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JOINTING IN THE SILESIAN NAPPE (OUTER CARPATHIANS, POLAND) — PALEOSTRESS RECONSTRUCTION

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Abstract: The joint network in the Silesian Nappe is composed of a shear system (diagonal sets — S_R, S_L) — striking in the present position at high angles to map-scale fold axes, a single extension set T — striking sub-perpendicular to these axes, fold-parallel joints L and L' striking parallel or at small angles to map-scale fold axes. For palaeostress reconstructions penetrative S_R, S_L and T joint sets were analysed from 197 outcrops. In the palaeostress analysis the angular difference between the σ_{Hmax} directions calculated from shear (S_R, S_L) and extension T joints is notable. The angular difference between these σ_{Hmax} directions suggests that it is a result of a slight tectonic bending of the investigated Silesian Nappe arc, which took place between the nappe thrusting phase and the proceeding uplift phase of this part of the Outer Carpathian arc.

Key words: Miocene, Oligocene, Outer Carpathian arc, Silesian Nappe, tectonic bending, shear and extensional joints, paleostress.

Introduction

The main objective of this paper is the general description and determination of the origin of the joint network in the Polish part of the Silesian Nappe (Fig. 1A), as well as a tentative reconstruction of paleostresses responsible for the creation of this network. It was also tested in Ukraine and in Romania (Fig. 1B).

This paper continues the research on jointing initiated in the Polish part of the Outer Carpathian arc, for example, by Książkiewicz (1968), Tokarski (1975), Henkiel & Zuchiewicz (1988), Aleksandrowski (1989), Mardal (1995), Zuchiewicz & Henkiel (1995), Mastella et al. (1997), Rubinkiewicz (1998), Zuchiewicz (1998), Mastella & Zuchiewicz (2000) and in the Inner Carpathians by Boretti-Onyszkiewicz (1968).

Penetrative systematic fractures, cutting singular beds without offset related to shear or only with a marked tendency for offset, generally perpendicular to bedding and at spacing roughly equal to bed thickness (Mastella 1972) are analysed in the paper. They can be entirely referred to as joints (Jaroszewski 1972; Hancock 1985; Dadlez & Jaroszewski 1994; Dunne & Hancock 1994).

Geological setting

The geological structure of the Polish part of the Silesian Nappe is well known (Książkiewicz 1977; Ślączka 1971), and documented by detailed maps at the scale of 1:50,000, as well as general maps at the scale of 1:200,000 (Sokołowski 1959a; Świdziński 1958a; Burtan et al. 1981; Golonka et al. 1979; Ślączka & Żytko 1979). According to these analyses, the Silesian Nappe comprises strongly deformed folds, imbricate thrust zones and faulted shaly-sandstone flysch beds, ranging in age from the Cretaceous to the Miocene (Figs. 2, 3).

Methods

The observations of joints were carried out in single large outcrops or in series of outcrops typically located in stream bottoms, rarely within quarries. Measurements were taken from sandstone and claystone beds of varying age, thickness and lithology. Measurements from 197 outcrops within the Silesian Nappe were subject to further analysis. Some of them were already studied earlier (Mastella et al. 1997).

The analysis is based on data from selected outcrops located in the Silesian Nappe. Joint planes were measured outside fault zones within the first order regional folds trending in accordance with the Carpathian arc.

The measurement resolution was ±2°. In each outcrop 50 to 120 joint surfaces were measured. According to earlier papers (Mastella 1988; Zuchiewicz 1997; Rubinkiewicz 1998) this number constitutes a statistically representative set for joint analysis.

In interpretations of the joints formation, the authors rely on the uplift model, where the main assumption is that rocks could retain residual strain energy (Price 1959, 1966).

Following Price (1959, 1966), Książkiewicz (1968), Jaroszewski (1972) and Aleksandrowski (1989) the majority of the joint sets had a prefolding origin (Sheperd & Huntington 1981) and they were controlled by the action of residual compressive tectonic stresses and tensile stresses, which tend to develop during uplift.

This is indicated by the fact that the joints of a single set with variable strike in fold limbs, attain the same orientation after the rotation of fold axis and fold limbs to horizontal, and the rotation of beds in limbs to horizontal about the bedding strike. This origin is also testified by the formation of jointing in poorly lithified horizontal beds (Mastella 1988) and the displacement of joints by flexural slip during folding (Mastella & Ozimkowski 1979).

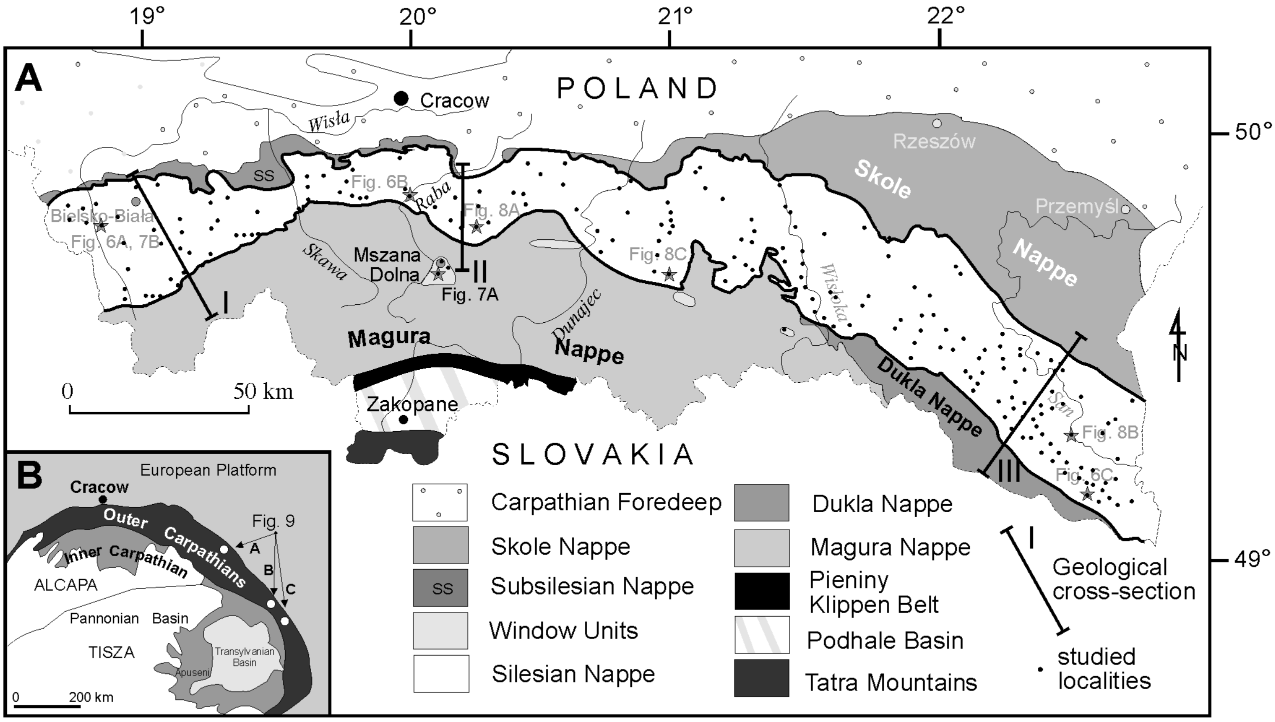

Fig. 1. A — Tectonic sketch of the Polish part of the Outer Carpathians (after Książkiewicz 1972), **B** — Tectonic sketch of the Carpathian-Pannonian region (after Linzer 1996).

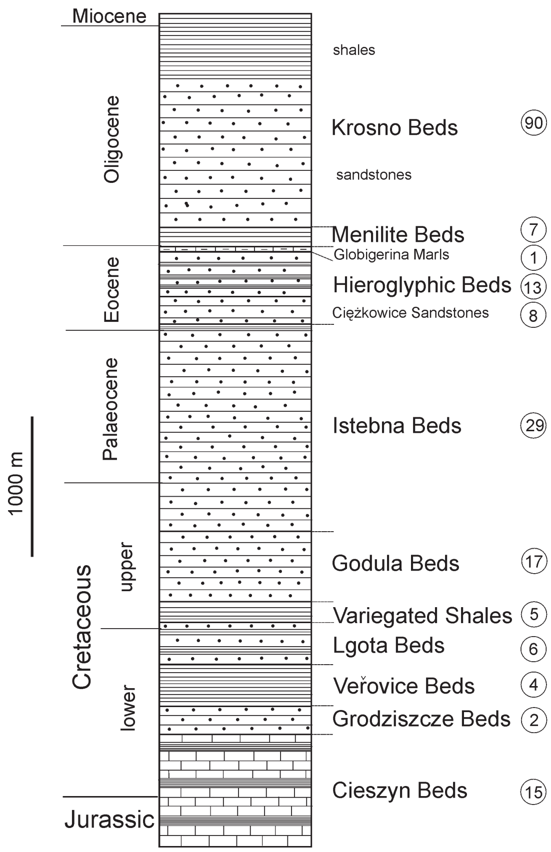

Fig. 2. Lithostratigraphic column of the Silesian Nappe in the Polish part of the Outer Carpathians (simplified after Unrug 1969; Żytko 1973; Ślączka & Kamiński 1998). The number of studied localities for particular lithostratigraphic beds are given in circles.

In consequence, following, for example, Murray (1967), Książkiewicz (1968) or Hancock & Al-Kadhi (1982), diagrams of measurements after back tilting of beds to horizontal were also prepared (Fig. 4). The stereograms with plotted contours of the normals to joint surface show a unified orientation of the particular joint sets. Along with rose diagrams, these projections made a basis for recognition of the dominant azimuths of joint sets. In further calculations (Fig. 4) (and see Mastella & Zuchiewicz 2000 — Fig. 5) this allows determination of the orientation of the maximum horizontal compressive stress axes (σ_{Hmax}) for particular joint sets.

To determine regional trends, for selected data the trend surface analysis tool was applied (e.g. Davis 1973). It helped to isolate regional anomalies by computing trend residuals. The residuals allowed determination of where differences from the regional background are localized. To smooth out the data the small differences were ommitted. The residuals were computed for the first polynomial order, representing the difference between observed values and trend values. The "order" of a trend surface equation refers to the highest values of the exponents used in the equation. On the basis of this information, a flat trend surface map was created.

Characteristics of the joint network

At regional scale the joint network comprises five sets of fractures (Figs. 5, 6A), which are, however, rarely all encountered together in individual outcrops. Typically, only two or three sets occur in a single outcrop (Fig. 7). Particular sets show relatively stable strike in relation to the strike of regional folds. In their present position two joint sets ($\mathbf{S_R}$ and $\mathbf{S_L}$) repre-

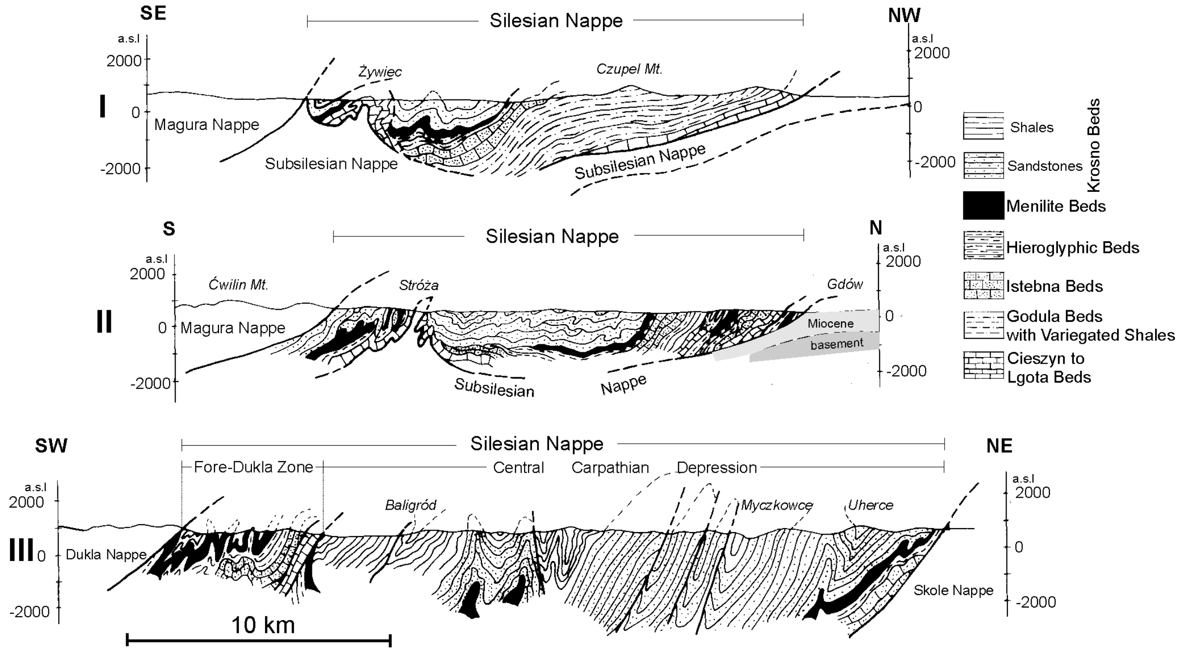

Fig. 3. Geological cross-sections through the Silesian Nappe (simplified after Sokołowski 1959b; Świdziński 1958b); for location see Fig. 1.

sent diagonal joints (Figs. 5, 7), whereas set **T** is almost perpendicular to the regional folds orientation. The remaining sets **L** and **L'** are sub-parallel to fold axis (Fig. 5). Due to their usefulness for paleostress reconstruction (Mastella et al. 1997; Mastella & Zuchiewicz 2000) the $\mathbf{S_R}$, $\mathbf{S_L}$ and **T** joint sets were mainly analysed.

The S_R and S_L sets of the diagonal joint system

Both sets are characterized by similar morphological features. They are generally perpendicular to the bedding. Fractures several millimetres wide are filled with calcite (Fig. 8). Both surfaces of a single non-mineralized joint fracture resemble mould and cast, or have plume structures with axes parallel to the joint/bedding surface intersection present on them. Even on surfaces belonging to one joint set the axes of the S-type plumes (Engelder 1985) are variably oriented, which indicates the random sense of the initial propagation of joints (Parker 1942). The presence of such structures is attributed to the extensional opening of these fractures (Bankwitz 1965, 1966; Engelder 1985).

Traces of joints on the bedding surfaces are typically rectilinear (Fig. 7). Locally, instead of a rectilinear trace, an *en echelon* shear array can occur. These fractures correspond to low angle (R) Riedel shears (terminology after Riedel 1929; Bartlett et al. 1981) (Fig. 8B), occasionally passing into continuous fractures (Fig. 8A,C). They probably represent incipient forms preceding the formation of continuous joint fractures of the analysed system. Riedel shears included within the *en echelon* arrays, cut only several millimetres into the beds. If the loosening of the joints was along the *en echelon* array, fringe structures appear on their surfaces.

Despite the different orientation in particular outcrops, both sets cross at acute angles within 45° –75° (Figs. 6, 7, 9), dominantly trending at 60°–69°.

T set

Joints of this set are distinctly different from joints of the diagonal system. Typically, the joint surfaces are sub-vertical. When, however, the fold axes are tilted, they are non-kathetally oriented. Traces of the intersection with bedding are irregular, mostly curvilinear, without *en echelon* fractures. Mainly S-type plume structures occur. The plume axes are commonly horizontal, but in rare cases they have different orientations.

Opening of these extension fractures is larger than in the case of other fractures. They are also less commonly filled with calcite, which, if present, is often crumbled (Tokarski et al. 1999). Joint surfaces are usually uneven and they lack fringe structures.

L and L' sets

Within the entire Silesian Nappe arc, joints sub-parallel to the orientation of the regional folds occur in two sets. Joints of set **L** are sub-parallel to map-scale fold axes, whereas joints of set **L'** strike at low angles (up to 20°) to these axes (Aleksandrowski 1989) (e.g. Fig. 6A).

Both sets display significant similarities with respect to joint surfaces and bed/joint intersection traces. In both sets there are no indications for their shear origin. Typically, the traces are curvilinear, fading, discontinuous and superimposed on one another (Fig. 7B). The fissures are several millimetres wide, rarely filled with calcite. The surfaces of a single fracture are usually of the mould and cast type or with plume structures. These are particularly common on the surfaces of most **L'** joints, in contrast to their rare occurrence on **L** joints. The latter case can be observed in the hinge zones of large folds, where the joints bear features of typical radial fractures (Jaroszewski 1980; Price & Cosgrove 1990).

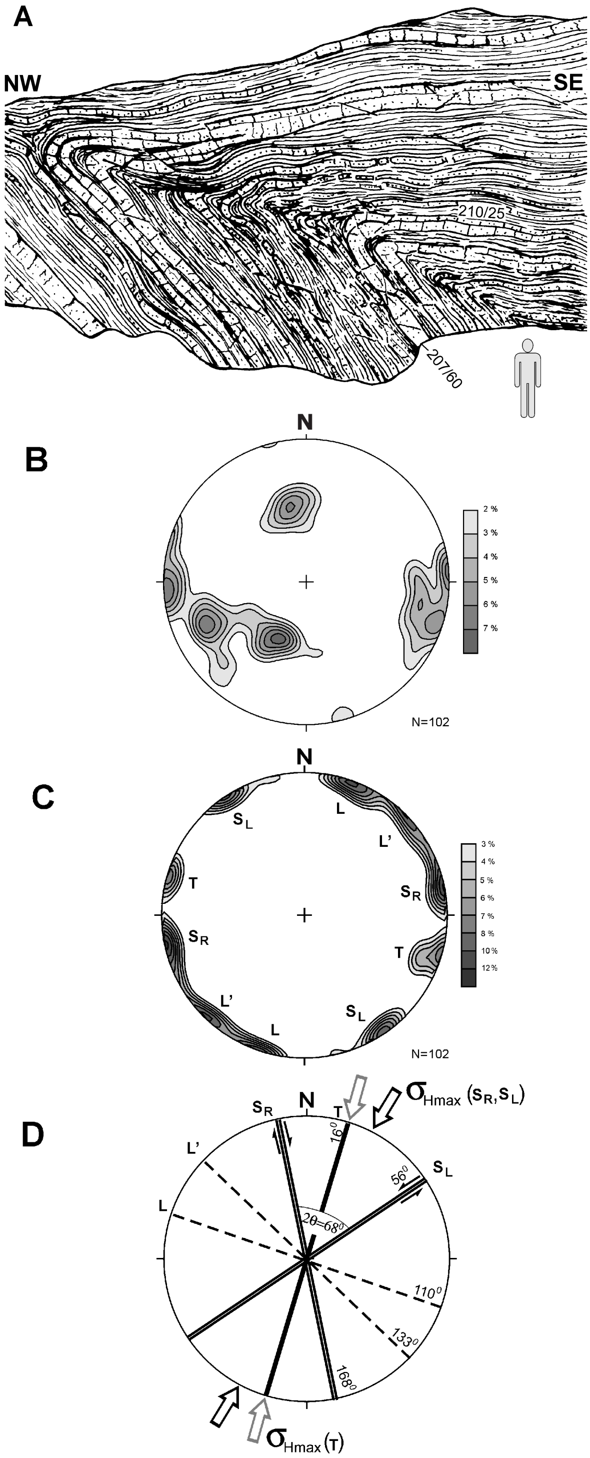

Fig. 4. Scheme showing the method of determining the dominating directions and parameters of the joint network, based on measurements in a recumbent fold from the Krosno Beds in the Biecz quarry (**A**). Diagrams with contours of joint planes (**N** — number of measurements): **B** — before back tilting of beds to horizontal, **C** — after back tilting of beds to horizontal, **D** — directions of join sets (shear system: $\mathbf{S_R}$ — dextral, $\mathbf{S_L}$ — sinistral; **T** — transversal; **L** and **L'** — longitudinal sets) inferred from the dominants of Fig. 4C (values of azimuths of the dominating directions of sets are given; the arrows indicate offset along the diagonal system). **E** — Selected parameters of the joint network: double value of the shear angle 2Θ, σ_{Hmax} — axis of maximum compressive stress. For other explanations see text.

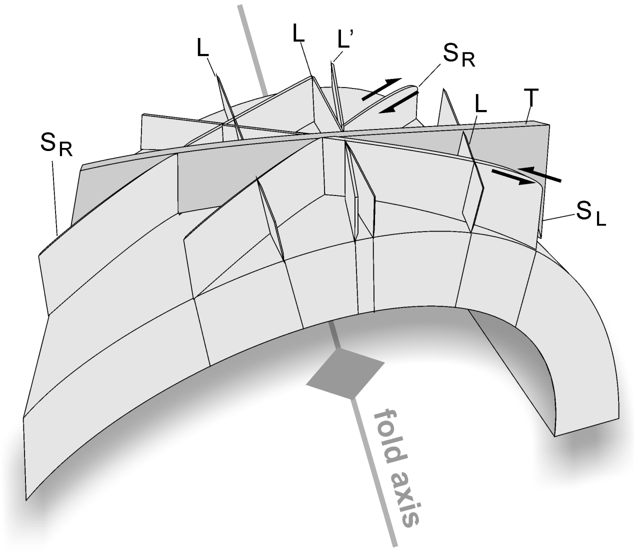

Fig. 5. Scheme of the joints pattern in folded sandstones (diagonal shear system: $\mathbf{S_R}$ — dextral, $\mathbf{S_L}$ — sinistral, **T** — transversal, **L** and **L'** — longitudinal sets) (after Książkiewicz 1968 — modified). For other explanations see text.

Regional variability of the orientation of diagonal (S_R, S_L) and transverse (T) joint sets

Despite the small variability of orientation within particular outcrops, all the described joint sets display a large regional variability (Figs. 6, 9).

Set $\mathbf{S_R}$ of the diagonal system in the westernmost part of the investigated part of the Silesian Nappe is W-E trending (dominant class 270–284°) (Table 1, Fig. 6A), gradually changing to 320–334° between the Skawa and Raba rivers, to an almost meridional orientation between the Dunajec and Wisłoka rivers (Fig. 7A) and NNE-SSW (dominant class 10–19°) in the easternmost part of the area (Fig. 6C).

Similarly, azimuths of $\mathbf{S_L}$ joints change from 335–349° in the westernmost part of the investigated section of the Silesian Nappe, N-S between the Wisła and Skawa rivers, NW-SE between the Raba and Wisłoka rivers to almost E-W (dominant class 75–84°) in the easternmost part of the area (Table 1). Therefore both $\mathbf{S_R}$ and $\mathbf{S_L}$ sets change their azimuths from the west to the east at about 100°.

T joints change their azimuths in a narrower range, ca. 75°, from ca. 320° in the western part of the area, ca. 0° in the central

Table 1: Variability of joint parameters.

	W part		Middle part		E part			
Azimuths	**Wisła**	**Wisła-Skawa**	**Skawa-Raba**	**Mszana**	**Raba-Dunajec**	**Dunajec Wisłoka**	**Wisłoka-Osława**	**Osława**
S_R	270÷284	285÷299	320÷334	335÷349	340÷354	355÷4	0÷9	10÷19
S_L	335÷349	350÷4	20÷34	20÷34	30÷54	45÷54	60÷69	75÷84
σ_{Hmax} (S_R,S_L)	310	325	357	2	12	27	35	47
σ_{Hmax} (T)	320	330	0	357	8	20	25	35
Δ*	-10	-5	-3	+5	+4	+7	+10	+12

* Δ magnitude of angular difference between the σ_{Hmax} directions calculated from shear joints (S_R, S_L) and extension joints (T)

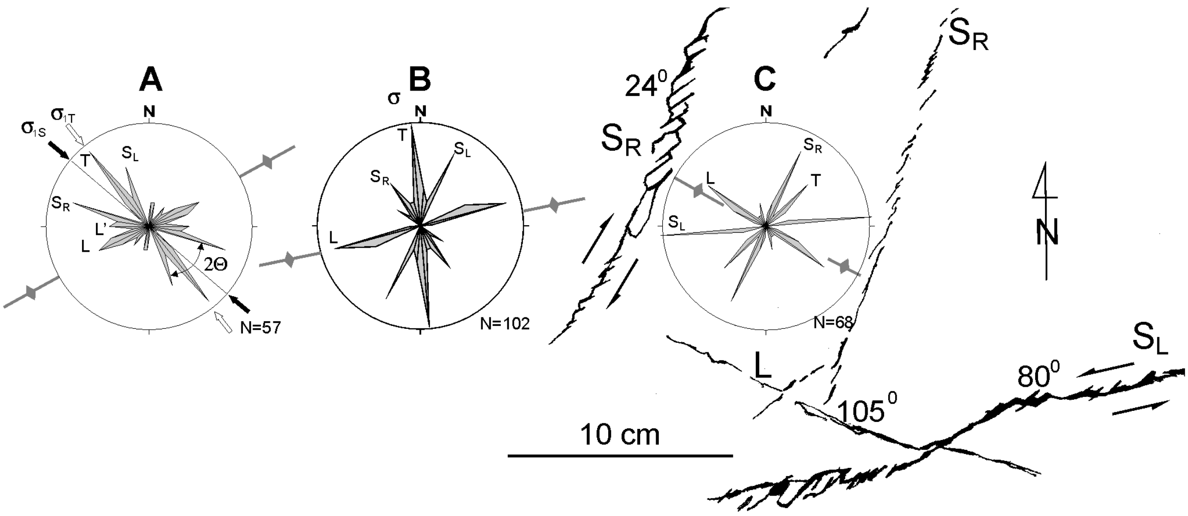

Fig. 6. Rose diagrams of joints in the Silesian Nappe: **A** — western part (Wisła region), **B** — middle part (Raba river), **C** — eastern part (Rabski stream); the sketch displays a sandstone bed with joints. **N** — number of measurements; for other explanations see Fig. 4. For location of diagrams see Fig. 1A.

part, 20–25° east of the Dunajec river and ca. 35° in the easternmost parts of the investigated area (Table 1). Their orientation is perpendicular to the regional fold axes (Mastella et al. 1997).

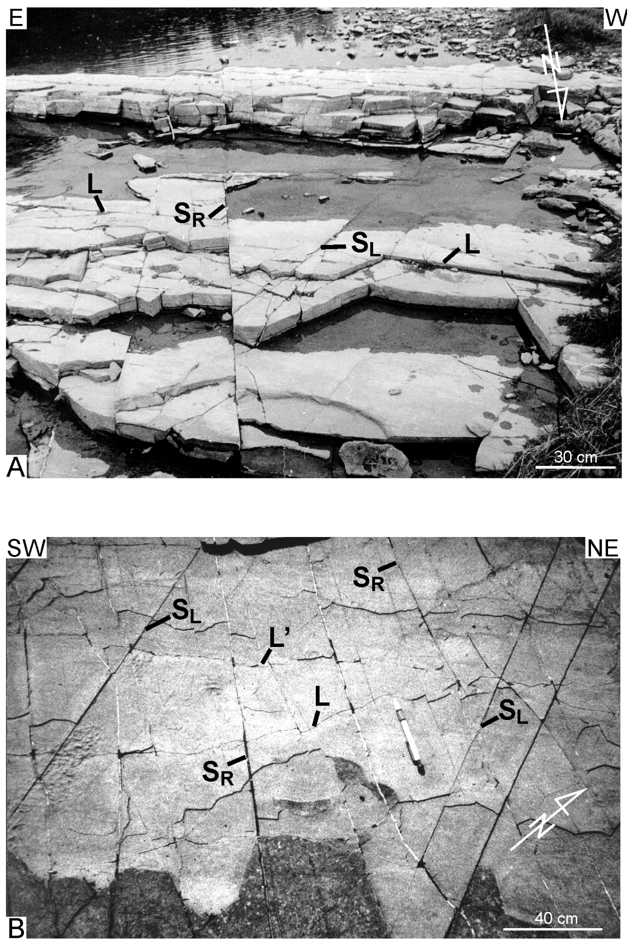

Fig. 7. Joints in a sandstone bed — **A** in the Mszana Dolna region (Mszanka stream); **B** — near Cieszyn. For location see Fig. 1. For other explanations see Fig. 4.

Origin of joints

Diagonal system S_R, S_L

The presented characteristic of both sets indicates that they were controlled by the action of residual stresses which reflect conditions in the particular tectonic phase (Price 1959, 1966).

During the incipient stage the joints were formed as initial shear surfaces (Jaroszewski 1972). In turn, their opening took place (Price 1959, 1966; Książkiewicz 1968; Jaroszewski 1972; Engelder 1985) in the extensional mode, when residual stresses acted (Zuchiewicz 1998; Mastella & Zuchiewicz 2000). The pattern of *en echelon* and feather fractures indicates that $\mathbf{S_R}$ and $\mathbf{S_L}$ joints represent dextral and sinistral shears, respectively (Figs. 6C, 8B). Abutting and cutting relationships (Fig. 8A,C) indicate (Jaroszewski 1980; Mandl 1988; Engelder 1989) that they are coeval. In this case the acute dihedral angle between these sets represents the double value of the shear angle (2Θ) (e.g. Handin et al. 1963; Hancock 1985).

Additionally, the uniform shear character of both sets within the investigated part of the Silesian Nappe and the stable orientation of the acute bisector between these two sets indicate that both $\mathbf{S_R}$ and $\mathbf{S_L}$ sets form a conjugate strike-slip system developed in a triaxial shear stress field ($\sigma_1>\sigma_2>\sigma_3$) (Fig. 10). This is in line with earlier observations from the Silesian Nappe (Mastella et al. 1997), as well as from the Dukla Nappe (Mastella & Zuchiewicz 2000).

Transverse T set

The common occurrence of fracture structures pointing to their extensional development (Bankwitz 1965, 1966), character of fissures and their filling, lack of shear indicators reveal the extensional development of this set in the analysed area (Książkiewicz 1968; Jaroszewski 1972; Aleksandrowski 1989; Tokarski et al. 1999; Mastella & Zuchiewicz 2000). On the basis of their perpendicular orientation to regional fold

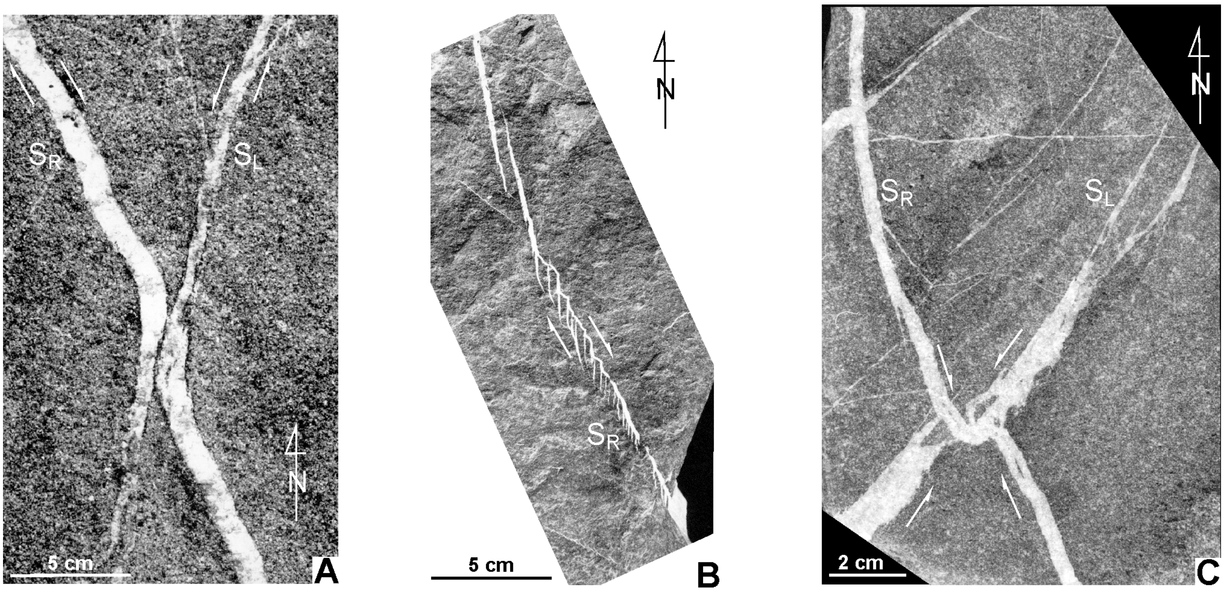

Fig. 8. Diagonal system of joints in a sandstone bed: **A** — in the Szczyrzyc region, **B** — in the San river region, **C** — in the Sękówka river region. For location see Fig. 1. Other explanations as in Fig. 4.

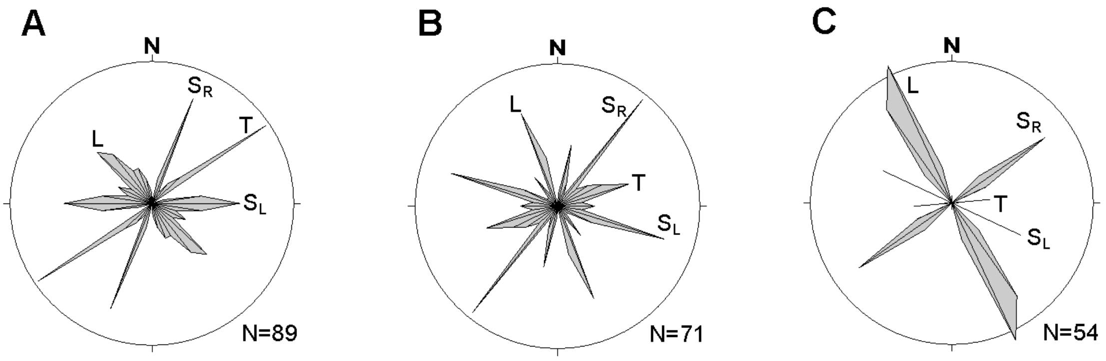

Fig. 9. Rose diagrams of joints from outcrops: **A** — in the Opór river region (Skole — Ukraine), **B** — in the Cacica stream region (Humorolui Mt. — Romania), **C** — in tributary of the Bistriti river region (Bacau — Romania). For location see Fig. 1A. Other explanations as in Fig. 4.

axes, and on theoretical (Price 1959, 1966; Jaroszewski 1972) and regional studies (Aleksandrowski 1989; Zuchiewicz 1998; Mastella & Szynkaruk 1998; Mastella & Zuchiewicz 2000), **T** joints are interpreted as a result of the parallel action of maximum, compressional principal stress and of the minimum, tensile principal stress acting perpendicular to this orientation (Fig. 10).

The prevailed presence of horizontal plume axes on the planes of the **T** joints and the discussed geometrical relationship between the **T** joints and joints of other sets indicate that the **T** joints are younger than the **S_R**, **S_L** sets and probably the **L** set. The regional tendency to vertical orientation of the surfaces of the **T** joints points to a late- or even post-folding formation of these fractures.

L and L' sets

Taking into account the tensional character of the **L** joints and their relationship to the hinge zones of regional folds, it

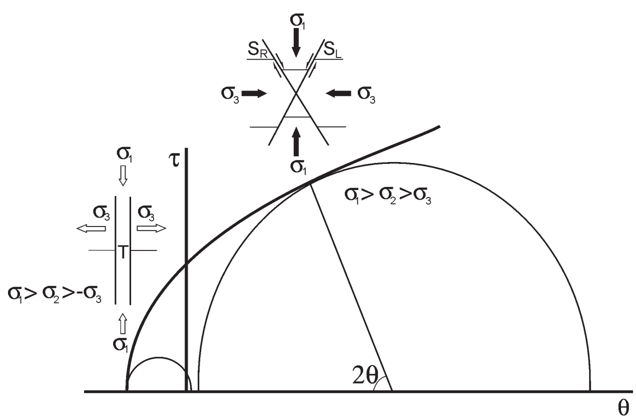

Fig. 10. Theorethical Mohr's stress circles representing rock stress conditions for S_R, S_L joints as well as T set development (after Price & Cosgrove 1990 — with modifications).

can be assumed that their formation is linked with early buckling of beds (Książkiewicz 1968; Aleksandrowski 1989). The origin of the **L'** set is unclear.

Reconstruction of the joint stress fields

The presented description shows that particular sets and systems of the regional joint network are of different origin. Therefore they can be linked with different stress fields of different age. The type and orientation of the stress fields is somehow recorded within the joints, and following, for example, Jaroszewski (1972) and Engelder (1985), and for the Polish part of the Outer Carpathians also Książkiewicz (1968), Zuchiewicz (1998), Rubinkiewicz (1998), Mastella et al. (1997), Mastella & Zuchiewicz (2000), it may be reconstructed, particularly from the diagonal ($\mathbf{S_R}$, $\mathbf{S_L}$) and transverse **T** sets.

Diagonal system S_R, S_L

The oldest diagonal system developed within horizontal beds in compressional conditions with positive $\sigma_1 > \sigma_2 > \sigma_3$ axes. The orientation of these stress axes can be reconstructed after back tilting of beds to horizontal (Bucher 1920, 1921; Ramsay & Huber 1987).

The axis of the maximum horizontal compressive stress, marked as σ_{Hmax} (S_R, S_L) can be estimated as the bisector of the double shear angle 2Θ (e.g. Fig 6A,C, 8C, 9B) (e.g. Hancock & Al-Kadhi 1978, 1982). Its orientation points to a distinct regional variability along the Silesian Nappe arc (Mastella et al. 1997). The generalized trend σ_{Hmax} (S_R, S_L) is 310° in the westernmost part of the area, and changes through N-S orientations in the central part, to 35° in the east and up to 47° in the easternmost part (Table 1). Thus a fan-like σ_{Hmax} (S_R, S_L) trajectory pattern was formed, with an obtuse angle of ca. 100° and trajectories perpendicular to the bending of the Silesian Nappe arc (Mastella et al. 1997). Similar patterns were suggested for this part of the Outer Carpathians for the Early and Middle Miocene (Nemčok 1993, Fig. 9b–d; Fodor et al. 1999, Fig. 5b–c) and for many compressional orogens (e.g. Laubscher 1972; Tapponier & Molnar 1976; Angelier et al. 1986; Huchon et al. 1986).

Transverse T joints

The **T** joints formed during the final phase of thrusting of the Outer Carpathians. This suggests that the maximum compressive stress was still nearly horizontal during **T** joints formation.

As commonly recognized (e.g. Price 1959; Jaroszewski 1972; Hancock & Al. Kadhi 1978, 1982; Zuchiewicz 1998), the strikes of these joints determine the orientation of the maximum horizontal compressive stress, marked as σ_{Hmax} (T). The orientation of this axis in the westernmost parts of the investigated area has an azimuth of ca. 320°, and eastwards changes gradually to roughly N-S between the Skawa and Dunajec rivers, to ca. N35°E in the easternmost parts of the area (Table 1) (Mastella et al. 1997). Thus, as in the diagonal system, the σ_{Hmax} (T) trajectories form a fan-like pattern, however at a smaller angle, ca. 70°. This pattern was also recognized in the Central Carpathians from the Late Miocene (Nemčok 1993 — Fig. 9f) to the Quarternary (Fodor et al. 1999 — Fig. 6), and has recently been identified the Polish part of the Outer Carpathians (Jarosiński 1998).

In the paleostress analysis, the angular difference between the σ_{Hmax} directions inferred from shear joints and extension joints was noted. Estimation of the regional differences, based on the smooth trend surface map, for the residuals computed for the first polynomial order points to the occurrence of slight differences between these σ_{Hmax} directions (Fig. 11).

In the westernmost part of the investigated fragment of the Silesian Nappe arc, the σ_{Hmax} (S_R, S_L) is deflected ca. 10° westwards from the σ_{Hmax} (T). The angular difference gradual-

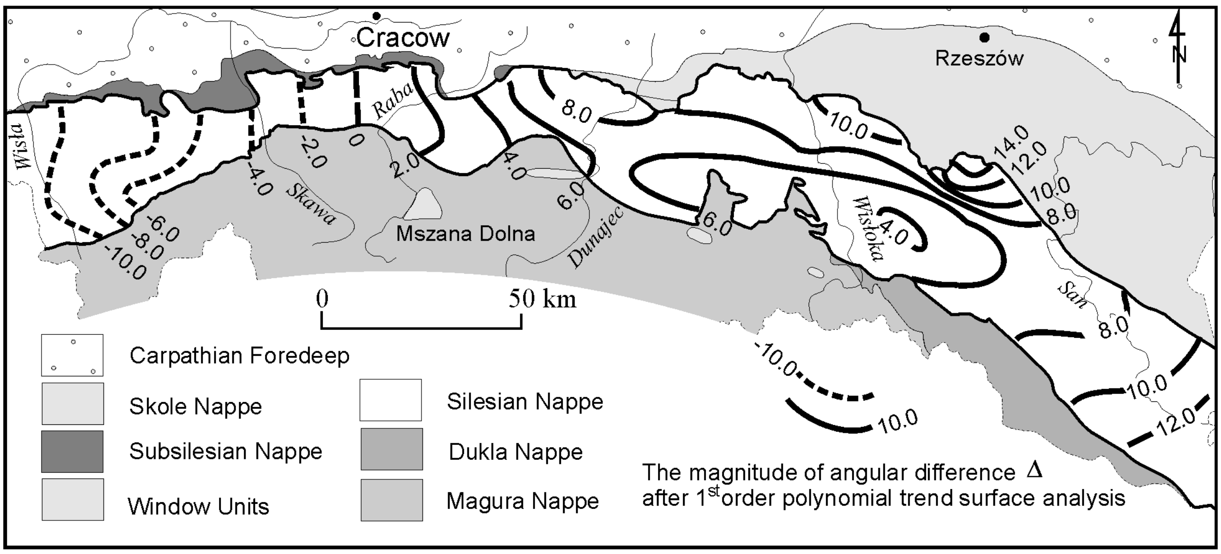

Fig. 11. Magnitude of angular difference between σ_{Hmax} directions inferred from the shear joints and extension joints, after 1st order polynomial trend surface analysis in the Polish part of the Silesian Nappe.

ly decreases eastwards and approximately at the Cracow meridian changes its orientation to ca. 12° eastwards in the easternmost part of the area (Table 1, Fig. 11). The identical tendency for the eastwards deflection of σ_{Hmax} (S_R, S_L) in relation to σ_{Hmax} (T) also occurs in the Polish part of the Dukla Nappe (Mastella & Zuchiewicz 2000). Comparison with data outside the Silesian Nappe from Ukraine and Romania suggests lack of angular differences (Fig. 9).

Conclusions

In the analysed part of the Silesian Nappe the joint network developed in several stages characterized by different stress orientation.

1. The beginning of the development of the joint network should be linked with the moment when the flysch rocks of the Outer Carpathians, still in horizontal position, were lithified enough to cumulate stresses resulting from the convergence of the European plate with microplates of Pannonia (Royden 1988), N Pannonia — ALCAPA (Alpine-Carpathian-Pannonian block system) (e.g. Csontos et al. 1992; Plašienka et al. 1997; Fodor et al. 1999), in a tri-axial stress field $\sigma_1>\sigma_2>\sigma_3$, with horizontal σ_1 and σ_3, and vertical σ_2 in original position. The general trend of the maximum horizontal compressive stress axis was N-S in this fragment of the Outer Carpathian arc (Tapponier 1977; Tokarski 1978; Fodor 1995; Fodor et al. 1999).

The shear joint system was initiated within horizontal beds in this stress field. In those places where the shear strength of the rocks was exceeded, $\mathbf{S_L}$ and $\mathbf{S_R}$ joints of this system appeared (Fig. 12 — I stage). According to Pescatore & Ślączka (1984) and Mastella (1988), this stage began in the Oligocene in the Silesian Nappe.

2. Along with the proceeding increase of N-S horizontal compression, folding began (Książkiewicz 1972), probably by the end Early Miocene–Ottnangian?, Karpatian (Oszczypko 1997, 1998). In wide fragments of the fold hinge zones, tension **L** joints with strikes parallel to the fold axes and features of radial fractures appear (Mastella & Zuchiewicz 2000). At the same time, along with the gradual uplift of the folded beds, $\mathbf{S_R}$ and $\mathbf{S_L}$ joints appeared as extension fractures, as a result of the relaxation of residual stresses. Such development of joints took place during the entire thrusting phase.

3. In the next phase, after the Middle Miocene, when the thrust front began to be fixed, the strong uplift of the analysed part of the Outer Carpathians commenced (Książkiewicz 1972; Żytko 1999; Fodor et al. 1999).

With the decrease of compression, the horizontal stress axis perpendicular to the maximum compressive axis attained negative values, what led to the formation of extension **T** joints (Fig. 12 — II stage) by extension sub-parallel to the Silesian

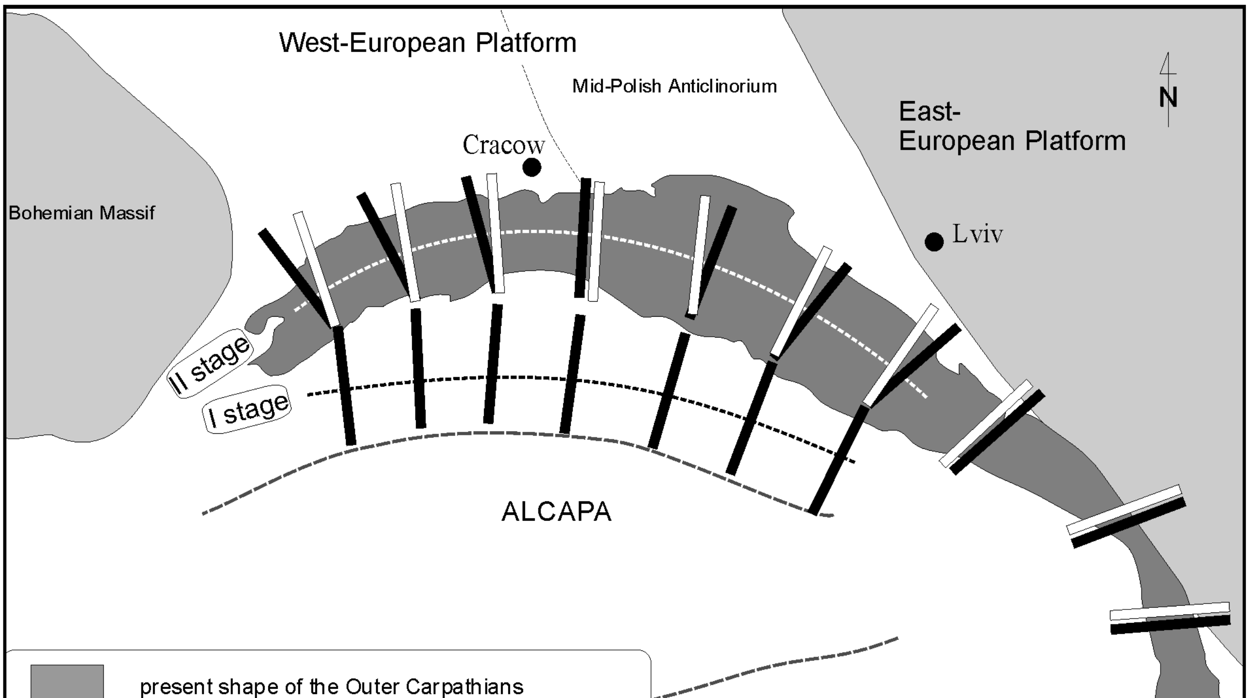

Fig. 12. Evolution of σ_{Hmax} trajectories in the Silesian Nappe — based on the shear joint system S_R and S_L and extension joint set T. (Sketch after Pożaryski 1979; Fodor et al. 1999; Kutek 2001 — simplified).

Nappe arc. This is a common feature in many collisional orogenic belts and in their forelands (e.g. Hancock & Bevan 1987; Julivert & Arboleya 1984; Dietrich 1989; Doglioni 1995; Nemčok et al. 1998a; Konon 2001).

The angular difference between σ_{Hmax} (S_R, S_L) and the σ_{Hmax} (T) orientations suggests that they reflect a slight tectonic bending of the investigated Silesian Nappe arc, which took place between the nappe thrusting phase and the phase of proceeding uplift of this part of the Outer Carpathian arc.

In the gradually bent Silesian Nappe arc, shear joints were rotated: counterclockwise (CCW) in the left part of the deformation belt, and clockwise (CW) in the right part of the deformation belt (Fig. 12 — II stage). In the thus bent Silesian Nappe arc **T** joints developed, as a result of extension sub-parallel to Outer Carpathian arc.

The tectonic bending of the Silesian Nappe in the final phase of its deformation is confirmed by the probable presence of a bending mechanism during the formation of this part of the Carpathian arc indented between the Bohemian Massif and the edge of the East-European Platform. It led to the CCW rotation of the Western Carpathians and CW rotation of the Eastern Carpathians, as can be concluded from the analysis of paleomagnetic data (e.g. Krs et al. 1991; Patrascu et al. 1994 and references therein; Márton & Fodor 1995 and data compiled by Fodor et al. 1999). Similarly, the oroclinal bending of the Inner Carpathians, after overthrusting of the Krížna Nappe (Kruczyk et al. 1992), confirm that the curvature of the Outer Carpathians originated due to tectonic deformations.

The same mechanism of the formation of the Carpathian arc can be inferred from structural data (e.g. Birkenmajer 1979, 1985; Marko 1993; Nemčok 1993; Nemčok & Nemčok 1994; Fodor 1995; Fodor et al. 1999; Mastella & Szynkaruk 1998; Nemčok et al. 1998a; Mastella & Zuchiewicz 2000; Konon 2001).

Test investigations in Ukraine and Romania have shown that the tectonic bending appeared only in the Polish part of the Outer Carpathians.

The method based on the estimation of the angular differences in the pattern of trajectories of maximum horizontal stresses for the $\mathbf{S_L}$ and $\mathbf{S_R}$ as well as the **T** joints allowed us to estimate the degree of bending of the Silesian Nappe between the development of the $\mathbf{S_L}$, $\mathbf{S_R}$ joints sets and the **T** joints set.

The constant stress field in the Silesian Nappe during the formation of joints points to the lack of considerable reflection of stress orientation changes in the investigated fragment of the Carpathian arc, induced by the relocation of the subduction zone towards the Eastern Carpathians due to the roll-back mechanism (e.g. Burchfiel & Royden 1982; Nemčok et al. 1998a,b; Fodor et al. 1999).

The probable lateral eastward escape of part of the Eastern Alps (Ratschbacher et al. 1989, 1991; Fodor 1995), as well as the Carpathians (Nemčok 1993) has left more significant traces in the Inner Carpathians.

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