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# Jointing in the medial segment of Magura Nappe, Outer West Carpathians, Poland: hint for the timing of deformation events

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*Abstract*: A study of joint pattern in the Cretaceous-Palaeogene flysch strata of the medial segment of the Bystrica slice, Magura Nappe, leads to a reconstruction of at least three episodes of folding in that area. The reconstructed positions of fold axes formed during individual deformation episodes are as follows: W to WNW, NW to NNW, and N to NNE, being coeval with successively clockwise rotating orientations of fold-related maximum compressive stress: from N (NNE) through NE to ESE. The first event is tentatively correlated with the latest Cretaceous (?)/Paleocene to early Miocene episode of N to NW-directed piggy-back thrusting, the second event could be related to the early through middle Miocene, NE-directed thrust reactivation and out-of-sequence thrusting, whereas the third deformation event was either associated with minor folding induced by strike-slip reactivation of the pre-existing thrust faults or caused by local transpressional motions along strike-slip faults.

*Key words*: Outer West Carpathians, Magura Nappe, jointing, folding

The study area is located in the medial segment of the Bystrica slice, Magura Nappe, close to a small tectonic window of Szczawa, Dukla s.l. Nappe (Figs. 1, 2). That part of the Bystrica slice is composed of Upper Cretaceous and Palaeogene flysch strata of variable thickness. Exposures of Cretaceous rocks are widespread and easily accessible; therefore, the area provides a rare opportunity in the Polish Outer Carpathians to compare different styles of deformation between tightly folded Cretaceous rocks and open-folded Palaeogene strata (Oszczypko et al., 1991). Examination of several generations of jointing present in the studied rocks enables also a comparison with the regional pattern of jointing in the Polish Outer Carpathians (Fig. 1). Axes of minor folds deforming upper Cretaceous strata in the study area are aligned W to NW in thin-bedded and N to NNW in thick-bedded turbidites, whereas map-scale folds deforming both Cretaceous and Tertiary strata trend predominantly E-W.

99 stations have been analysed, representing Upper Cretaceous (Turonian through Maastrichtian; 54) and Paleocene to Eocene flysch strata (40) of the Magura Nappe, as well as Oligocene strata of the Dukla s.l. Nappe, exposed in the Szczawa tectonic window (5). At each station 50 to 100 joint surfaces have been measured, a figure statistically representative for the region (Oszczypko et al., 1991; Zuchiewicz, 1998). The data have been plotted on lower hemisphere Schmidt projection and then bedding- and fold plunge-corrected.

The regional joint network comprises five sets, although at individual exposures three to four sets can be encountered. Sets showing the same regional orientation display both similar surficial features and the type of intersection with bedding surfaces. Cross-fold joints comprise a single set T, striking perpendicular or subperpendicular to map-scale fold axes, and two diagonal sets ($D_1$, $D_2$) striking under high angles to these axes. The acute bisector between these two sets is orientated perpendicular to map-scale folds. Fold-parallel joints (L, L') strike parallel or under small angles to map-scale fold axes and are perpendicular or subperpendicular to bedding.

Morphological properties of the diagonal joints indicate that the incipient stage of their development was a shear one, whereas their further opening proceeded in extensional mode (Ksiazkiewicz, 1968). The pattern of en echelon arranged gashes and feather fractures shows that the $D_1$ and $D_2$ sets represent, respectively, dextral and sinistral shears. Abutting relationships suggest that these joints are roughly coeval and were formed as "potential shear surfaces" in the triaxial stress field (Engelder, 1989). The joints are, therefore, shear fractures (Hancock, 1985) that form a conjugate system. Some of these were formed when the host strata were poorly lithified, as shown by contamination of mineral veins that fill the joints by material derived from host strata (cf. also Swierczewska & Tokarski, 1998; Tokarski et al., 1999). The morphology of T joints, in turn, indicates that their development proceeded without the initial "shear" stage and that they are mode I fractures (Price & Cosgrove, 1994). Both the L and L' sets are devoid of properties that would point to their shear origin. Their morphology and type of intersection with bedding planes appear to indicate tensional origin. These joints probably originated during early stages of folding (cf. Aleksandrowski, 1989).

Joint sets shown in Fig. 2 reveal considerable scatter in orientation resulting from the presence of differently

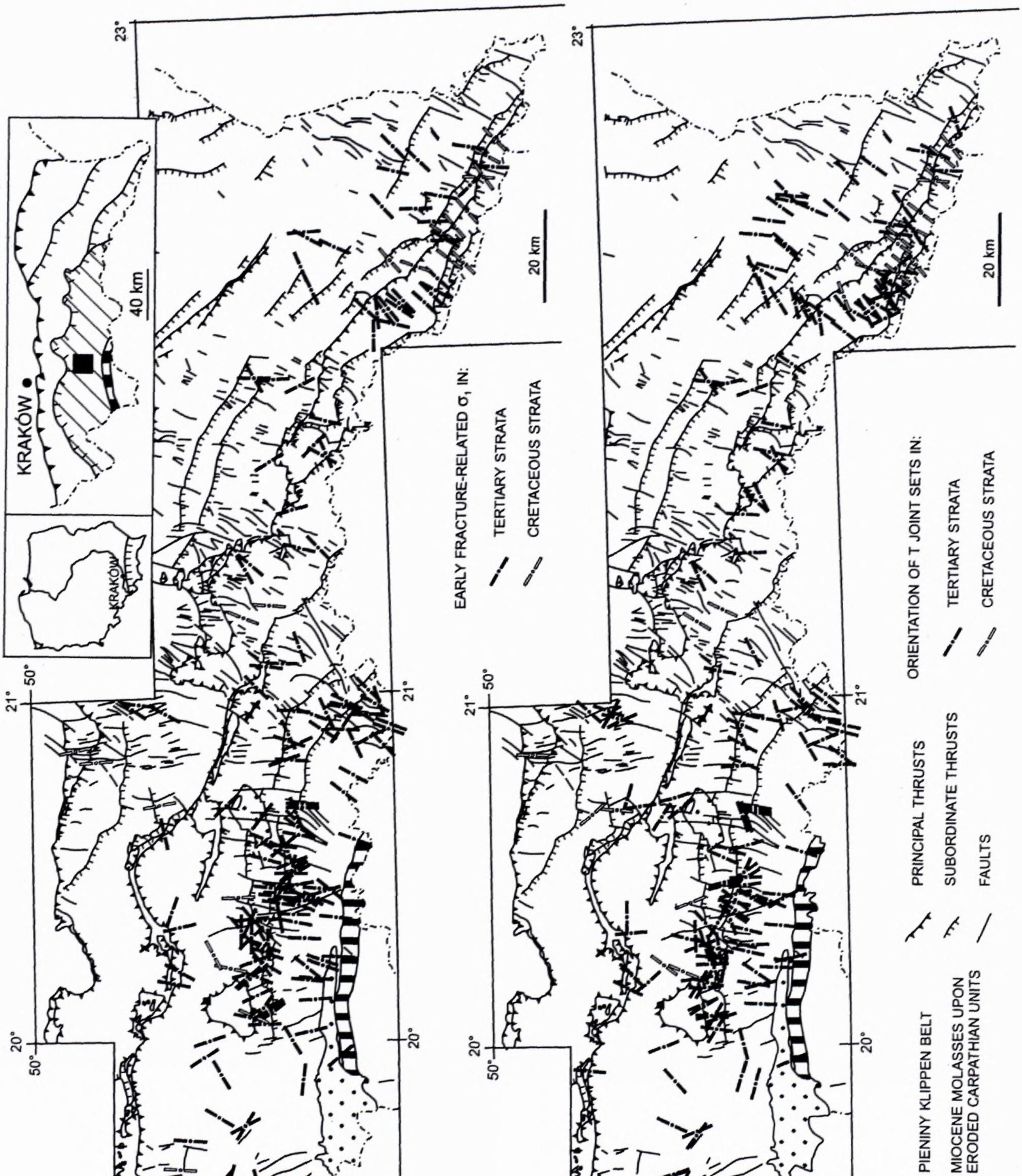


*Fig. 1. Orientation of the cross-fold shear joint-related $?_J(a)$ and fold-perpendicular extensional T joints in the Polish Outer Carpathians. Inset map shows location of the area portrayed in Fig. 2.*

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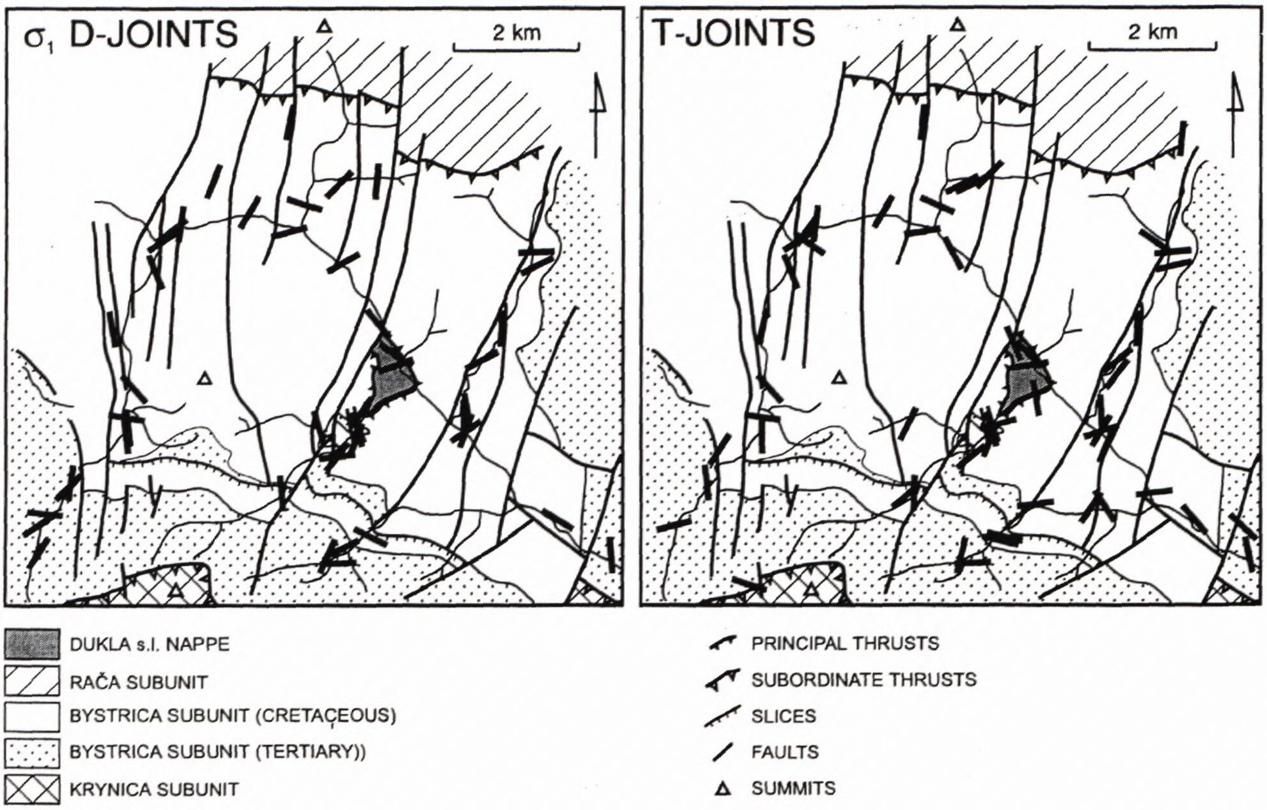


*Fig. 2. Orientation of shear joint-related ? $_1$ (a) and fold-perpendicular extensional T joints (b) in the medial segment of Magura Nappe close to tectonic window of Szczawa.*

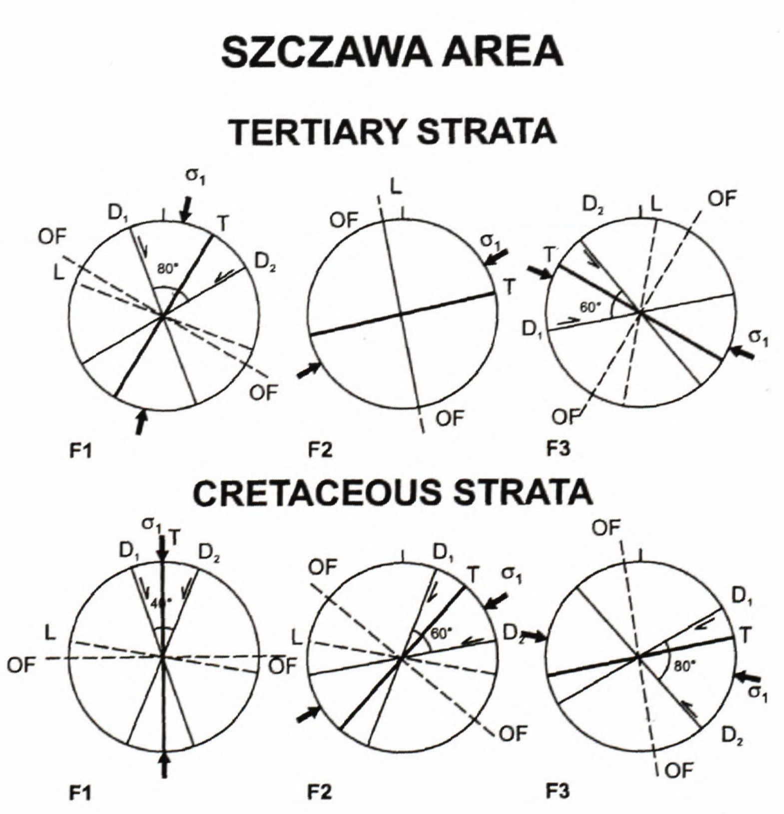


*Fig. 3. Summary diagram showing principal joint sets associated with three consecutive episodes of folding ($F_1$ through $F_3$) in the medial segment of Magura Nappe. OF - dominant orientation of fold axes; see text for other explanations.*

arranged folds. Abutting relationships are strongly indicative of at least three generations of folds and related joint sets in that area. Discrepancy in structural style between Cretaceous and Palaeogene series has already been reported by Oszczypko et al. (1991), basing on large-scale mapping of the area, as well as by Aleksandrowski (1985, 1989), Zuchiewicz (1998) and Tokarski et al. (1999) in respect to the whole mid-western segment of the Magura Nappe. This discrepancy used to be associated with the presence of superposed buckle folds originated during folding of the East Carpathians (Aleksandrowski, 1985, 1989), post-folding rotation of fault-bounded blocks (Zuchiewicz, 1998), and/or reactivation of the pre-existing thrust faults (Tokarski et al., 1999). Recent structural studies support an idea of at least three episodes of folding of the Cretaceous-Palaeogene flysch strata in the medial segment of the Bystrica slice of Magura Nappe.

The reconstructed positions of fold axes formed during individual deformation episodes are as follows: W to WNW, NW to NNW, and N to NNE

(Fig. 3), and are coeval with successively clockwise rotating orientations of fold-related maximum compressive stress: from N (NNE), through NE to ESE. The first event is tentatively correlated with the latest Cretaceous (?) /Paleocene to early Miocene episode of N to NW-directed piggy-back thrusting in the Outer Carpathians of Poland. The thrusting was initiated in the southern tectonic units and propagated to the northern units through a series of foreland-propagating in-sequence thrusts (Decker et al., 1999). The second event, in turn, could be related to the early through middle Miocene, NE-directed thrust reactivation and out-of-sequence thrusting (Decker et al., 1999; Fodor et al., 1999). The third deformation event was either associated with minor folding induced by strike-slip reactivation of the pre-existing thrust faults (Decker et al., 1998, 1999; Tokarski et al., 1999) or caused by local transpressional motions along strike-slip faults.

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