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Deformation mechanisms of cataclastic rocks from fault zones in the Magura nappe in the Beskid Wyspowy Mountains (Poland)

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ABSTRACT:

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Analyses of intact orientated samples of incompetent fault rocks from thrusts within the Magura nappe in the Beskid Wyspowy Mountains indicate an arrangement of clay mineral plates parallel to numerous shears present in the rocks. Reconstruction of the development of the shears suggests several phases of formation. Maximum palaeotemperatures in the range 80 – 160°C were reconstructed from the fault zones.

Key words: Deformation mechanisms, Cataclastic rock, Fault zones, Palaeotemperatures, Magura nappe.

INTRODUCTION

In most of the thrust zones observed within the Magura nappe in the Beskid Wyspowy Mountains (Text-fig. 1A) no structures indicating directions of tectonic transport (Text-fig. 2) can be detected macroscopically. In order to find a precise and sensitive tool for the determination of the geometry and origin of the tectonic microstructures, as well as for the reconstruction of tectonic transport directions, a comparative microscope analysis of fault rocks (in the sense of SIBSON 1977), based on intact orientated samples from thrust zones, has been carried out.

Additionally, maximum palaeotemperatures in the fault zones were analysed to determine more precisely the deformation mechanism which influenced the fault rocks.

GEOLOGICAL SETTING

Several lithostratigraphic successions (ŚWIDERSKI 1953a, 1953b, BURTAN & SKOCZYLAS-CISZEWSKA1966, BURTAN 1974, 1978) corresponding to first-rank tectonic units (KSIĄŻKIEWICZ 1972) occur in the study area (Text-fig. 1A). The Magura nappe is present in the southern part of the area, the Silesian nappe is situated to the north, and the units within the Mszana Dolna tectonic window lie in the south (Text-fig. 1B).

The development of the Magura succession in the study area is typical of the Rača unit (SIKORA & ŻYTKO 1959, WĘCŁAWIK 1969, OSZCZYPKO 1973, 1992; CIESZKOWSKI 1992, MALATA & *al.* 1996, KONON 1996, 1997) and comprises the Inoceramian Beds (Senonian-Palaeocene), the Variegated Shales (Łabowa Shale Formation, Lower Eocene), the Hieroglyphic Beds (Middle Eocene – Upper Eocene)and the Magura Beds (Magura Formation, Upper Eocene – Oligocene).

The Magura nappe mainly comprises the Beskid Wyspowy subunit (Góry Wyspowe skiba – ŚWIDERSKI 1953b) and a fragment of the Kiczora subunit (Kiczora skiba – ŚWIDERSKI 1953b).

Two main tectonic zones are present in the Beskid Wyspowy subunit: the zone of synclines (i.e. the Łopień,

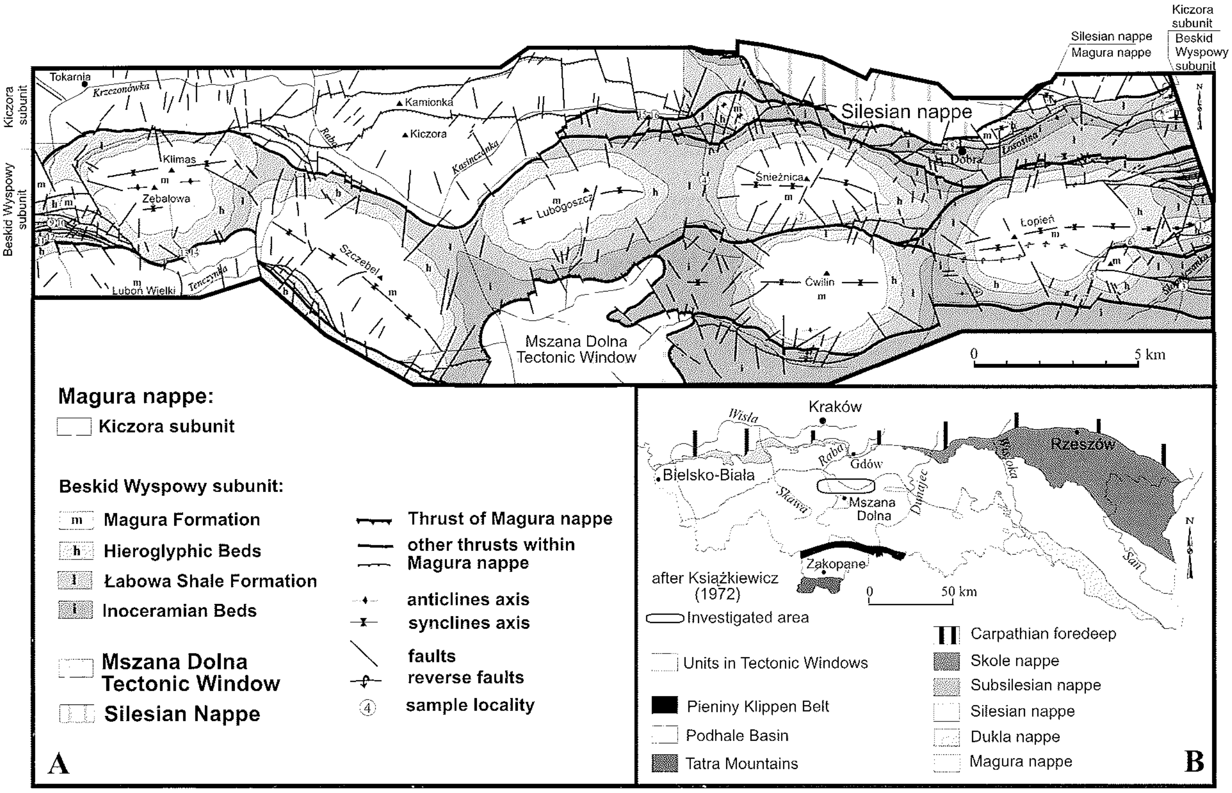

Fig. 1. Tectonic map of central part of the Magura nappe in the Beskid Wyspowy region (with sample localities)

Śnieżnica, Lubogoszcz, Szczebel, Klimas – Zębalowa and Luboń Wielki synclines) and the marginal slices to the north (Text-fig. 1A), together forming a classic duplex (KONON 1997).

Fault rocks from the thrusts and fault zones are very similar on a macroscopic scale (Text-fig. 2). They consist predominantly of a clayey-silty blue-grey homogeneous matrix containing sporadic rock fragments, typically sandstone, up to 1 cm long. Rarely, when more competent rocks, mainly sandstones, disintegrated, they occur as breccia or microbreccia.

METHODOLOGY

Deformation analysis

The orientation of the mineral particles, the origin of the shears and the mechanism of deformation were analysed in the fault rocks by means of SEM and optical microscope. Samples were taken from several sites, situated either directly in the thrust zones or in their vicinity, within the Magura nappe in the Beskid Wyspowy Mountains (Text-fig. 1A). Orientated, intact samples were subjected to analysis. The observations were carried out on the vertical plane directed N – S and on the horizontal plane.

Samples were first dried using the sublimation method in vacuum by rapid freezing of the wet sample in fluid nitrogen, which enabled preservation of the microstructures (OSIPOV & *al.* 1989, KACZYŃSKI & TRZCIŃSKI 1997). A JSM 840A type SEM microscope was used to differentiate between pores and particles on the basis of differences in brightness (SERGEEV & *al.* 1984, KACZYŃSKI & TRZCIŃSKI 1997). SEM photographs were studied with the use of STIMAN computer software based on the methods of SERGEEV & *al.* (1984) and OSIPOV & *al.* (1989).

Methodology of palaeotemperature analysis

In order to determine the maximum palaeotemperatures reached during diagenesis within the rocks in the study area, the pyrolysis Rock-Eval method (ESPITALIE & *al.* 1977, 1985) and mixed-layer illite/smectite mineral analysis (PERRY & HOWER 1979, POLLASTRO 1993, ŚRODOŃ 1995, 1996a, 1996b) were carried out.

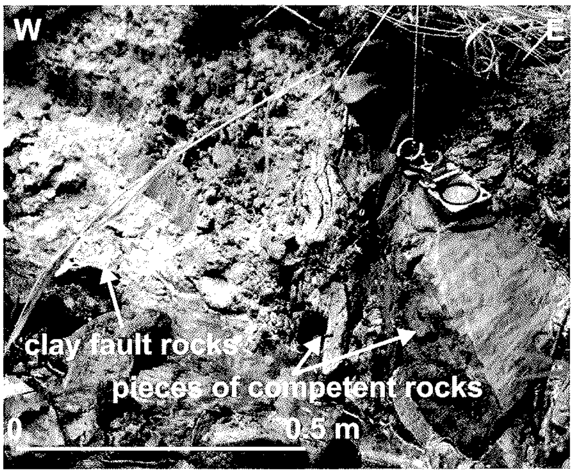

Fig. 2. Thrust zone of the Beskid Wyspowy subunit (north of Lubogoszcz syncline)

The Rock-Eval method is based on analysis of kerogen. One of the parameters that can be measured is T_{max}, i.e. the temperature at which the largest amount of hydrocarbons is liberated. Determination of T_{max} is a more representative method of testing the evolution of type II organic matter (Espitalie *& al.* 1985) than vitrinite reflectance. In the case of type III kerogen the method is as good as the vitrinite reflectance method (Espitalie & *al.* 1985). Samples of shales and sandstones containing a macroscopically high organic content were collected for analysis.

The illite/smectite method is based on the ratio of illite to smectite layers as well as on the determination of the junction probability coefficient R. Argillaceous fault rocks from thrusts and other faults were subjected to analysis (Text-fig. 1). Diffractograms of normal, air-dried samples, saturated with ethylene glycol as well as heated to 550°C, were made for both raw samples, as well as for the < 2 µm and < 0.2 µm fractions, under the following conditions: range 2.7 ÷ 50-60° 2θ, radiation CoKα (or CuKα).

Carbonates, organic matter and the so-called free iron oxides were removed according to the procedures of Jackson (1975).

Deformation mechanism in fault rocks

The thrusts mainly cut siltstones and clayey shales within the Inoceramian Beds, Variegated Shales (Łabowa Shale formation) and Hieroglyphic Beds. The fault rocks are compact and contain macroscopic fragments <0.1 cm as well as over 80% of matrix. According to the classifications of fault rocks of Sibson (1977) and Wise & *al.* (1984) these features indicate cataclasites in most cases.

Where siltstones underwent cataclasis, their fragments are preserved in fault rocks as less ductile bodies than the matrix (Text-fig. 3a, c). The investigated fault rocks are cut by many narrow zones of microfractures (Text-fig. 3a, c). These continuous fractures cut boundaries between grains as well as pass through grains of various composition (Text-fig. 4c), a characteristic of brittle deformation (Mitra 1984). The matrix composition, including plates of clay minerals surrounding grains of other minerals, is nevertheless characteristic of ductile rocks.

Under SEM and in thin sections the investigated samples present a high degree of clay mineral arrangement (Text-figs 3d, 4), similar to that described by Lash (1989) and Maltman (1988).

The clay mineral plates are transposed to positions parallel to the numerous slip planes (Text-fig. 4). This textural rebuilding, to parallelism with the shearing plane, is common in poorly lithified rocks containing slaty minerals (Petit & Laville 1987). These minerals are orientated more or less parallel to the shears (Morganstern & Tchalenko 1967, Petit & Laville 1987, Maltman 1988).

Many zones of microdislocations were observed in the investigated rocks (Text-figs 3, 4). Shears termed R_1 predominate (Text-fig. 3a, c). Much less developed high-angle shears, termed R_1'are also present (Text-fig. 3b). R_1 and R_1' have the character of normal faults.

Shears nearly parallel to the main shear, termed Y (sensu Bartlett & *al.* 1981), low-angle shears termed P_1, as well as high-angle shears termed P_1' were also observed (Text-fig. 3).

The Y shears occur as quartz veins or as slip planes to which the clay plates are parallel. According to the Bartlett & *al.* (1981) terminology, the P_1 and P_1' shears, which have the character of reverse faults, could correspond to the P shears. They probably formed due to local rotation of stresses within the R_1 and R_1' shears, similar to the generation of series R-P shears (Gamond & Giraud 1982, Gamond 1983).

The strongly inclined positions and sense of movement along the planes of the R_1 and R_1' shears indicate that they formed as a result of simple shearing due to the thrust movement and weight of overburden, similar to the interpretation of Jaroszewski (1972) and Mastella (1988) for the development of cleavage.

According to the analysis of mineral orientation on the basis of brightness measurements (Osipov & *al.* 1989) in SEM images, the strikes of the observed dislocations are usually W – E.

Apart from the observed shears, other indicators of movement have also been noted (Text-fig. 3c) including structures known as 'dead-fish structures' (SIBSON 1996) comprising (Text-fig. 3d) dismembered lenses of competent components within a strongly deformed clay matrix. All of these structures point to a generally S→N direction of tectonic transport.

Palaeotemperature analysis

Samples were taken from the quarry on the southern slopes of the Śnieżnica Mountain (Text-fig. 1A – sample 7), and close to the overthrust of the Magura nappe on to the Silesian nappe, near Dobra (Text-fig. 1A – sample 8). The sample from Dobra is characterised by T_{max} = 448°C, while the sample from Śnieżnica quarry yielded a T_{max} = 441°C. Pyrolysis analysis determined the kerogen type in the analysed rocks as type II (sample 8) and type III (sample 7) (ESPITALIE & *al.* 1985, SNOWDON 1989, THOMPSON 1994).

Comparison of T_{max} with the SCI – Spore Colour Index (THOMPSON 1994), in the case of type II kerogen, as well as with the vitrinite reflectance in the case of type III kerogene (THOMPSON 1994) suggests that the investigated samples from Dobra and Śnieżnica (from the Magura nappe) were subject to maximum palaeotemperatures between 80 and 120°C.

Fault rocks tested with the illite/smectite method have revealed the presence of illite/smectite phases characteristic (ŚRODOŃ 1995, 1996a) of the R0 – R1 transition, with 40%S (smectite) layers (Text-fig. 1A – samples 2 and 5), which correspond to palaeotemperatures of about 100°C. At three points (Text-fig. 1A – samples 3, 4, 6), the presence of 20 – 25% smectite layers has been established, which indicates palaeotemperatures around 120°C (ŚRODOŃ 1995, 1996a). The highest temperature noted by this method is from a sample from the thrust zone (Text-fig. 1A – sample 1), where the 10% content of smectite layers indicates maximum palaeotemperatures of around 160°C.

The investigations suggest that the rocks in the studied part of the Magura nappe were subjected to maximum palaeotemperatures between 80° and 130°C, in some cases reaching close to 160°C. Similar palaeotemperatures, between 95° and 175°C, were recorded by WIESER (1992) on the basis of copper mineralisation in rocks of the Magura nappe in the vicinity of the Mszana Dolna tectonic window (Text-fig. 1A, B).

The same temperature interval was indirectly confirmed by the investigations of MŁYNARCZYK (1996) on inclusions in Marmaros diamonds from sandstones of the Magura nappe near Mszana Dolna, suggesting palaeotemperatures between 75° and 137°C in the migrating solutions during the late stages of diagenesis.

Studies by ŚRODOŃ (1995) of illite/smectite mixed-layer mineral phases also confirm that rocks in the western Outer Carpathians were subjected to similar maximum palaeotemperatures of around 150 – 160°C. The relatively low palaeotemperature values within the Magura nappe do not exclude the possibility of higher palaeotemperatures at the southern margin of the Mszana Dolna tectonic window (BURTAN & ŁYDKA 1978, MASTELLA 1988, WIESER 1992) as well as at its contact with the Grybów unit (JASIONOWICZ & WIESER 1988) as a consequence of passing over basement ridges by the overthrusting Magura nappe (MASTELLA 1988).

The elevated palaeotemperatures could have distinctly influenced the decrease in the coefficient of internal friction. Decrease of rock resistance to shearing was also facilitated by the release of extra water through dehydration of clay minerals at temperatures above 100°C. Crystallisation of new minerals in pores, i.e. the creation of ferric chlorite as a by-product of illitisation of smectite (ŚRODOŃ 1996a), could have caused the increase in pore pressure and therefore the initiation of shears.

SUMMARY

According to the fault rocks classifications of SIBSON (1977) and WISE (1984), both cataclasites and breccias predominate in the thrust zones of the Magura nappe. In fault rocks that appear homogenous on a macroscopic scale, microscope investigations reveal a large number of good indicators of tectonic transport and deformation mechanisms.

In the faulted siltstones and shales the clay mineral plates have been strongly reorientated to a position parallel to small shears striking generally W – E and with a variable dip.

The R_1 and R_1' shears originated first. Local reorientation of the greatest principal stress within the R_1 shears caused the P_1 shears to originate. Similar zones of R – P type shears formed as a result of the local reorientation of stress axes within the rotated bands of R'_1 shears. The influence of a pair of forces caused the formation of dead-fish structures in the shear zones.

According to the criteria by MITRA (1984), all shears originated mainly due to brittle deformation mechanisms, probably close to the transition to ductile deformation.

The deformation of the fault rocks was facilitated by the influence of palaeotemperatures between 80° and 130°C, and locally up to 160°C.

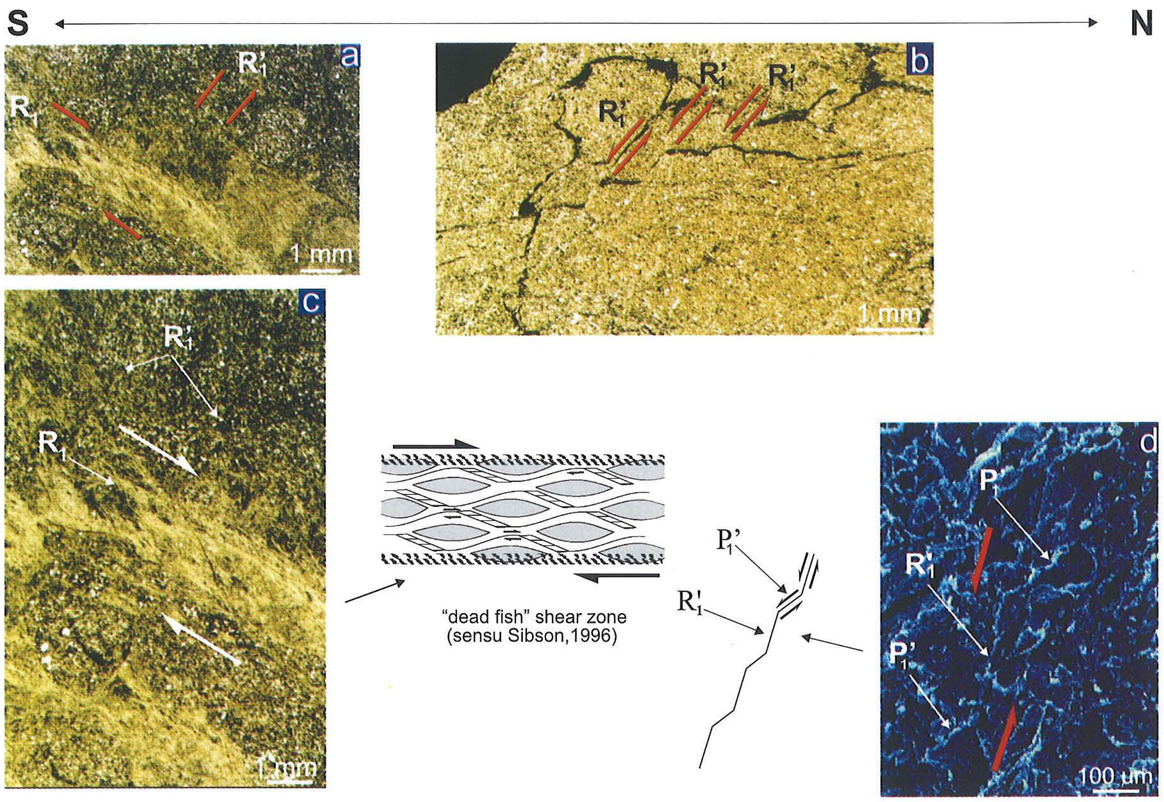

Fig. 3. Tectonic microstructures observed under optical microscope and SEM in vertical plane

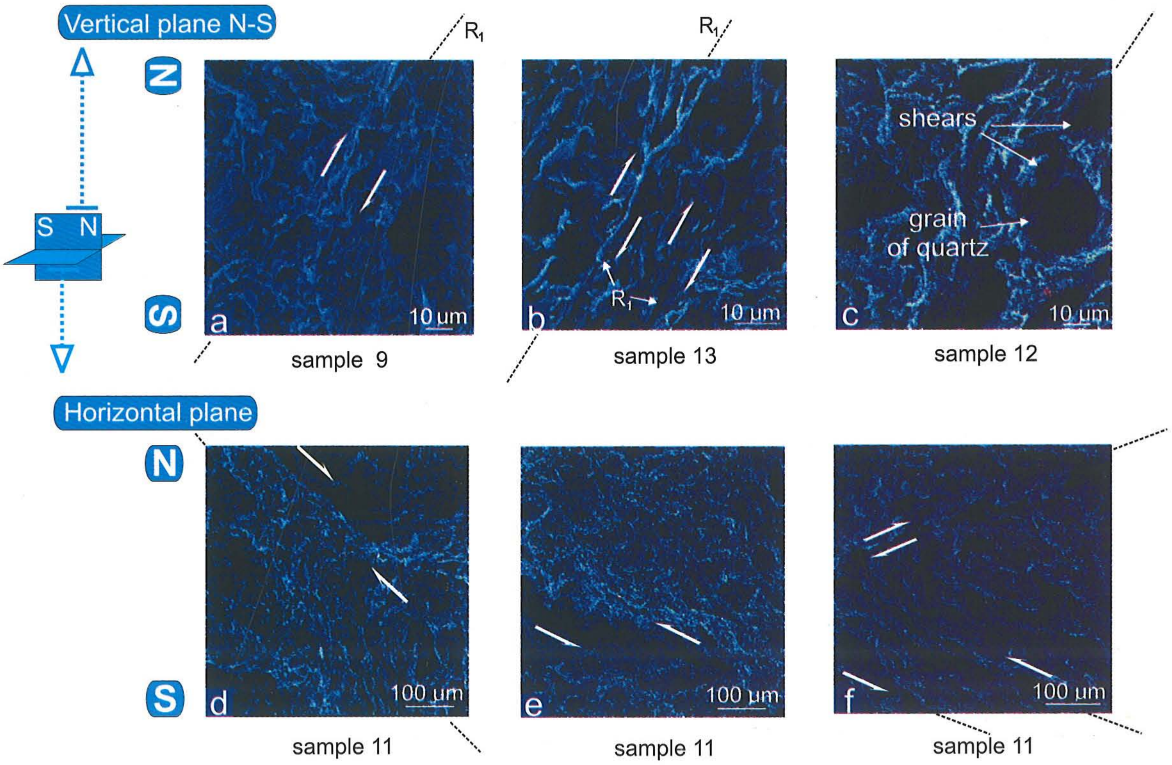

Fig. 4. Tectonic microstructures observed under SEM in horizontal and vertical planes

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