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Non-planar strike-slip Gnieździska – Brzeziny fault (SW Mesozoic margin of the Holy Cross Mountains, central Poland)

LEONARD MASTELLA & ANDRZEJ KONON

Institute of Geology, University of Warsaw, Al. Żwirki i Wigury 93, PL-02-089 Warsaw, Poland.
E-mails: mastella@geo.uw.edu.pl, konon@geo.uw.edu.pl

ABSTRACT:

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Based on the analysis of detailed geological maps, air photos, radar images and tectonic mesostructures the geometry and mechanism of formation of the Gnieździska-Brzeziny fault have been determined. The fault represents a typical example of a dextral strike-slip fault occurring in the SW margin of the Holy Cross Mountains. The trace of the fault is curvilinear-sinusoidal, which produced restraining and releasing bends as well as restraining stepovers.

Key words: Non-planar dextral strike-slip fault, Restraining and releasing bends, Restraining stepover, Transpression, Holy Cross Mountains.

INTRODUCTION

Along its contact with the Palaeozoic core (Text-fig. 1), the southwestern Mesozoic margin of the Holy Cross Mountains is cut by a series of large dislocations sub-parallel to the Mesozoic regional structures (CZARNOCKI 1938, KUTEK & GŁAZEK 1972, STUPNICKA 1972). Generally, these dislocations were referred to as dip-slip faults (STUPNICKA 1972; HAKENBERG 1973, 1974; FILONOWICZ 1967, 1968; FILONOWICZ & LINDNER 1986). Only some authors (JAROSZEWSKI 1972, KUTEK & GŁAZEK 1972, KOWALSKI 1975, STUPNICKA 1972) suggested that they can also have a strike-slip component.

A representative example of such structures is a fragment of a large regional fault marked already on CZARNOCKI's map (CZARNOCKI 1938), analysed along transect of ca. 27 km, from Gnieździska in the west to Brzeziny in the east (Text-fig. 2A).

This paper is focused on determining the geometry of this part of the fault and the occurrence of the strike-slip component as well as the mechanisms and stages of its development.

METHODS

The analyses were based on detailed mapping at the scale 1:10 000, locally also at the scale 1:1000. The maps were supplemented with analysis of the morphology at the scale 1:25 000, interpretation of air photos at the scale 1:18 000 and radar images at the scale 1:100 000 (Text-fig. 3). Side-looking airborne radar (SLAR) made the radar images at wavelengths of 2.6 cm. The transmitted and received signal was horizontally polarised. The system's resolution was ca. 30 m. This method omits the effects of rock debris and vegetation cover (e.g. DOKTÓR & GRANICZNY 1982), allowing precise observation of the fault zones (MASTELLA & SZYNKARUK 1998). A dense network of faults transverse or oblique to the axes of regional structures cuts the

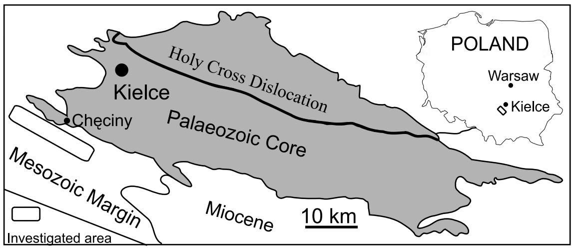

Fig. 1. Location of the investigated area

analysed area (HAKENBERG 1973, FILONOWICZ 1967, FILONOWICZ & LINDNER 1986). Not being genetically linked with the dislocation under discussion, these faults are omitted in this study.

In order to determine the types of faults and the geometry of particular parts of the first order faults, the authors relied on mesostructure analysis, that is analysis of fault planes with associated striae and stylolites. For palaeostress reconstruction fault-slip analysis was applied according to e.g. ANGELIER (1979, 1984). Fault planes were shown as great circles with slip vectors of the hanging wall (e.g. ANGELIER 1979, 1984). Data on stereograms were projected on the lower hemisphere.

The measurements were collected along first order fault zones in outcrops and quarries. In regions with a large variety of palaeostress trajectories the measurements were more densely spaced.

Correlation with tectonic patterns detected on radar images and geological maps (e.g. CZARNOCKI 1938, STUPNICKA 1972, OZIMKOWSKI & *al.* 1999) supported the determinations of the palaeostress axes. In the reconstruction of the palaeostress axes based on simple geometrical analysis on strike-slip conjugate sets it was assumed that the maximum compressive stress axis corresponds to the bisects of the acute angle between the fault sets and that it is horizontal (e.g. ANGELIER & *al.* 1986).

Stylolitic peaks produced by solution phenomena were also analysed in particular outcrops. Stylolites are common small structures within limestones of the Mesozoic margin of the Holy Cross Mountains. Several sets of stylolites were observed in the SW part of the Mesozoic margin (WARTOŁOWSKA 1972, ŚWIDROWSKA 1980, KONON & MASTELLA 2001). For palaeostress analysis based on azimuths of columns (e.g. BLAKE & ROY 1949, RISPOLI 1981), only the stylolites not linked with the folds development were applied (III set of KONON & MASTELLA 2001).

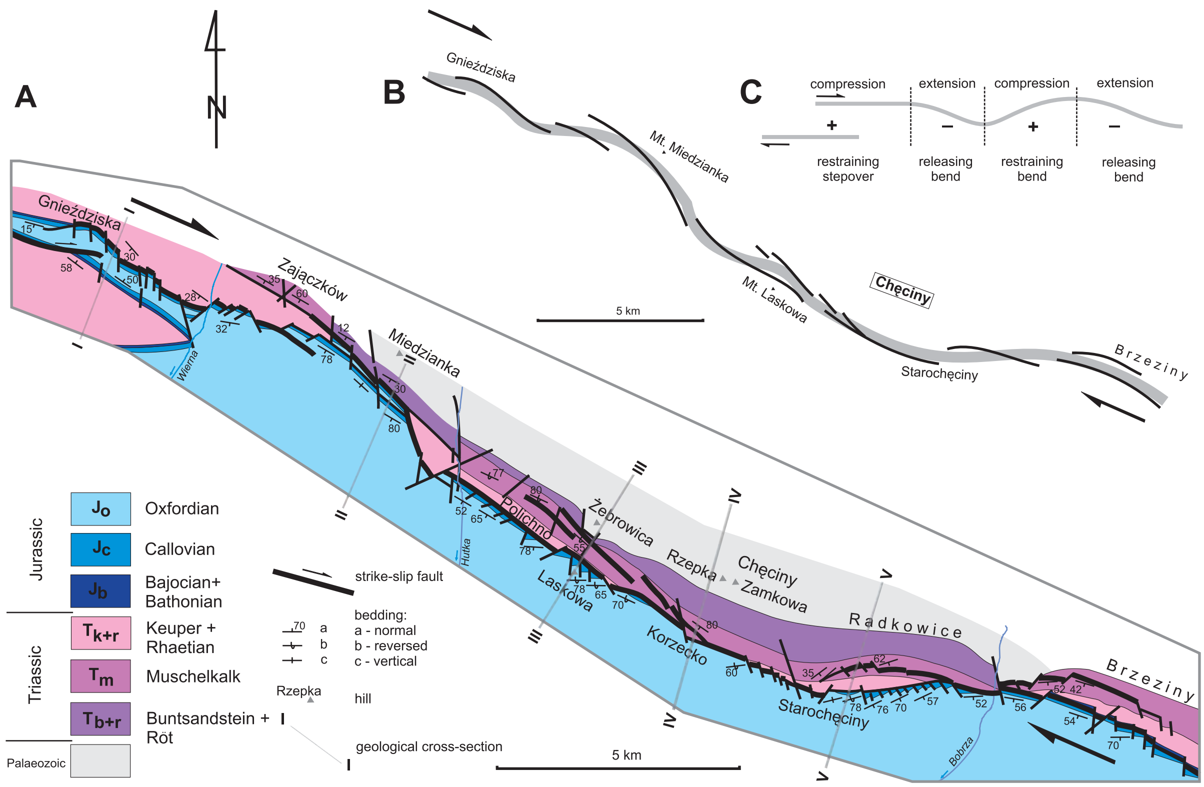

Fig. 2. A – Simplified geological map of the Gnieździska – Brzeziny fault zone. Arrows indicate sense of strike-slip movement; B – Sketch-map with the location of first order faults in the Gnieździska – Brzeziny fault zone (black lines) with generalised trend of this zone (grey lines); C – Scheme of the structural geometries along the dextral strike-slip fault

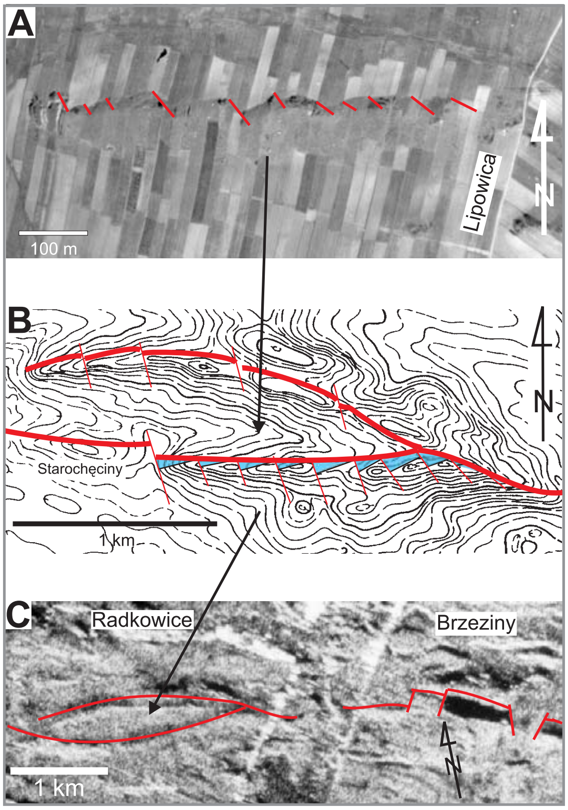

Fig. 3. Image of part of the Gnieździska-Brzeziny fault zone – east of Starochęciny:
A – air photo, B – contour map, C – radar image. Continous red lines – first order faults, oblique red line – en echelon R_1 faults

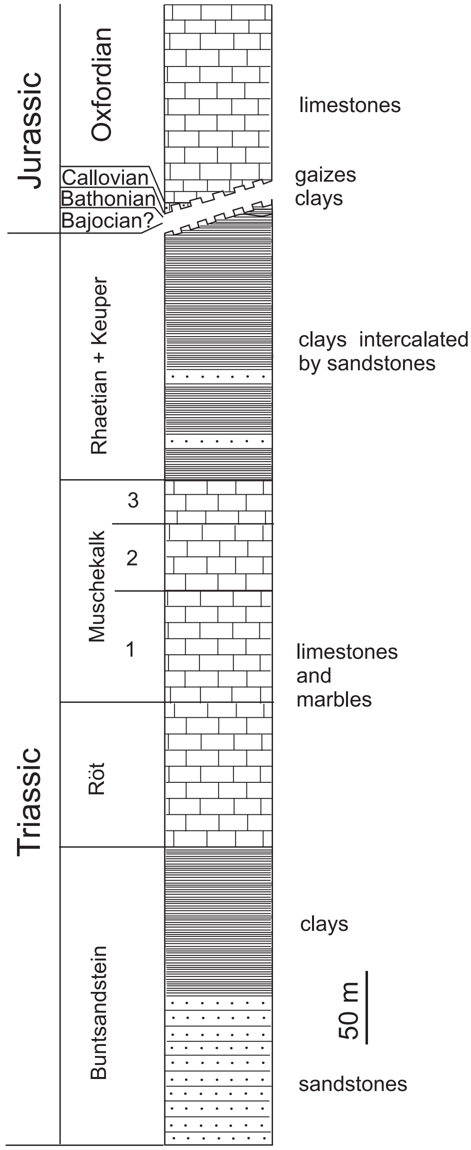

Fig. 4. Simplified lithostratigraphic column of the SW Mesozoic margin of the Holy Cross Mountains. Broken line – tectonic contact

LITHOSTRATIGRAPHY

The strata occurring along the investigated fault (Text-fig. 2A) comprise part of the Triassic and Jurassic stratigraphical column (Text-fig. 4) of the southwestern Mesozoic margin of the Holy Cross Mountains (FILONOWICZ & LINDER 1986, 1987). The presented stratigraphy is simplified. The subdivision conforms generally to the rock competence. The oldest strata representing the Buntsandstein comprise a sandstone-conglomerate complex, in the upper part dominated by red claystones. This complex passes into yellow and grey limestones and marls of the Röt (Text-fig. 4), which are overlain by grey, dark grey and yellow limestones and marls representing the Muschelkalk. Clays, claystones and siltstones of the Keuper and Rhaetian represent the youngest Triassic. They are overlain, probably with a stratigraphic gap, by black clays representing the Bajocian and Bathonian (GIŻEJEWKA 1975, FILONOWICZ & LINDNER 1986) and the lowermost Callovian (SIEMIĄTKOWSKA-GIŻEJEWSKA 1974, BARSKI 1999). The Callovian is represented mainly by yellow calcareous gaizes with cherts.

The Oxfordian comprises white marly limestones, platy limestones and spotty limestones, locally with massive limestones (MATYJA 1977, MATYJA & *al*. 1996).

SETTING OF THE GNIEŹDZISKA – BRZEZINY FAULT ZONE

Determining the trending of the investigated dislocation is rather easy due to direct contact of stratigraphic members differing in lithology (Text-figs 2A, 4, 5). In the

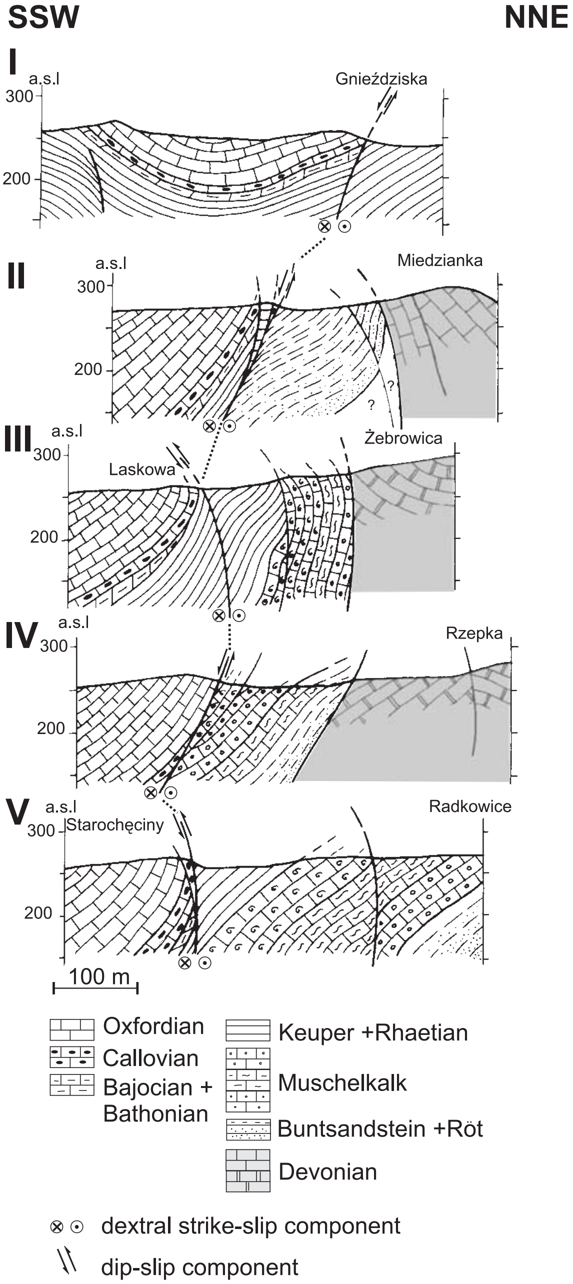

Fig. 5. Geological cross-sections across the Gnieździska – Brzeziny fault zone (after KUTEK & GŁAZEK 1972, slightly modified). Circles below cross-sections: right – with offset towards the reader, left – with offset away the reader. Arrows indicate sense of strike-slip movement. For location see Text-fig. 2A

southern wall resistant Callovian gaizes and Oxfordian massive limestones occur (Text-figs 2A, 4, 5). In turn, the northern wall comprises claystones and siltstones of the Keuper and Rhaetian, and, in the vicinity of Miedzianka, clayey deposits of the upper Buntsandstein. Only in the vicinity of Korzecko does this wall comprise marls of the upper Muschelkalk (Text-figs 2A, 4, 5IV). In this part breccia and cataclasites are present in the debris. The dislocation is effectively marked in the field by a readily distinguishable (Text-fig. 3) distinct morphological step (Text-fig. 5), of a cuesta character over a longer section.

Additionally, detailed determination of the trend of the dislocation is possible through the observation of a thin band of yellow-weathering Callovian gaizes cropping out in the northern limb, which contact the red debris of the Keuper – Rhaetian and Buntsandstein claystones in the southern wall.

The dislocation, thus determined, is a complex fault zone with locally occurring slices (Text-figs 2A, 5), a feature often noted in fault zones (WOODCOCK & FISHER 1986). It comprises *en echelon* strike-slip faults with a similar geometry to those noted by NAYLOR & *al*. (1986, Fig. 12). In the case of the zone under discussion they represent first order faults (Text-fig. 2B). The faults disappear laterally, as e.g. in the vicinity of Zajączków or northwards from Polichno (Text-fig. 2A). Most of them, however, are linked with smaller faults, e.g. SW of Miedzianka or eastwards of Starochęciny (Text-fig. 2A). In effect, the intersection line of the fault zone is sinusoidal (Text-fig. 2A, B) (see also STUPNICKA 1972, fig. 8). In the trace of the continuous fault numerous bends occur, which can be subdivided into bends with convexities trending northwards – "N bends", and bends with convexities trending southwards – "S bends" (Text-fig. 2 A, B).

The N bends are distinct in the vicinity of Miedzianka and in the Bobrza river axis, and much less distinct in the vicinity of Gnieździska, Laskowa Hill and Starochęciny (Text-fig. 2A, B). The S bends occur in the axis of the river Wierna, in the vicinity of Polichno and in the eastern part of the analysed area (Text-fig. 2A, B). It is worth noting that, in the case of the N bends, Muschelkalk and even Buntsandstein deposits occur at the fault contact (Text-fig. 2A). In the case of the S bends, Keuper and in the easternmost and westernmost parts also Bathonian deposits are preserved (Text-fig. 2A).

The generalised trend of the fault zone has an azimuth of 115°. Due to its curvilinear trace, the trend changes from 85° near Starochęciny, to 130° near Miedzianka (Text-fig. 2A, B).

The dips of the main faults comprising the analysed zone are very steep. In the westernmost part near Gnieździska the dips reach ca. 70°/S (Text-fig. 5I) and gradually become steeper, to pass into vertical dips eastwards from Miedzianka to Polichno (Text-fig. 5II). In the vicinity of Laskowa Hill the dips are ca. 70°/N (Text-fig. 5III), and change to southern dips along Korzecko (Text-fig. 5IV). More to the east, towards the river Bobrza, the faults are vertical or steeply dip northwards (Text-fig. 5V). Steep south-dipping faults are present in the easternmost parts of the analysed area.

ATTITUDE OF BEDDING

Beyond the fault zone beds with NW-SE strikes prevail, with dips ca. 20^{o}-30^{o}/S-N (Hakenberg 1973, 1974; Filonowicz 1967, 1968; Filonowicz & Lindner 1986, 1987). In turn, considerable variation in the attitude of the bedding occurs within the fault zone and in its direct vicinity. In the westernmost parts, this is manifested by the much steeper dips of the Gnieździska Syncline, which is cut by the fault (Konon & Mastella 2001). Westwards from Hutka, the dips are initially rather gentle (Text-figs 2A, 6I), between Miedzianka and Hutka, however, 110^{o}-120^{o}/70^{o}-80^{o}S normal beds prevail (Text-figs 2A, 6II); locally reversed beds with northern dips also occur. The complex of reversed beds crops out in the quarry on Laskowa Hill (Text-figs 5III, 7). The band of reversed beds with a dominant trend 105^{o}/65^{o}N is observed between Polichno (Text-figs 2A, 6-III) and Korzecko (Text-fig. 6IV). The bedding attitude changes eastwards. Near Starochęciny, within vertical beds (Text-figs 2A, 5V), 80^{o}/84^{o}S beds become prevalent (Text-fig. 6V). More to the east, beds with southerly dips and inclinations up to ca. 60^{o} (Text-fig. 2A) occur. It is worth noting that along the entire fault zone the bedding strikes are slightly oblique, rotated anticlockwise by 15^{o}-20^{o} in relation to the azimuth of the fault zone (Text-fig. 6).

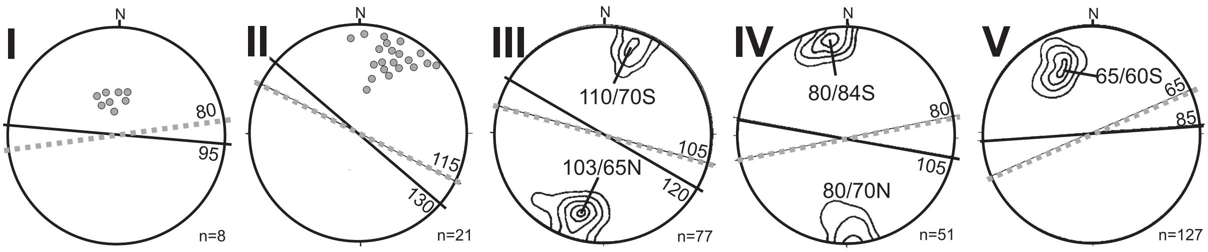

Fig. 6. Point and contour diagram of the bedding (projection on the lower hemisphere of the Schmidt net) with marked dominating attitude (dashed line) and generalised trend of the fault zone: : I – river Wierna region, II – Miedzianka region, III – Laskowa Hill region, IV – Korzecko region, V – Starochęciny region. N – number of measurements

SECONDARY FAULTS

In many cases the first order faults comprising the fault zone are cut by a series of *en echelon* steep faults of lower order, sufficiently large to be mapped (Text-figs 2A, 3A, B). Observations in outcrops show that the single faults are, in fact, composed of fans of smaller faults (Text-fig. 7). Their fault zones, up to 30 cm wide, are filled with breccia, cataclasites and gouge. In some cases they pass into layer-parallel slips (Text-fig. 7), where they are manifested by numerous slickensides. Typically these are slickensides without mineralization and with horizontal striae. On slickensides with calcite coatings the striae trends are variable, albeit commonly vertical.

Fig. 7. Sketch of a fragment of the quarry with Oxfordian limestones on Laskowa Hill with secondary faults. For other explanation see Text-fig. 5

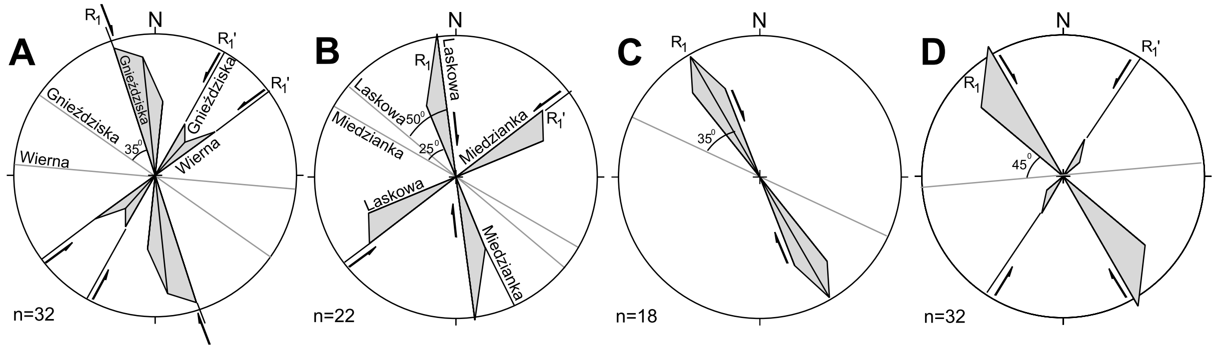

Fig. 8. Rose diagrams of secondary faults with marked generalised trends of the Gnieździska – Brzeziny fault zone (grey line): A – Gnieździska and river Wierna regions, B – Miedzianka and Laskowa Hill regions, C – Korzecko region, D – Starochęciny region. For other explanations see Text-fig. 6 and in the text

Two distinct sets of oblique faults can be distinguished: the dominant R_1, and the much rarer R_1' (Text-fig. 8). The first set varies from 340-355° in the west (Text-fig. 8A) to 310-350° in the east (Text-fig. 8D). The second set R_1' varies from 30° in the marginal parts of the analysed area (Text-fig. 8A, D) to 50-65° in its central part (Text-fig. 8D). According to analysis of maps, air photos as well as tectoglyphs and slickolites, the R_1 faults represent dextral strike-slip faults, and the R_1' faults are sinistral faults. The faults cut each other at 50° to 70° (Text-fig. 8A, B, D), and according to the criteria of FREUND (1974) and JAROSZEWSKI (1980), represent conjugate faults.

The acute angle at which R_1 set faults cut the main fault zone varies within 25-55°, with a dominant value of 35°. The largest values occur in those cases when the zone trends to the NNW-SEE, e.g. in the vicinity of Laskowa Hill (up to 50°) and to the W-E, directly eastwards from Starochęciny (up to 55°) (Text-figs 2A, B; 8B, D). In contrast, the smallest values occur in those cases where the zone trends to the NW-SE, between Miedzianka and Polichno (25°) (Text-figs 2A, B; 8B).

FAULT-SLIP AND STYLOLITIC ANALYSIS

Based on the fault-slip and stylolitic analysis carried out along the Gnieździska – Brzeziny fault zone, two sections of this fault in the vicinity of Gnieździska and Starochęciny were selected for more detailed analysis.

Measurements of slickensides allowed the application of a detailed stress trajectory analysis. A characteristic stress trajectory pattern was determined (Text-fig. 9), where the σ_1 trajectories observed in the northern part trend distinctly eastwards, and those observed in the southern part trend westwards. This stress trajectory pattern fits with FREUND's model (1974) and differs only slightly from the theoretical stress trajectories noted by SEGALL & POLLARD (1980) or by BERTOLUZZA & PEROTTI (1997).

Detailed investigations indicated that N bends observed in the vicinity of Gnieździska and Starochęciny consist of two parallel, discontinuous sections of the fault (Text-figs 2, 9). The geometry of such complexities in the trace of the fault (FREUND 1974) indicates that transpression conditions prevailed here.

MECHANISM OF FAULT ZONE DEVELOPMENT

The series of *en echelon* bands of strike-slip faults (Text-fig. 2A) represent typical (e.g. WILCOX & *al*. 1973, SCHREURS & COLETTA 1998) initial forms of strike-slip faults, which in the following stages of its development are incorporated within the fault zone (TCHALENKO 1970, MOLLEMA & ANTONELLI 1999). Their pattern in relation to the fault zone and the sense of strike-slip movement along the fault zone indicate, however, that the most probable cause of their formation was dextral simple shear in a horizontal plane. In this case the first order faults should be treated as typical dextral strike-slip faults corresponding to the low angle Riedel shears (R) synthetic to the fault zone (Text-fig. 10A).

Oblique secondary dextral R_1 faults should be identified as shears corresponding to RIEDEL shears synthetic to the fault zone (RIEDEL 1929). However, because the acute angle in relation to the fault zone is distinctly larger in comparison to the 15° typical of R shears (RIEDEL 1929), based on the papers by e.g. VIALON (1979), GAMOND & GIRAUD (1982) and MASTELLA (1988), it can be assumed that R_1 faults developed under transpression conditions (Text-fig. 10A, B). This pattern finds confirmation at the microscale (Text-fig. 10C) and regional scale (TCHALENKO 1970, NEUGEBAUER 1995). In turn, R_1' faults would be Riedel shears antithetic to the fault zone, developed uder the same conditions (Text-fig. 10A).

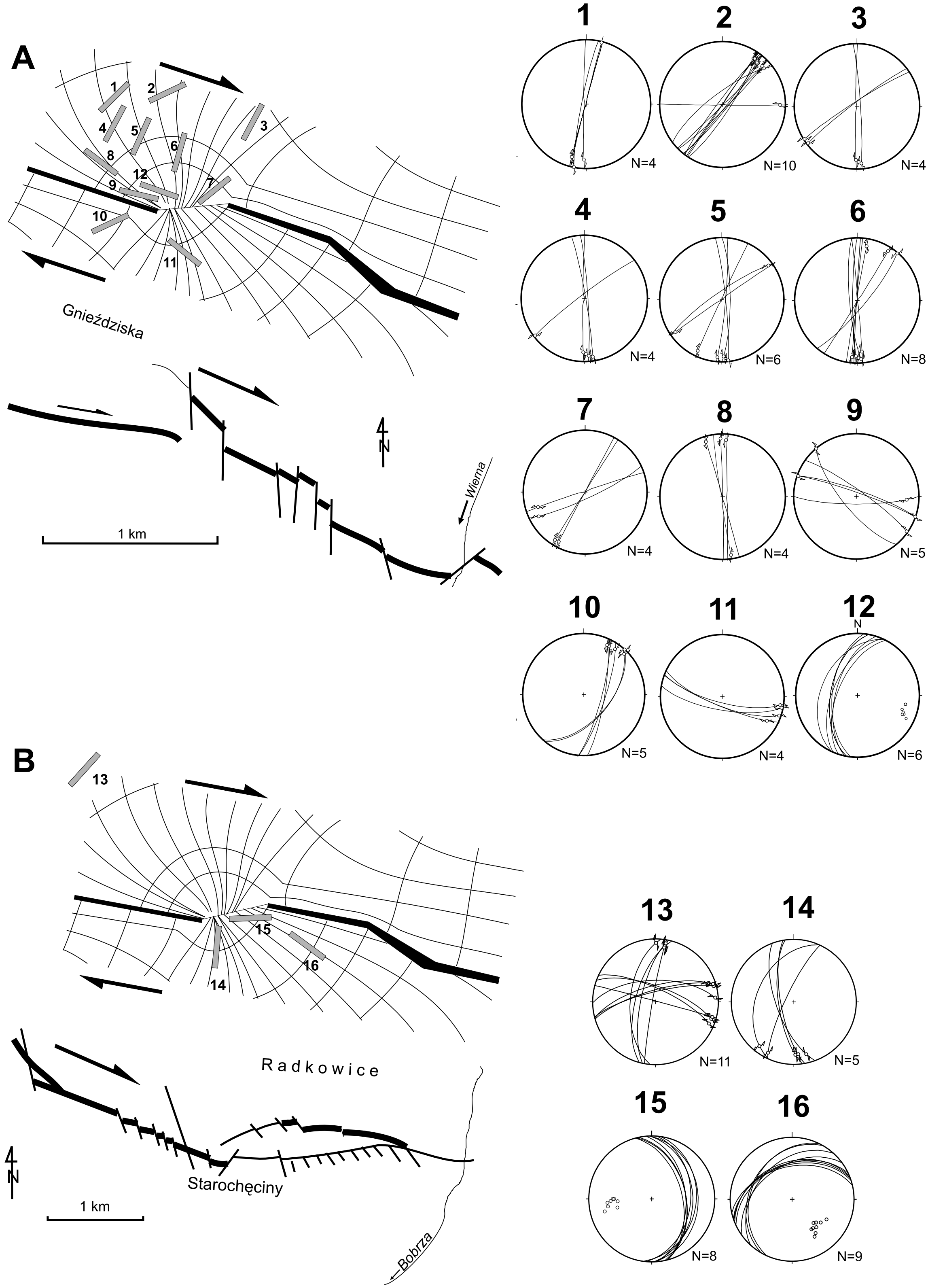

Fig. 9. Stress trajectory patterns based on fault-slip and stylolitic analyses, in comparison to FREUND's model (1974). A – restraining stepover in the Gnieździska region; B – restraining stepover in the Starochęciny region. Solid lines – σ_1, dashed lines σ_3

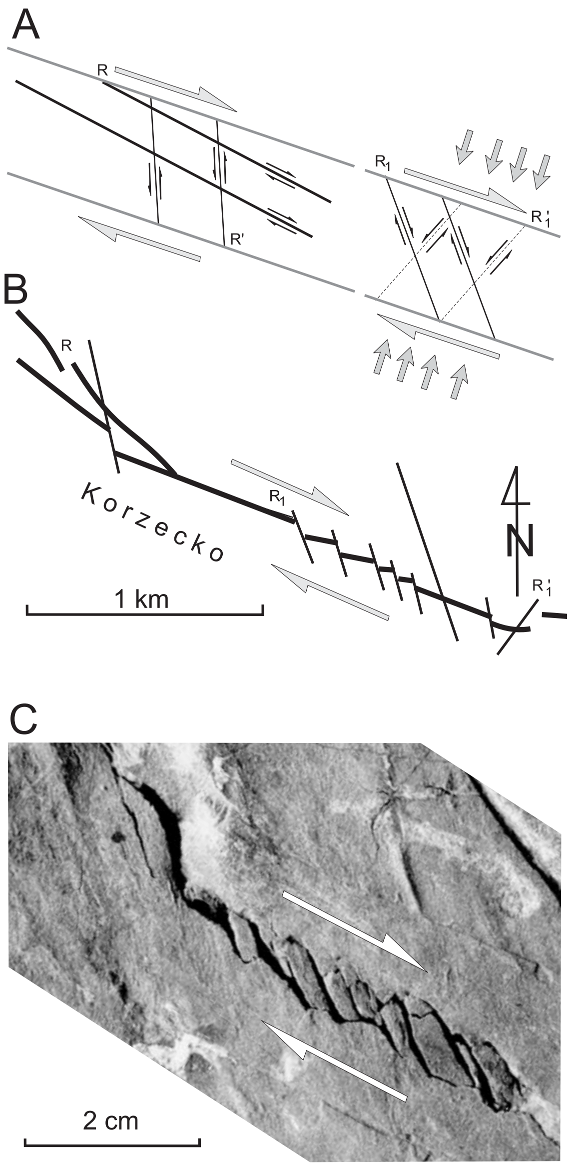

Fig. 10. A – Scheme of the classic R - R' Riedel system (left part of the figure) and R_1 - R'_1 system formed due to transpression; B – Part of the Gnieździska Brzeziny fault zone in the Korzecko region (see Text-fig. 2A);C – Minor fault formed along joint fracture in sandstone of the Cieszyn Beds in Silesian Nappe (Outer Carpathians) – outcrop in the Rabski stream, Bieszczady

DIP-SLIP FAULTS

The dip-slip character of the fault zone under discussion was already noted previously (KUTEK & GŁAZEK 1972, KOWALSKI 1975, STUPNICKA 1972). The existence of the dip-slip component is indicated by: 1) distinct increase in bed dips, even to their overturning along the entire analysed zone; 2) tectonic contact of different lithostratigraphic members e.g. Buntsandstein with Middle Oxfordian limestones in the vicinity of Miedzianka.

Additional confirmation of the existence of a dip-slip component is provided by vertical striae on numerous calcite-coated slickensides occurring within fractures of variably oriented faults. In many cases, the vertical striae are imposed on slickensides with horizontal striae. This indicates that the horizontal movements were older than the vertical movements.

The dip-slip amplitude of the fault zone is estimated at ca. 1300 m (STUPNICKA 1972) or 500-1500 m (KOWALSKI 1975). The dip-slip values estimated from the cross-sections (Text-fig. 5) including the thicknesses of the lithostratigraphic members and the magnitude of the near-fault bed bending are smaller than presented above (STUPNICKA 1972, KOWALSKI 1975). The smallest dip-slips up to several tens of meters occur in S bends in the vicinity of river Hutka and Starochęciny (Text-fig. 2). The largest dip-slips, albeit not exceeding 1000 m, were observed in N bends e.g. in the vicinity of Miedzianka (Text-fig. 2A).

DISCUSSION AND CONCLUSIONS

The characteristic sinusoidal trace of the Gneździska – Brzeziny fault indicates the irregular trace, typical of not perfectly planar faults, that is commonly observed along strike-slip fault zones (e.g. WILCOX & *al*. 1973, HEYL & *al*. 1966, FREUND 1974, GARFUNKEL & *al*. 1981, HEIMANN & RON 1987). The numerous deflections in the trace of the continuous fault, the N bends and S bends, represent the typical (e.g. WOODCOCK & SCHUBERT 1994) restraining and releasing bends respectively (Text-fig. 10).

The stress trajectory patterns of maximum horizontal compressional axes obtained for two sections of the Gnieździska – Brzeziny fault from the vicinity of Gnieździska (KONON & MASTELLA 2001) and Starochęciny, indicate that the analysed sections have a setting typical of discontinuities in the fault trace, that is for restraining stepovers (AYDIN & NUR 1982, WOODCOCK & SCHUBERT 1994).

Analysis of the faults included within the main fault zone indicates that the Gnieździska – Brzeziny fault developed in several phases. During the first stage, in which *en echelon* strike-slip faults included within the main fault zone were developed, they did not undergo transpression. During the next stage, with the appearance of transpression, the secondary strike-slip faults developed (R_1 and R_1'). Due to the continuous activity of a strike-slip component along the entire Gnieździska – Brzeziny fault, linking of the individual sections of the fault took place.

Based on the variability of the angle between the zone azimuth and the R_1 faults, it can be assumed that the largest transpression took place in those parts where the analysed dislocation was NW-SE trending, and the smallest in those parts where it was W-E.

According to the model of NAYLOR & *al*. (1986) the poorly bifurcating, *en echelon* low-angle Riedel shears and the small number of slices, indicate a small, up to several tens of metres strike-slip along this fault zone.

During the last stage of the fault formation, the dip-slip component was activated, which was largely induced by the tectonic inversion of the Mid-Polish Swell (KUTEK & GŁAZEK 1972, KUTEK 2001). The curvilinear character of the fault trace and the preservation of Keuper deposits in the S bends testify to predominance of the strike-slip movement.

The structural analysis, geological mapping, interpretation of air photos and radar images, occurrence of the characteristic complexities in the form of bands and stepovers as well as the secondary conjugate steps of strike-slip faults R_1 and R_1' demonstrated that the first order Gnieździska – Brzeziny fault is a non-planar dextral strike-slip fault. It developed under transpression conditions, which prevailed during its formation.

The strike-slip Gnieździska – Brzeziny fault developed due to the influence of the maximum compressive stress axis trending 175^o-10^o.

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