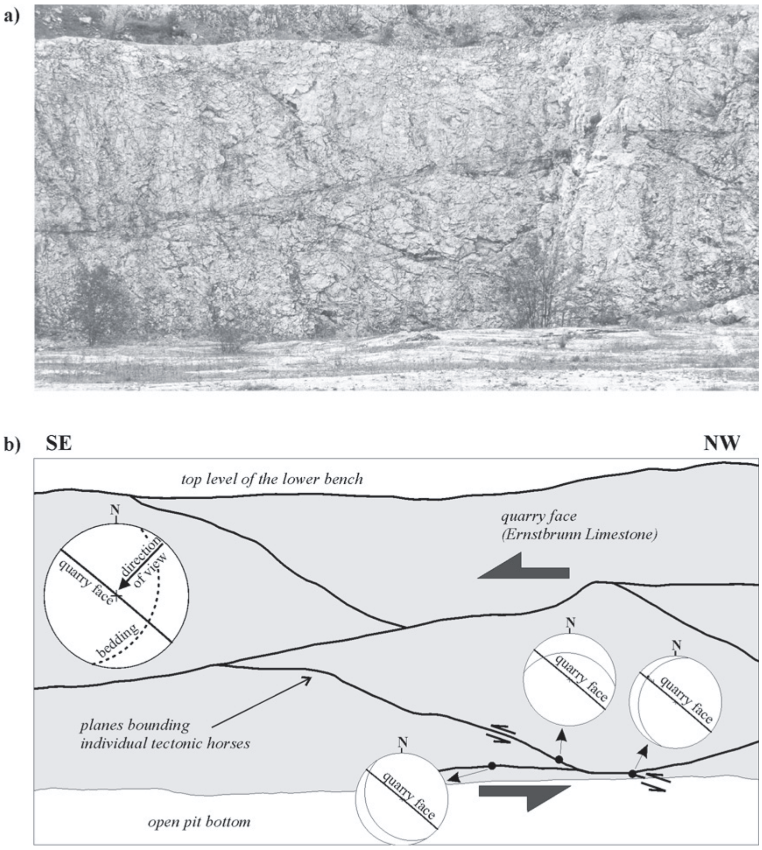

Fig. 5. Scheme of the duplex fabric of the Ernstbrunn Limestone observed in the Svatý kopeček quarry (site 104). Diagrams (Lambert projection, lower hemisphere) show measured orientations of planes bounding individual tectonic horses (grat circles), arrows show sense of displacement. Striations on the tectonic planes bounding individual horses (tectonic slices) prove oblique movements along these planes (not dip-slip movements).

118A) and about 35° in the case of other solutions determined from the large thrusts and from strike-slip faults (solutions 118B, 118C and 118D). Some oblique thrusts and strike-slip faults are cut by the tectonic boundaries of duplexes. On the other hand, some other thrusts and strike-slip faults cut the duplex fabric. These facts prove the activity of the oblique thrusts and strike-slip faults both before and after the forming of the duplex fabric (Fig. 6). The azimuth of eigenvector of acceptable σ_1 axes varies from 125° up to 161°, in the case of individual solutions from site 118. The faults older than duplex fabric correspond mostly to the NNW-SSE orientation of σ_1 axis, the faults younger than duplex fabric correspond mostly to the NW-SE orientation of σ_1 axis. At the Janišův vrch site (118), the youngest paleostress field (solution 118E) is represented by sub-horizontal NE-SW σ_3 axis and steep σ_1 axis.

Two solutions with different azimuth of the σ_1 axes were also determined at the Svatý kopeček site (104). This azimuth is 155° in the first case and 167° in the second case.

The discussed fact shows that paleostresses with the predominantly NW-SE compression and NE-SW extension affected the Ernstbrunn Limestone in the Pavlov Hills region during more than one stage of movements along faults. Individual stages probably passed each into other continuously. The differences between solutions representing individual stages of fault activity could be explained by one of two hypotheses:

— rotation of the principal paleostress axes between individual stages and change of the value of principal stresses;

— rotation of faulted block of affected rocks between individual stages and change of the value of principal stresses. The anticlockwise block rotation is presumed by Fodor (1991, 1995) in the West Carpathian flysch nappes. The solutions determined at site Janišův vrch (118) show the possibility of the clockwise rotation of the Svatý kopeček block.

At Dívčí hrad site (114) situated on the northern boundary of the Pavlov Hills region, the σ_1 and σ_3 axes significantly dip to the NW and NE respectively. Two similar solutions were determined from the N-S oriented faults. The plunge of measured striations varies from 48° to 83°. On some fault planes more than one striation was measured, different striations correspond to different dip of the principal paleostresses. The determined orientation of the principal paleostresses shows the significant northward tilting at site 114 (Fig. 7). During the predominantly NW-SE compression and NE-SW extension, the block rotation around the probably sub-horizontal E–W axis occurred. The value of the angle of this rotation was probably about 20°–30°. The significant dip of all striations could be explained by continuing rotation after the end of fault movements connected with the NW-SE compression.

The strike-slip faults and oblique thrusts used for determination of the discussed paleostress dislocate not only the Ernstbrunn Limestone, but also the overlaying Upper Cretaceous sediments of the Klement Formation. It means that the predominantly NW-SE compression could be active after the Late Cretaceous. In the Pavlov Hills 1 borehole, the tectonic slice of the Lower Karpatian sediments were found (Stráník et al. 1962). It proves the existence of Karpatian (or younger?) predominantly NW-SE compression.

NE-SW compression and NW-SE extension

In the case of five solutions, the maximum compression is oriented NE-SW and maximum extension is oriented NW-SE. The E-W trending sinistral and N-S to NNE-SSW trending dextral strike-slips correspond to this orientation of principal axes. At site Kotel (109), the fault population attributed to this paleostress also contains NW-SE trending sinistral strike-slip faults. The NE-SW compression and NW-SE extension was found at sites situated both in the southern and northern parts of the studied area. Individual faults which geometrically correspond to this orientation of principal paleostresses were also measured at some other sites. It shows the regional significance of this paleostress field. The NE-SW compression and NW-SE extension affected the whole Pavlov Hills region. The less frequent fault striae data corresponding to this paleostress field could be explained by older age or smaller intensity of this paleostress field in comparison with the predominantly NW-SE compression.

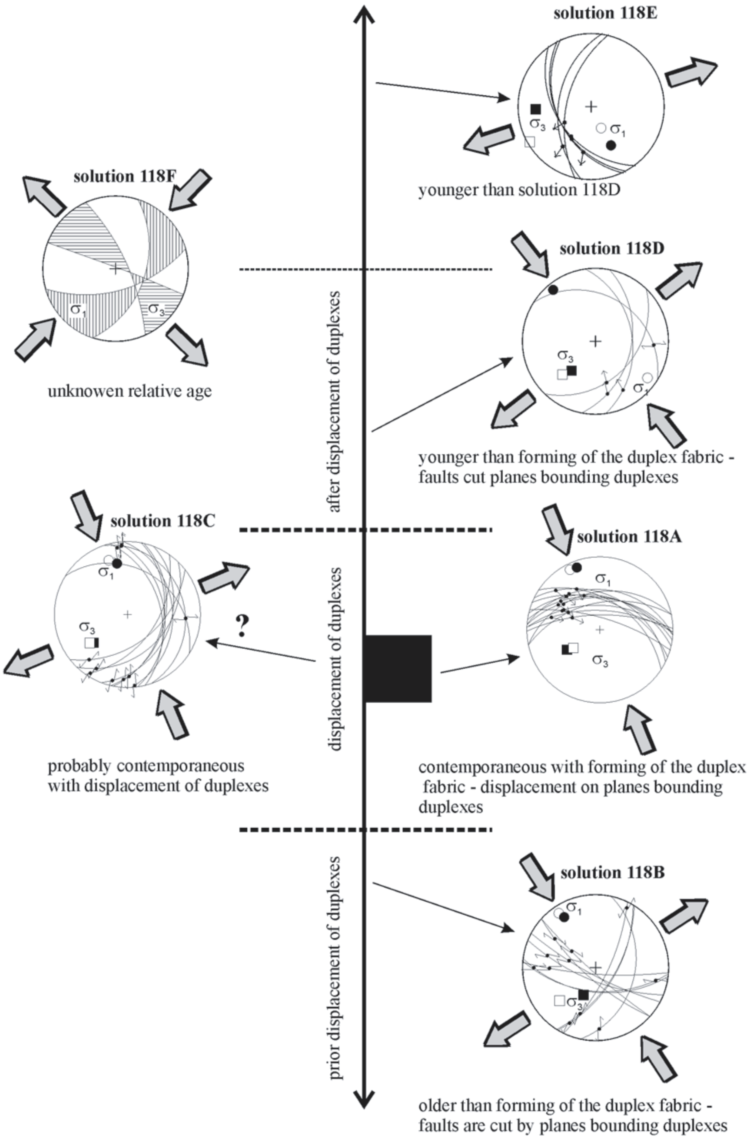

Fig. 6. Scheme of relative ages of paleostress fields at the Janišův vrch site (118). Orientations of principal stresses are computed by program BRUTE3 (Hardcastle & Hills 1991) — solutions 118A, 118B, 118C, 118D and 118E — or determined using the method of Angleier & Mechler (1977) — solution 118F (Lambert projection, lower hemisphere). For symbols see Fig. 2 (see text for more information).

At the Kotel site (109) near the Klentnice, two different paleostress fields with NE-SW compression and NW-SE extension were found. This fact shows that the Mesozoic blocks on the front of the West Carpathian flysch nappes were probably affected by the NE-SW compression and NW-SE extension during more (at least two) different tectonic episodes.

The orientations of paleostresses in relation to the tectonic development

While the collision started in the Alpine region already during the Eocene, in the Carpathian region continuing subduction caused the Oligocene to Miocene large-scale movements of the Carpathian units to the NE (Kováč 2000; Nemčok et al. 1998b). Thus the contact of the Bohemian Massif and the Western Carpathians was strongly affected by the lateral movement of the West Carpathian units. During the Neogene sinistral transpression, the Carpathian flysch nappes were obliquely thrust onto the eastern margin of the Bohemian Massif. The last movements of the Ždánice Nappe terminated during the Karpatian in the southern Moravia region (Kováč 2000).

The Paleogene and the Early Neogene WNW-ESE to NNW-SSE orientation of maximum compression is documented from the junction area of the Western Carpathians and Eastern Alps (for instance Fodor 1991, 1995; Marko et al. 1995; Nemčok et al. 1998a; Peresson & Decker 1997). This orientation corresponds well to the results discussed in this article. Paleostress field is represented by predominantly NW-SE compression and NE-SW extension was computed at a number of sites in the Pavlov Hills region. The determined WNW-ESE to NNW-SSE compression was connected with the nappe movements during the Oligocene–Early Miocene transpression in the westernmost Carpathians. The Cenozoic NW-SE to NNW-SSE compression significantly affected the eastern margin of the Bohemian Massif. For instance, the Neogene NW-SE compression was found at several sites on the south-eastern margin of the Nízký Jeseník region and in the Maleník block (Havíř 2002).

Fodor (1991, 1995) has supposed the stable N-S orientation of maximum compression in the westernmost Carpathians and easternmost Eastern Alps during the Oligocene–Early Miocene and anticlockwise block rotation which affected the observed faults. The blocks rotated in a broad zone affected by sinistral transpression.

The rotation of the tectonic blocks should be taken into account. This possible rotation, which accompanied the movement of the Ždánice Nappe, can explain the time and space variation of the orientation of the principal stresses found in the Pavlov Hills region. The variability of the orientation of individual klippen in the Pavlov Hills region can also be explained by this rotation (Stráník et al. 1996). The different tectonic scales (or tectonic blocks) probably rotated in different directions. In the case of some blocks, the anticlockwise rotation can be supposed, other blocks were affected by clockwise rotation. The value of angle of the discussed rotation can be estimated as up to 40°.

During the Early Badenian the orientation of the principal stresses was changed in the junction area of the Western Carpathians and Eastern Alps. After termination of nappe movements, the maximum compression axis was turned to NNE-SSW, while maximum extension was WNW-ESE (for instance Fodor 1991, 1995; Marko et al. 1995; Nemčok et al. 1998a; Peresson & Decker 1997). This orientation of the principal stresses was connected with transtensional regime. In the Vienna Basin, the transtension is proved by the negative flow-

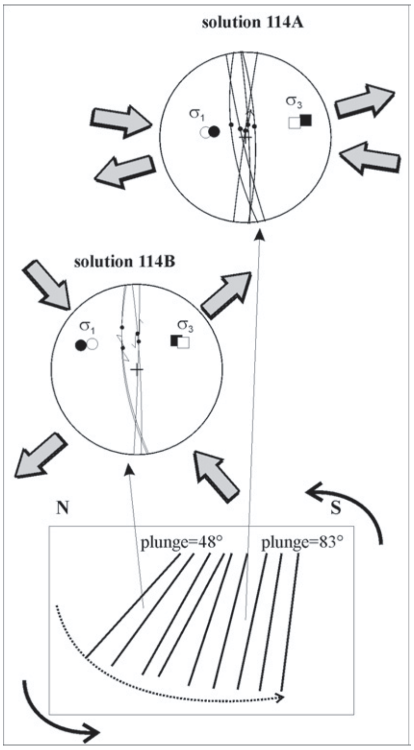

Fig. 7. Orientations of principal stresses computed at the Dívčí hrad site (114) (Lambert projection, lower hemisphere) and scheme of orientation of striations on steep N–S trending faults. Plunge of striations varies due to northward tilting (see text for more information). For other symbols see Fig. 2.

er structures (Hubatka & Krejčí 1996). The NE-SW compression and NE-SW extension were also found at several sites in the Pavlov Hills region. Some of these determined solutions can correspond to the discussed transtensional regime. But two different solutions computed at site 109 show that the existence of an other (probably older) stress field with similar orientation of the principal stresses also has be taken into account.

Conclusion

The results of paleostress analysis show that two paleostress fields played dominant roles during Cenozoic tectonic development in the Pavlov Hills region.

The first paleostress field is represented by predominantly NW-SE compression and NE-SW extension. This paleostress field is connected with the Early Neogene movements of the Ždánice Nappe. The variability of the orientation of principal stresses can be explained by rotation and tilting of individual tectonic scales during movement of the nappe.

The second paleostress field is characterized by NE-SW compression and NW-SE extension. The field with this orientation of the principal stresses affected the Mesozoic blocks on the front of the West Carpathian flysch nappes during more (at least two) different tectonic stages. One (younger) tectonic stage can correspond to the Badenian (or younger?) transtensional regime.

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