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ORIENTATIONS OF RECENT PRINCIPAL STRESS AXES IN THE JESENÍKY REGION

Josef HAVÍŘ

Institute of Physics of the Earth, Masaryk University, Tvrdého 12, 602 00 Brno
Corresponding author's e-mail: havir@ipe.muni.cz

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ABSTRACT

Seven focal mechanisms computed for micro-earthquake events located into the Jeseníky region were used for the stress analysis. The epicentres of these discussed seven events occurring in period 2001-2003 are situated in four separated epicentral areas. In spite of this dispersion of locations, the focal mechanism data are homogeneous. Seeming heterogeneity of the collection of all nodal planes is probably caused only by influence of the auxiliary nodal planes which are not real faults. These auxiliary nodal planes can contradict the stress conditions.

The axis of maximum compression is sub-horizontal or only gently dipping and it is orientated in the direction NNW-SSE. The axis of maximum extension is orientated in the direction ENE-WSW. This orientations well corresponds with published orientations of horizontal stresses investigated using breakouts (Peška, 1992) and hydrofracturing method (Staš et al., 1997) in the Czech part of the Upper Silesian Basin, similar stress fields were found also in other regions of the Bohemian Massif (Havíř, 2000; Peška, 1992; Reinecker and Lenhardt, 1999).

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KEYWORDS: NE part of the Bohemian massif, recent stress field, recent tectonic activity, focal mechanism

1. INTRODUCTION

The weak seismo-tectonic activity, which is known from the NE part of the Bohemian Massif (for instance Holub et al., 1994; Skácelová and Havíř, 1999), is significant evidence of the recent tectonic activity of this area including the Jeseníky region. These recent tectonic movements are monitored also by high-accuracy geodetic measurements (Kontny et al. 2000; Schenk et al. 2002). The Pliocene/Quaternary subsidence of the block of the Hornomoravský úval (Grygar and Jelínek, 2002; Růžička, 1973; Zeman et al., 1980) and the Tertiary/Quaternary volcanic activity occurring in the Jeseníky region (Přichystal, 1993; Ulrych et al., 1999) also demonstrate the significant young (the Pliocene and the Quaternary) crustal movements.

Since the eightieth years of 20th century, the tectonic events have been monitored by seismological stations operated by the Institute of Physics of the Earth (IPE) and by Institute of Geonics AS ČR (ÚGN). Technical University Ostrava, Institute of Geonics AS ČR and Geophysical Institute AS ČR collaborate on the operation of the station OKC. Detailed monitoring of seismo-tectonic activity in the NE part of the Bohemian Massif has begun in 2001 when the temporary local network Dlouhé Stráně (Sýkorová et al., 2002, 2003) situated in the Hrubý Jeseník Mts. was put into operation by IPE. In the case of several events, this detailed monitoring produced sufficient amount of data for the computation of the focal mechanism. Seven most reliable focal mechanisms were used for the stress analysis which is discussed in this article.

2. GEOLOGICAL AND STRUCTURAL SETTING

At least three orogenesis (Cadomian, Variscan and Alpine) formed the tectonic setting of the northeastern part of the Bohemian Massif. The Brunovistulian units situated on the eastern margin of the Bohemian Massif (Dudek, 1980; Finger et al., 2000) forms the Cadomian basement covered by the Paleozoic to the Tertiary sediments, which represents the foreland both of the Variscan and the Alpine accretionary wedges (Grygar and Vavro, 1995). The Cadomian origin of the equatorial and meridional faults occurring in this Cadomian basements is considered (Grygar, 2000; Kumpera, 1983).

During the oblique Variscan collision, Moldanubian-Lugian units were obliquely overthrust over the Brunovistulian platform and the Moravo-Silesian metamorphic belt (Mate et al., 1990; Parry et al. 1997; Schulmann et al. 1994; Suess, 1912) and the complicated Variscan nappe structure was formed (see Cháb and Opletal, 1984; Cháb et al., 1990; Krejčí et al., 2002; Schulmann et al, 1991, 1994). The Silesian domain (in the Hrubý Jeseník Mts.) represents strongly deformed and imbricated part of the Brunovistulian platform and its the Devonian cover on the boundary of the Brunovistulian and the Moldanubian-Lugian units (Parry et al., 1997). Westwards (in the Nízký Jeseník Mts.), the significantly thrust and folded Paleozoic sediments of the Variscan flysch (and early molasse in the most eastern part of the Nízký Jeseník Mts.) cover the basement (Dvořák, 1994). Their age and deformation generally decrease eastwards or south-eastwards (Dvořák, 1994; Hrouda, 1979; Kumpera, 1983). The NNE-SSW orientation of the strike of thrusts and fold axes predominates both in the Silesian crystalline units and in the Paleozoic sediments in the NE part of the Bohemian Massif (Grygar and Vavro, 1995; Kumpera, 1983; Parry et al., 1997). During the Devonian to the Carboniferous Variscan tectonics, also the WNW-ESE to NW-SE large strike-slip faults and shear zones played significant role and strongly affected the NE part of the Bohemian Massif (Aleksandrowski, 1995; Aleksandrowski et al., 1997; Grygar ad Vavro, 1995; Kumpera, 1983).

The NE part of the Bohemian Massif was strongly affected by the large-scale lateral movement of the Western Carpathians during Alpine orogeny. The Western Carpathians Flysch nappes obliquely overthrust over the eastern margin of the Bohemian Massif (Fodor, 1995; Kováč, 2000). In response to this overthrusting, the elastic flexure of the foreland platform was formed in front of the Western Carpathian nappes (Krejčí et al., 2002). Last movements of the Outer Western Carpathian nappes terminated during the Early Badenian in the northern Moravia region (Kováč 2000). Due to Alpine tectonics, the Cadomian (mostly in the eastern part) and the Variscan (mostly in the western part) structures were reactivated (Grygar and Jelínek, 2002; Kaláb et al., 1995). The youngest movements along the older WNW-ESE to NNW-SSE striking faults dislocate also the Pliocene and the Quaternary sediments in the Hornomoravský úval region (Růžička, 1973; Zeman et al., 1980). In front of the Western Carpathian nappes, new NE-SW faults were formed on the northeastern margin of the Bohemian Massif (Kaláb et al., 1995). The older (Variscan) NNE-SSW thrust were reactivated during the Tertiary, the evidence of the Neogene compressive reactivation of this dislocations were found at several sites on the eastern margin of the Bohemian Massif (Krejčí et al., 2002; Havíř, 2002b).

3. GEOMETRY OF FOCAL MECHANISMS AND APPLIED METHODS OF STRESS ANALYSIS

In the cases of seven micro-earthquakes registered not only by stations of the local network Dlouhé Stráně but also by other seismological stations operated by IPE, the focal mechanisms were computed by P. Špaček (see Sýkorová et al., 2003). These seven events occuring in period 2001-2003 were located into four separated epicentral areas: area NW of Bruntál, area NNE of Šternberk, area NW of Šumperk and area NNE of Uničov (Fig.1).

All computed focal mechanisms (Table 1) are similar to each other. Each mechanism consists of steep or moderately dipping WNW-ESE to NW-SE trending nodal plane and of another steep NNE-SSW to NE-SW trending nodal plane. Only one nodal plane is a real fault and only its kinematics has to correspond to stress condition. Especially in the case of reactivated faults, the orientation of "slip" along auxiliary nodal plane (which is not real fault) can contradict the stress condition. This fact was shown already by Lisle (1992) and it is a basis of his Right Trihedra Method. It is, however, impossible to recognize the real fault without any additional information. In the case of the discussed focal

Table 1 Focal mechanisms of events located into the Jeseníky region used for stress analysis. Nodal planes geometry: α_P – dip azimuth of the nodal plane, ϕ_P – dip of the nodal plane, α_L – trend of the slip axis, ϕ_L – plunge of the slip axis. Sense of movements: s – sinistral strike-slip, d – dextral strike-slip.

	date	time	region	ML	α_P	ϕ_P	α_L	ϕ_L	sense
1	13.6.2001	06:50	NW of Bruntál	0.9	115	83	28	23	s
					208	67	295	7	d
2	13.6.2001	14:38	NW of Bruntál	1.0	110	84	22	18	s
					202	72	290	6	d
3	9.5.2002	23:55	NNE of Šternberk	0.8	304	66	34	1	s
					214	89	124	24	d
4	21.6.2002	17:48	NW of Šumperk	1.0	314	80	36	37	s
					216	53	134	10	d
5	21.6.2002	17:57	NW of Šumperk	0.9	315	81	37	39	s
					217	51	135	9	d
6	15.1.2003	20:28	NNE of Šternberk	1.1	295	88	207	38	s
					27	52	115	2	d
7	14.6.2003	05:54	NNE of Uničov	0.8	273	72	185	6	s
					5	84	93	18	d

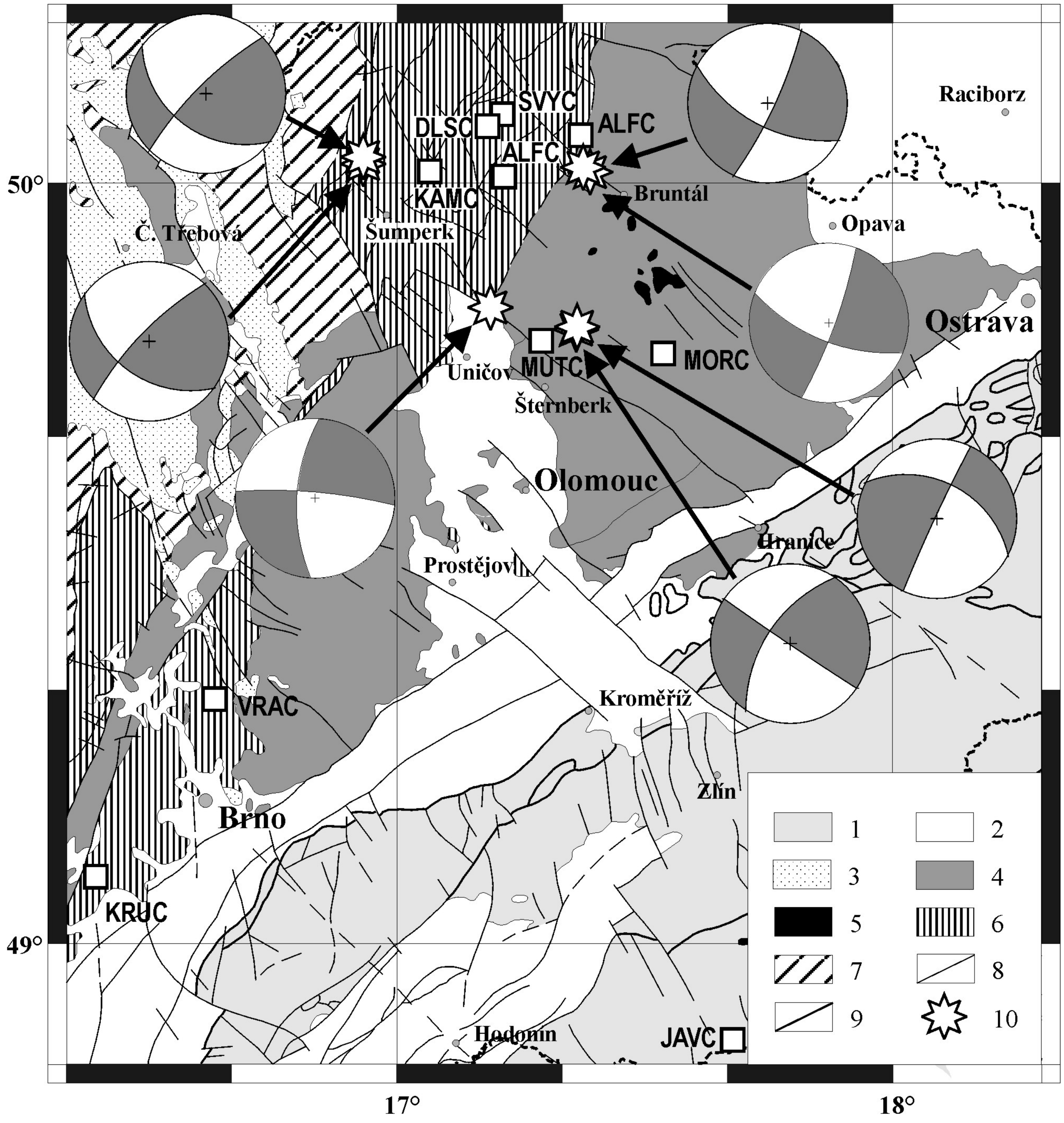

Fig. 1 Geological scheme of the northeastern margin of the Bohemian Massif (compiled and modified after Kodym et al., 1957 and Maheľ, 1973) and situation of the epicentres of events for which the focal mechanism was computed. Stations operated by IPE (white squares) are marked, geometry of focal mechanisms (beach-ball graphs) are displayed (white quadrants – compression, grey quadrants – extension). Legend: 1 – Western Carpathian nappes, 2 – Neogene, 3 – Mesozoic sedimentary cover of the Bohemian Massif, 4 – Paleozoic sediments, 5 – Tertiary/Quaternary volcanic rocks, 6 – Moravo-Silesian and Brunovistulian units including granites, metamorhosed volcanic rocks and metamorhosed Devonian sediments, 7 – Moldanubian-Lugian units, 8 – major faults, 9 – front of nappes, 10 – epicenters of micro-earthquakes for which the focal mechanism was computed

mechanisms, strike of WNW-ESE to NW-SE system of nodal planes very well corresponds to orientation of WNW-ESE and NW-SE "sudetic" faults. The epicentres of micro-earthquakes are often located in the vicinity of NW-SE or NNW-SSE trending faults, mostly close to the crossing of these faults with faults orientated E-W and NNE-SSW (Holub and Müller, 1997; Kaláb et al., 1995; Skácelová and Havíř, 1999). This fact demonstrates recent tectonic activity of the NW-SE "sudetic" faults. Thus at least some of the WNW-ESE to NW-SE nodal planes can be identified as real faults. But the NNE-SSW faults, hypothetically corresponding to NNE-SSW to NE-SW system of nodal planes, also occur in the tectonic setting of the NE part of the Bohemian Massif. These tectonic lines significantly modify the morphology in some regions, the epicentral area near Rýžoviště, NNE of Šternberk (the most seismically active area in the Jeseníky region) is situated near the crossing of the NNE-SSW and NNW-SSE faults (Havíř, 2002a). Thus, the real movement along the NNE-SSW nodal planes is also possible and has to be taken into account.

Two different methods of stress analysis were applied to the focal mechanism data. In the first stage, the simple graphical method of Angelier and Mechler (1977) was used because this method does not require the real fault plane and auxiliary nodal plane to be distinguished and it is very easily applicable to focal mechanisms. Nodal planes limit the areas of all theoretically possible orientations of the σ_1 axis (or the σ_3 axis respectively) in the "beach-ball" diagram of the focal mechanism. The principle of the method consists in looking for orientations of axes that lie only in the area of the possible orientations of the σ_1 axis (or the σ_3 axis respectively) for the whole analysed homogeneous set of focal mechanism data, other orientations are excluded.

During next step of the stress analysis, the numerical grid method was applied. The acceptable reduced stress tensors (see Angelier, 1990) were determined using the program BRUTE3 (Hardastle and Hills, 1991). The reduced stress tensor has four degrees of freedom. Three variables describe the orientations of the principal stress axes, the fourth variable is the shape ratio ϕ defined by Angelier (1975) as $\phi=(\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$. Using the program BRUTE3 all possible reduced stress tensors were tested against the data. The reduced stress tensors were chosen for each orientation of principal axes (by increments of 10°) and for each value of shape ratio selected in the range from 0.1 to 0.9 (the program cannot test the extreme cases of uniaxial compression and uniaxial extension) with increment of 0.1. The result of numerical analysis is a collection of all tested reduced tensors that satisfy the limits. The most important factor observed during the used test was the maximum limit of 25° for the angular difference between the rake of maximum resolved shear stress and the rake of the slip along the nodal plane. For each principal axis the relevant eigenvector of orientation matrix was computed as the "most probable" orientation. The mean value of the angular difference θ between the rake of maximum resolved shear stress and the rake of the slip along the nodal plane was also computed for each reduced tensor. The "best" solutions are reduced tensors with the greatest number of fitting tested nodal planes and with least mean value of θ.

In the cases of analysed focal mechanisms of events located into the Jeseníky area, the identification of real fault plane is unreliable. Thus, both nodal planes had to be taken into account during the stress analysis. The whole collection of all nodal planes were analysed together. But auxiliary nodal planes (which are not real faults) can affect the result of stress analysis. That is why the additional analyses of separate sub-sets containing only one nodal plane of each focal mechanism were carried out. The analyses of sub-set of the WNW-ESE to NW-SE trending nodal planes and sub-set of the NNE-SSW to NE-SW trending nodal planes are discussed in this article.

4. RESULT OF STRESS ANALYSIS

The result of simple graphical method of Angelier and Mechler (1977) indicates the orientation of the maximum compression σ_1 in the direction NNW-SSE and the maximum extension σ_3 in the direction ENE-WSW (Fig.2). Both these principal axes are sub-horizontal to moderately dipping. In spite of different locations of events which focal mechanisms were used for stress analysis, well defined areas of the possible orientations of σ_1 and σ_3 axes show that the focal mechanism data set is more or less homogeneous.

The numerical test of whole collection of all nodal planes shows that there is not reduced stress tensor satisfying the all nodal planes. In the case of best solution, only 13 planes (from 14) fit this reduced stress tensor. Also during the stress analysis of sub-set containing the NNE-SSW to NE-SW trending nodal planes, solutions which satisfy all of these planes were not found. Only 6 planes (from 7) fit the reduced stress tensors computed in this case. Reason of this fact can be:

- real heterogeneity of data
- influence of the auxiliary nodal planes (which are not real fault)
- inaccurate determination of focal mechanisms

Similarity of the analysed focal mechanisms verifies a small importance of the real heterogeneity of data and of accuracy of focal mechanism determination in the case of applied stress analysis. It has to be taken into account, that only half of used 14 nodal planes represent real faults. It means that, most probable reason of the observed "heterogeneity" of the discussed collections of nodal planes is the influence

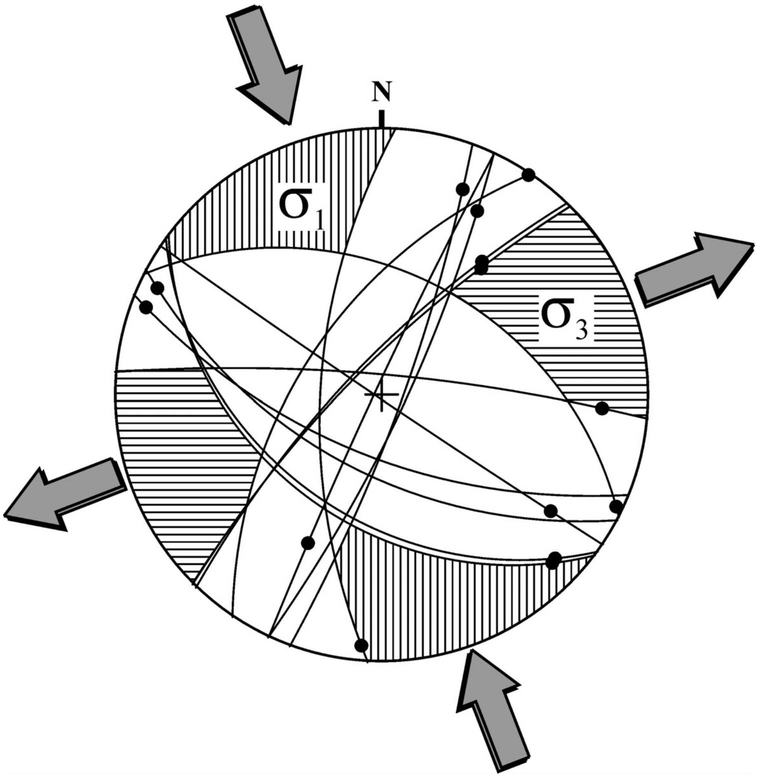

Fig. 2 Result of simple graphical method of Angelier and Mechler (1977). Vertical hatching – possible orientations of the maximum compression σ_1, horizontal hatching – possible orientations of the maximum extension σ_3 (Lambert projection, lower hemisphere).

of the auxiliary nodal planes. Analysis of the sub-set of WNW-ESE to NW-SE nodal planes produces well result which demonstrates the homogeneity of this sub-set. Observed results of stress analysis can be explained by assumption that some of the NNE-SSW to NE-SW trending nodal planes are not real faults and that some of these auxiliary nodal faults do not satisfy the real stress conditions. Thus, at least some of WNW-ESE to NW-SE trending nodal planes (but not necessarily all of them) represent real faults. This result of stress analysis show that "sudetic" faults are really active up to recent in the Jeseníky region.

Result of stress analysis of the WNW-ESE to NW-SE trending nodal planes indicates that the maximum compression σ_1 is sub-horizontal and its orientations is NNW-SSE. The maximum extension σ_3 is gently dipping to ENE (Fig.3). The acceptable solutions have small value of the shape ratio (Fig.4). Almost same result (difference is only in the distribution of the shape ratio of the acceptable tensors) was found also in the case of solutions satisfying at least 50% of all nodal planes. In the case of the NNE-SSW to NE-SW trending nodal planes, the result of stress analysis differs from other discussed solutions only in dip of the maximum compression and in the distribution of the shape ratio. The maximum extension σ_3 is gently dipping to ENE but the maximum compression σ_1 is medium to steeply dipping to NNW or NW in this case. The value of shape ratio is high. But the data set of the NNE-SSW to NE-SW trending nodal planes is "heterogeneous", their analysis is affected by auxiliary nodal planes which are not real faults. That is why the solutions with sub-horizontal or only gently dipping maximum compression σ_1 are more reliable.

5. CONCLUSION

The results of discussed stress analysis of the focal mechanisms show NNW-SSE maximum compression σ_1 and WSW-ENE maximum extension σ_3 in the Jeseníky region. Both σ_1 and σ_3 axes are sub-horizontal or only gently dipping. This stress field allows the easy reactivation not only of the steep WNW-ESE to NW-SE trending "sudetic" faults but also of the contingent steep NNE-SSW trending faults. The reactivation of the NNE-SSW faults becomes less easy with decreasing value of dip.

The found orientations of the principal stress axes well correspond with published orientations of the horizontal stresses which were studied using breakouts (Peška, 1992) and using hydrofracturing method (Staš et al., 1997) in the Czech part of the

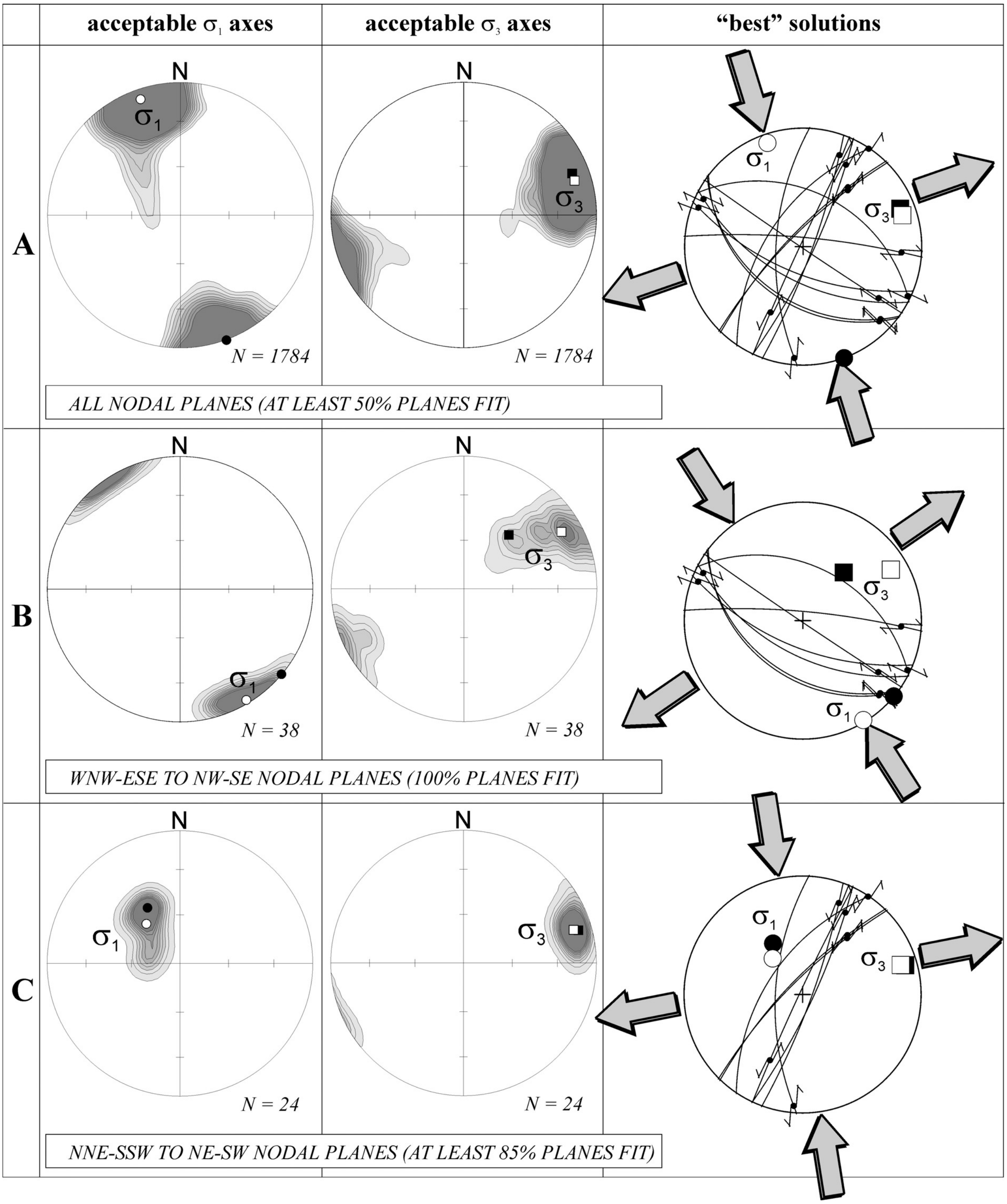

Fig. 3 Contour diagrams of acceptable orientations of principal stress axes computed by the program BRUTE3 (Hardcaste and Hills, 1991) and diagram of the "best" computed orientations of principal stress axes (Lambert projection, lower hemisphere), A - result computed for all nodal planes (50% planes fit), B – result computed for WNW-ESE to NW-SE nodal planes (100% planes fit), C – result for NNE-SSW to NE-SW nodal planes (85% planes fit): white circle – eigenvector of all acceptable orientations of the σ_1 axis, black circle – best solution of the σ_1 axis; white square – eigenvector of all acceptable orientations of the σ_3 axis; black square – best solution of the σ_3 axis; N – number of acceptable solutions; great circles – nodal planes used for stress analysis; grey arrows – orientations of principal horizontal stresses.

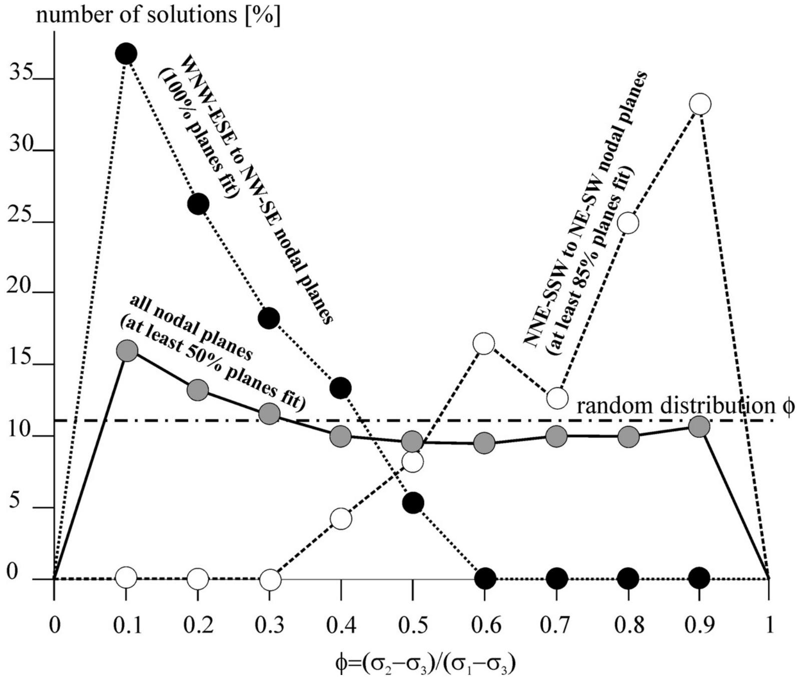

Fig. 4 Histogram of distribution of acceptable resulting shape ratios f: grey circles – result of analysis of all nodal planes (50% planes fit), black circles – result of analysis of WNW-ESE to NW-SE nodal planes (100% planes fit), white circles – result of analysis of NNE-SSW to NE-SW nodal planes (85% planes fit).

Upper Silesian Basin. Similar orientations of recent principal stresses are known also from other part of the Bohemian Massif (see Havíř, 2000; Peška, 1992; Reinecker and Lenhardt, 1999). NNW-SSE orientation of the maximum compression agree with the predominant NW-SE or NNW-SSE orientation of the largest horizontal principal stress in the Central Europe in the front of Alps and Western Carpathians (see Müller et al., 1992).

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