Jointing in Eocene flysch strata of the mid-eastern Magura Nappe, Polish outer Carpathians: implications for the timing of deformation

NESTOR OSZCZYPKO & WITOLD ZUCHIEWICZ

Institute of Geological Sciences, Jagiellonian University, Oleandry 2A, PL-30 063 Kraków, Poland
(e-mail: nestor@ing.uj.edu.pl; witold@ing.uj.edu.pl)

Abstract. The paper focuses on early joint pattern in the mid-eastern segment of the Magura nappe in the outer West Carpathians of Poland. The studied stations in the Krynica, Bystrica and Rača subunits of the Magura nappe represent northward-younging members of the Eocene flysch sequence. Morphological properties of cross-fold shear or hybrid shear joints point to their formation at the time when the host strata were nor fully lithified, whereas their geometric relation to map-scale folds implies genetic relationship with the early stages of syndepositional folding. The age of this folding was different in different subunits of the Magura nappe, migrating in time from the Early through Late Eocene times. The associated shear joint-related σ_1 showed a 15 ° counterclockwise rotation, from N35 °E in Krynica subunit to N10 °E in Rača subunit, possibly due to a change of the sense of subduction of the European plate under Alcapa. The subsequent Miocene folding and thrusting, as well as minor rotations of fault-bounded blocks disturbed the Eocene pattern of cross-fold jointing. Fold-parallel, extensional joints represent younger episodes of deformation, related to post-orogenic, variably orientated extension.

Key words: jointing, palaeostress reconstruction, Magura nappe, outer West Carpathians, Poland

Introduction

The aim of this paper is to test usefulness of joint pattern analysis in reconstructing structural history of a portion of the outer Carpathian fold-and-thrust belt that shows variable orientation of map-scale folds and thrusts.

The outer Carpathian belt was formed as an accretionary prism during the southward-directed subduction of the European plate under Alcapa (i.a. Pescatore & Ślączka, 1984; Oszczypko & Żytko, 1987; Tomek & Hall, 1993; Zoetemeijer et al., 1999; and references therein), resulting in north-verging folding and thrusting, followed by major rotation of either the regional stress field (Aleksandrowski, 1985 a; Decker & Peresson, 1996; Decker et al., 1997; Zuchiewicz, 1998 a) or the belt itself (Márton et al., 1999), postdated by regional collapse associated with normal faulting (Decker et al., 1997).

Some authors claim that jointing generally precedes faulting (Shepherd & Huntington, 1981; Segall & Pollard, 1983) and folding (i.a. Cook & Johnson, 1970; Tokarski, 1977), whereas others maintain that systematic jointing in fold-thrust belts postdates the main orogenic compressional event (Meere & Rogers, 1999) and that it can rarely be used as a far-field stress indicator (e.g. Pollard & Aydin, 1988). Still another group of geologists concludes that joints can be initiated before, during and after folding (Hancock, 1964, 1985; Rixon et al., 1983). It has recently been suggested that joints in young fold-and-thrust belts are related to far-field stresses and that they can easily be used in palaeostress reconstructions (Mastella et al., 1997; Świerczewska & Tokarski, 1998; Zuchiewicz et al., 1998; Tokarski & Świerczewska, 1999). Testing this hypothesis in a structurally complicated portion of the largest outer Carpathian nappe is the main objective of our study.

We have chosen the mid-eastern segment of the Magura nappe (Fig. 1) because this area has a fairly good coverage by detailed geological maps and that jointing has been studied here extensively during the past decade. The term "joint" is applied in this paper as a field term, following the definitions given by Hancock (1985) and Dunne & Hancock (1994).

State of research

Joints are ubiquitous structures in the Cretaceous through Tertiary flysch strata of the Polish outer Carpathians, and have been studied by numerous authors (i.a. Bober & Oszczypko, 1964; Książkiewicz, 1968; Tokarski, 1975, 1977; Lenk, 1981; Mastella, 1988; Aleksandrowski, 1985 a, b, 1989; Mardal, 1995; Zuchiewicz & Henkiel, 1995; Mastella et al., 1997; Zuchiewicz, 1997 a, b, 1998 a, b; Rubinkiewicz, 1998; Tokarski & Świerczewska, 1998). Relation of jointing to regional fold trends has become easy to establish owing to recently published calculations of map-scale fold axes within homogeneous domains throughout nearly the whole of the Polish outer Carpathians (Mastella et al., 1997; Zuchiewicz et al., 1998; Szczęsny, 1998).

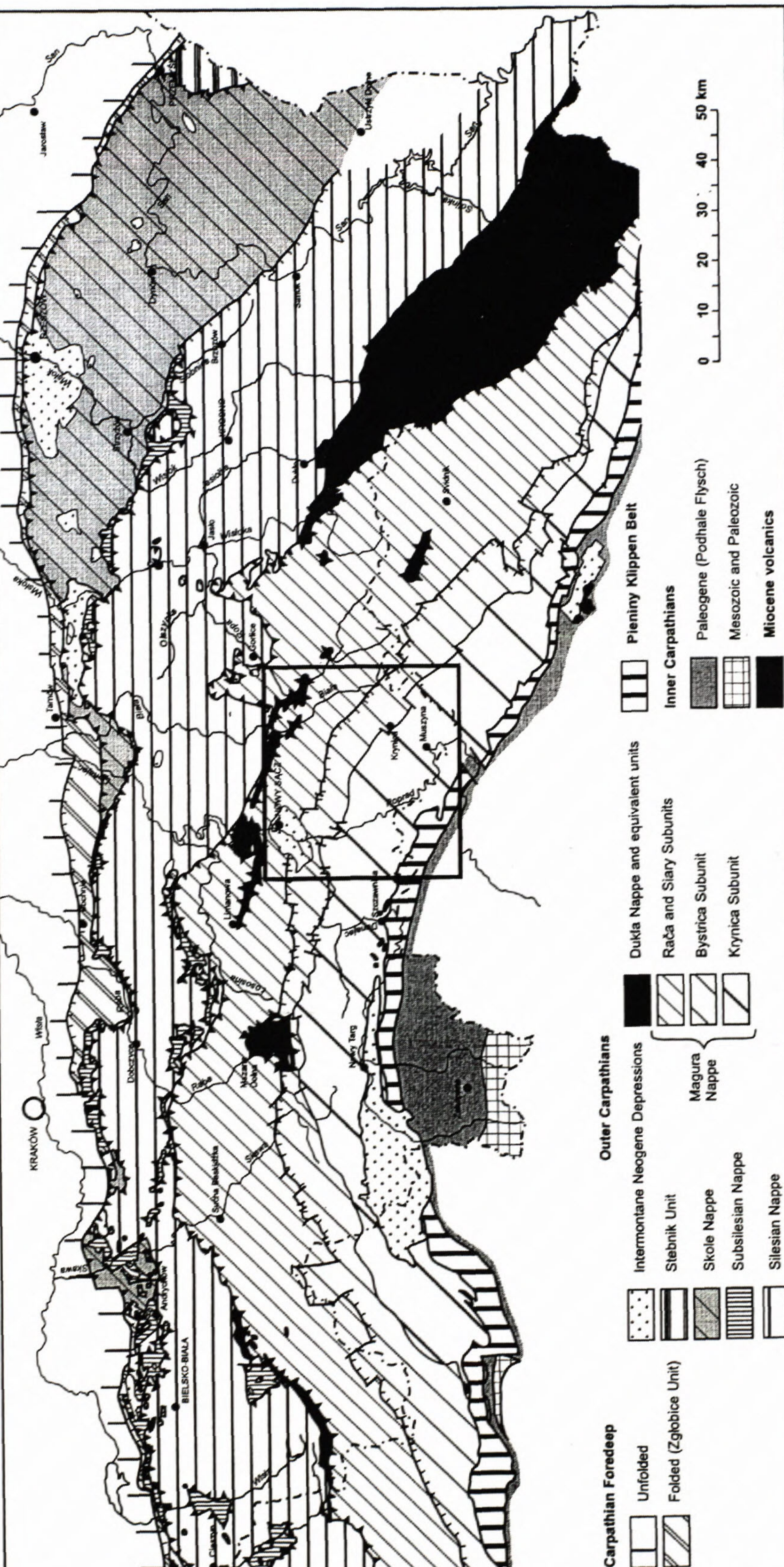

Fig. 1: Tectonic sketch of the Polish Carpathians (based on Żytko et al., 1989). Area shown in Fig. 2 is boxed.

Książkiewicz (1968) was the first who distinguished in the Polish outer Carpathians transversal (cross-fold joints clustering into two conjugate sets of shear or shear-extensional joints, whose acute bisector strikes perpendicular to map-scale folds), and longitudinal (fold-parallel, mostly extensional) joint sets. The former were to be associated with folding (the age of jointing being different depending on depth), the latter were considered to postdate the main episode of folding. Some of cross-fold joints were thought to be extensional fractures. Książkiewicz (*op. cit.*) also noted the presence of diagonal joints, less distinctly marked as compared to the other sets, and thought them to have originated during post-orogenic uplift.

Tokarski (1975, 1977) hypothesized about pre-folding age of two sets of shear-extensional cross-fold joints, and syn-folding age of shear and extensional sets of longitudinal (fold-parallel) joints in the medial segment of the Magura nappe.

Aleksandrowski (1985 a, b, 1989) described from the Western outer Carpathians three sets of cross-fold joints, including a pair of conjugate shears (T_1, T_2) and one set of extensional joins (T'), two sets of fold-parallel joints (L, L'), as well as two sets of diagonal joints (D_T, D_L). Sets L, T_1 and T_2 were to originate during fold-and-thrust event in Oligocene-early Miocene times (F_L folding), L' and T' sets during the early Badenian compression ($F_{L'}$), and D_T and D_L sets in the post-early Badenian (Aleksandrowski, 1989) or post-early Sarmatian (Aleksandrowski, 1985 b) compressional event, associated with folding in the Eastern Carpathians (F_D). Longitudinal folds (F_L) in the Western Carpathians were to be superimposed by diagonal, buckle folds (F_D), the latter being accompanied by transversal folds (F_T) formed at the same time due to cross-fold faulting.

Mastella et al. (1997), summarising a few year study project on jointing in the Silesian nappe, have distinguished cross-fold joints, composed of a single set of extensional (T) and two sets of conjugate shear and/or hybrid (D_1, D_2) joints, formed in poorly lithified, horizontal strata before regional folding, as well as fold-parallel joints without giving any explanation as to origin of the latter. Similar conclusions can be drawn from papers published by Rubinkiewicz (1998), Tokarski & Świerczewska (1998) and Zuchiewicz et al. (1998) with respect to the other nappes in the Polish outer Carpathians.

Recently, Tokarski & Świerczewska (1999) and Tokarski et al. (1999) have concluded about early-folding age of cross-fold joints, followed by opening of fold-parallel joints during synsedimentary folding and thrusting in the Krynica subunit of the Magura nappe. Subsequent stages of structural evolution are thought to include several episodes of faulting, nearly exclusively utilising the pre-existing joint surfaces, and associated first with 90 ° dextral rotation of the outer Western Carpathians in middle Miocene times, and then, since the late Miocene, with structural collapse of the orogen.

Geological setting

The Magura nappe is the largest and innermost nappe of the Polish segment of the Outer Carpathians which during the thrusting movements has been completely uprooted from its substratum along the ductile Upper Cretaceous strata. The oldest rocks of this nappe (Albian/ Cenomanian spotty marls) are exposed only close to the southern margin of the Mszana Dolna tectonic window (Burtan et al., 1978; cf. also Fig. 1). On the basis of facies differentiation of Palaeogene deposits, the Magura nappe has been subdivided into four facies-tectonic subunits, namely the Krynica, Bystrica, Rača and Siary subunits (Koszarski et al., 1974; Książkiewicz, 1977).

Lithostratigraphy

The Upper Cretaceous-Palaeogene sedimentary sequence of the Magura nappe is subdivided into three turbiditic complexes of the Campanian/Maastrichtian-Paleocene, early through late Eocene, and late Eocene through early Miocene ages (Oszczypko, 1992; cf. also Fig. 4). Each complex begins with pelitic basinal deposits (variegated shales) which pass into thin- and medium-bedded turbidites with intercalations of allodapic limestones and/or marls, being replaced higher upwards by thick-bedded and, finally, thin-bedded turbidites.

The Upper Cretaceous sequence begins with variegated hemipelagic mudstones bearing intercalations of thin-bedded turbidites of Cenomanian/Turonian through Santonian/Maastrichtian age (Malinowa Fm.; cf. Fig. 4). The Malinowa Fm. passes upwards into thin- to medium-bedded turbidites of the 50-m-thick Kanina beds which include up to 30-cm-thick intercalations of turbiditic limestones (Cieszkowski et al., 1989). These strata are replaced higher up the section by thick-bedded sandstones and conglomerates of the Szczawina sandstones, 100 m to 350 m thick. The youngest member of this complex, 80-300 m thick, is composed of thin- to medium-bedded turbidites (Ropianka beds) of Paleocene age (Malata et al., 1996).

In the Krynica subunit, the variegated shales of the Malinowa Fm. are overlain by thin- to medium-bedded, calcareous turbidites of the 300-m-thick Szczawnica Fm., dated to Paleocene-early Eocene time (Birkenmajer & Oszczypko, 1989; Oszczypko et al., 1999 b). The Szczawnica Fm. passes upwards into thin-bedded turbidites of the Zarzecze Fm. (Early Eocene), 400-500 m thick, intercalated by thick-bedded sandstones and conglomerates of the Krynica Member, up to 250 m thick (Oszczypko et al., 1999 b).

North of the Krynica subunit, the Ropianka beds are overlain by 20-150-m-thick variegated shales of the Łabowa Fm., Early to Middle Eocene in age (Oszczypko, 1991). These shales pass upwards into thin-bedded turbidites of the Beloveža and Hieroglyphic Formations, a few hundred metres thick (Fig. 4). In the Bystrica subunit, the Beloveža Fm. is overlain by thin- to medium-bedded turbidites with intercalations of the Łącko-type marls (Oszczypko, 1991).

In all the subunits studied, the youngest deposits of Early through Late Eocene age belong to the Magura Fm., some 1,500 m thick (Oszczypko, 1991, 1992; cf. also Fig. 4). This formation is represented by thick-bedded turbidites and fluxoturbidites. In the Krynica and Bystrica subunits, the Magura Fm. includes Middle Eocene variegated shales of the Mniszek Mb. (Birkenmajer & Oszczypko, 1989). In the Krynica and Rača subunits, the Magura Fm. is locally overlain by the Oligocene Malcov Fm. (Birkenmajer & Oszczypko, 1989; Oszczypko-Clowes, 1998). The upper part of the Malcov Fm. in the Nowy Sącz Basin region, represented by marls and glauconitic sandstones (Oszczypko, 1973), has recently been distinguished as the Zawada Fm. of Early Miocene age (Oszczypko et al., 1999 a).

Tectonics

The Magura nappe is flatly overthrust upon the Fore-Magura group of units and partly upon the Silesian nappe (Fig. 2). East of the Raba river, the Fore-Magura group of units is represented by the Dukla nappe and the narrow and discontinuous Grybów unit, which is wedged between the Dukla and Magura nappes.

The total amplitude of the Magura overthrust is at least 50 km, the post-Middle Badenian displacement exceeding 12 km (cf. Oszczypko, 1998). The northern boundary of the nappe is of erosional character, whereas the southern one coincides with a subvertical strike-slip fault that follows the northern margin of the Pieniny Klippen Belt (PKB; Fig. 2). According to Nemčok (1985), the PKB and Magura nappe are separated east of Szczawnica by a subvertical backthrust fault.

The Magura sole thrust is developed mainly in ductile Upper Cretaceous variegated shales. The sub-thrust morphology of the nappe is highly differentiated, controlling the shape of the northern limit of the nappe and the distribution of its tectonic windows. The "embayments" of the frontal thrust are related to transversal bulges in the Magura's basement, whereas the "peninsulas" are located upon basement depressions. The zone of tectonic windows (Mszana Dolna, Szczawa, Klęczany, Ropa, Ujście Gorlickie, Świątkowa) is situated 10 to 15 km south of the

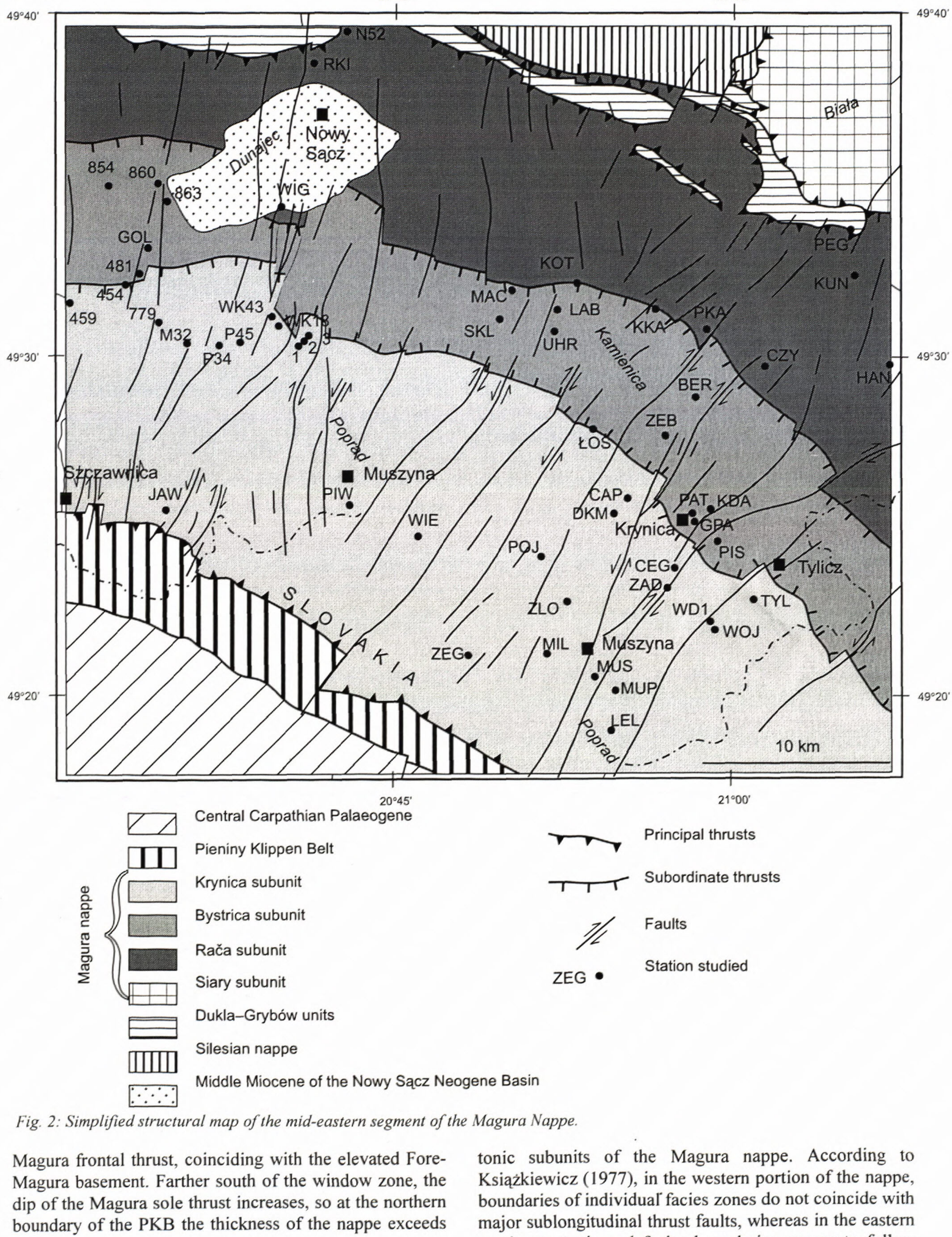

Fig. 2: Simplified structural map of the mid-eastern segment of the Magura Nappe.

Magura frontal thrust, coinciding with the elevated Fore-Magura basement. Farther south of the window zone, the dip of the Magura sole thrust increases, so at the northern boundary of the PKB the thickness of the nappe exceeds 5 km.

Among Polish geologists a controversy still exists as to the mutual relationship between facies zones and tectonic subunits of the Magura nappe. According to Książkiewicz (1977), in the western portion of the nappe, boundaries of individual facies zones do not coincide with major sublongitudinal thrust faults, whereas in the eastern portion tectonic and facies boundaries appear to follow one another (Sikora, 1970; Świdziński, 1972). As far as the eastern segment of the Magura nappe is concerned, only the northern limit of the Bystrica subunit is mapped as an important thrust fault (Żytko et al., 1989). In our opinion, the Krynica, Bystrica and Rača facies zones east of the Mszana Dolna tectonic window are separated by faults (cf. Oszczypko, 1973; Oszczypko & Wójcik, 1992; Oszczypko et al., 1999 b; Malata et al., 1996), the character of which, however, can be observed at few localities only. Due to the lack of necessary pieces of evidence, it is difficult to define these zones as thrust slices or thrust sheets. The Bystrica zone is the only unit that fulfills the definition of a thrust sheet. That is the reason why the above-mentioned zones have been named "facies-tectonic units" (Sikora, 1970; Koszarski et al., 1974), "facies-tectonic zones" (Oszczypko, 1973) or "tectonic subunits" (Birkenmajer & Oszczypko, 1989). The problem can be solved both by new drillings and detailed structural mapping of the contact zones.

West of the Poprad river, the Krynica and Bystrica subunits are probably separated by a W-E-trending thrust fault (Fig. 2). The Krynica subunit is thrust upon the youngest strata (variegated shales of Middle/Late Eocene age) of the Bystrica subunit. The frontal part of the Krynica subunit is represented by a narrow zone of few imbricated folds, composed of the Szczawnica and Zarzecze Formations, as well as by a syncline built up of the Magura Fm. (Oszczypko et al., 1999 b). East of the Poprad river, the Bystrica and Krynica subunits contact along a NW-trending, subvertical thrust fault dipping to NE (cf. Oszczypko et al., 1999 b). This fault, known as the "Krynica dislocation", is well recognised by wells drilled in the Krynica spa (Świdziński, 1972). In the latter area, the marginal part of the Krynica subunit is built up by a 200-500-m-wide anticline, composed of strongly deformed Paleocene-Lower Eocene strata of the Szczawnica Fm. Mesoscopic imbricated folds, accompanied by shear zones lined with 20-cm-thick calcite veins are a common feature in this zone. The overlying, Lower through Middle Eocene strata of the Zarzecze and Magura Formations are moderately deformed. It is important to note that the eastern segment of he Krynica fault and the northern boundary of the PKB are of backthrust character.

The Bystrica and Rača subunits are separated by a NW-trending thrust fault (Figs. 2, 3). The base of the Bystrica subunit is composed of Lower Eocene strata of the Beloveža and Łabowa Formations. In the Nowy Sącz Basin area, the Bystrica subunit is subvertically thrust upon Lower Miocene strata of the Rača subunit (Oszczypko et al., 1999 a). This thrust fault was reactivated during the Late Badenian.

All these units in the discussed portion of the Magura nappe display two different orientations of map-scale folds. -diagrams constructed by Szczęsny (1998) for homogeneous structural domains reveal that in the western part of the study area W-E to WNW-ESE orientated, westward-plunging (2-9°; in the northern Bystrica subunit exceptionally 15°) folds occur, whereas in the eastern segment (i.e., east of 20 °45 'E) folds plunging 3-16° southeastwards dominate.

The study area is cut by numerous, mostly NE-trending, both sinistral and dextral strike-slip faults (Fig. 3). Of particular importance is the Poprad-Dunajec fault system (Fig. 2) which was active at the time of deposition of the Late Badenian-Sarmatian infill of the Nowy Sącz Basin (Oszczypko, 1973; Oszczypko et al., 1992). Detailed studies in the Krynica area imply that the originally N35 °E - orientated sinistral faults were subsequently reactivated as dextral and dextral-reverse ones, whereas the younger generations of predominantly normal faults strike N10 °W and, less frequently, N45 °W and N85 °W (Zuchiewicz, unpublished data).

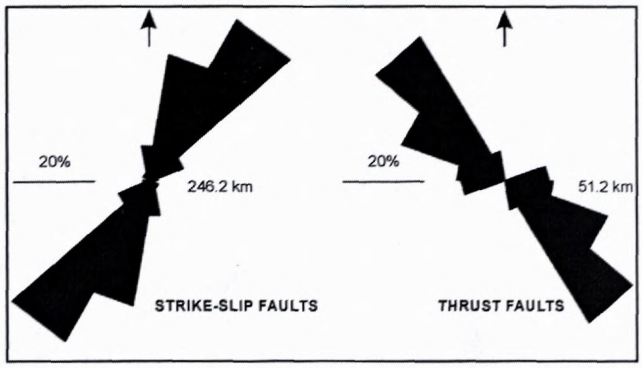

Fig. 3: Dominant orientation of map-scale thrust and strike-slip faults in the eastern segment of the study area (between Poprad and Biała rivers).

The Magura nappe reveals upward-diminishing degree of tectonic deformation. Close to the Mszana Dolna and Szczawa tectonic windows, the basal part of the nappe composed of upper Cretaceous-Paleocene flysch strata is strongly deformed (cf. Oszczypko et al., 1991, 1999 c), whereas in the Rača and Krynica subunits, built up mostly of Eocene flysch strata, broad, E-W trending synclines, separated by narrow anticlines, predominate. The southern limbs of synclines are frequently reduced and overturned. In the Bystrica subunit, in turn, subvertical thrust faults are a common feature. Both the northern limbs of anticlines and southern limbs of synclines are tectonically reduced and usually overturned. The youngest, Late Eocene-Early Oligocene, weakly deformed strata of the Krynica and Bystrica subunits unconformably overlie the older Eocene rocks (cf. also Oszczypko, 1973; Oszczypko & Żytko, 1987).

Material and methods

We have analysed 55 stations located in Eocene flysch strata of variable thickness and age that are exposed in the Krynica, Bystrica and Rača subunits of the mid-eastern segment of the Magura Nappe (Figs. 2, 4). Most of the data from the Krynica subunit represent Lower and Middle Eocene strata, those of Bystrica and Rača subunits coming from the Middle and Upper Eocene rocks. In all the subunits, stations located in thick-bedded sandstones dominate (75 %; Fig. 4).

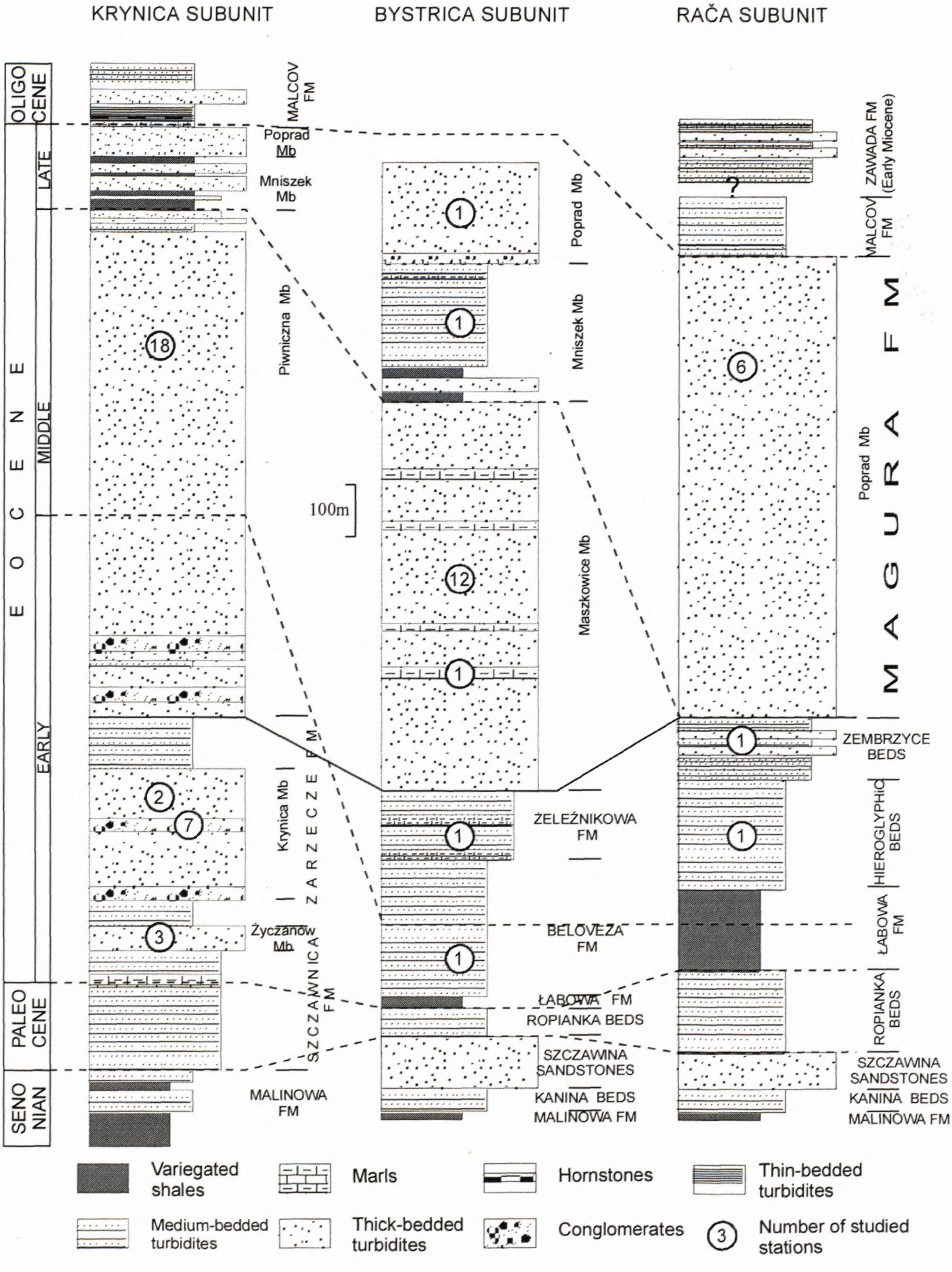

Fig. 4: Lithostratigraphic logs of the Krynica, Bystrica and Rača subunits. Circled numbers denote the number of stations studied.

At each station 50 to 100 measurements have been taken. The data have been plotted on lower hemisphere Schmidt projection and then bedding- and fold plunge-corrected. Interpretation of individual stereoplots is shown in Figs. 6 and 7.

Joint pattern: description

The regional joint network comprises five sets (Figs. 5-7). At individual exposures, however, usually two to four sets can be encountered. The sets maintain a relatively stable orientation in respect to the strike of map-scale folds. Sets showing the same regional orientation display both similar surficial features and the type of intersection with bedding surfaces.

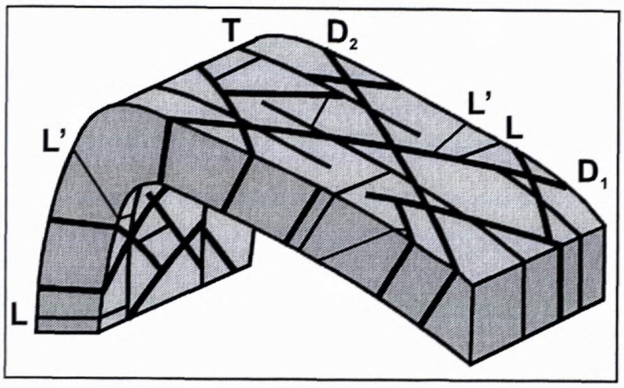

Fig. 5: Joint pattern in a folded sandstone bed (after Tokarski et al., 1999; modified).

Cross-fold joints comprise a single set (T) striking perpendicular or subperpendicular to map-scale fold axes (80-90°) and two sets (D_1, D_2) striking under high angles (60-80 °) 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 (70-90°).

Cross-fold joints

The surfaces of *T joints* are non planar, and their traces on bedding surfaces are usually curvilinear. The T joints are not accompanied by feather and *en echelon* fractures, and are lined by mineral (usually calcite) veins, particularly in calcareous thick-bedded sandstones. Joint surfaces are usually devoid of fringe structures. Fissures associated with this set are commonly open, unlike those related to the diagonal sets.

The strike of T joints varies along the studied segments of the Magura nappe from N30 °W to N60 °E in Raca, through N55 °W to N70 °E in Bystrica, to N25 °W - N75 °E in Krynica subunits, clustering at N15 °E and N5 °W in Bystrica and N15 °E in Krynica subunits (Figs. 6-8). These orientations are highly scattered, depending on local attitude of map-scale fold axes which changes from W-E to NW-SE and WNW-ESE in the western, central and eastern portions of the studied segment of the Magura nappe, respectively.

The surfaces of *D_1 and D_2 joints* are planar and their traces on bedding surfaces are rectilinear. Some of D_1 joints terminate on D_2 joints and vice versa. Both sets intersect one another under acute angle, whose bisector is orientated NNW to NE throughout the study area (Figs. 6, 7, 9). Fissures associated with both the sets, a few millimetres wide, are filled at places by calcite.

Numerous joints of the D_1 and D_2 sets are accompanied by millimetre-scale feather fractures of dips not exceeding 30° that represent low-angle Riedel shears (*sensu* Riedel, 1929; Bartlett et al., 1981). Locally, instead of a linear trace, an *en echelon* array composed of low-angle Riedel shears can be encountered, passing sometimes into a continuous joint surface. Some of *en echelon* cracks are filled by material derived from country rocks or by calcite contaminated by this material.

The orientation of D_1 joints changes from N25 °W in Raca and Bystrica subunits to N5 °E in Krynica subunit (Figs. 6-8), that of D_2 joints being N40 °E, N55 °E, and N45 °E in Raca, Bystrica and Krynica subunits, respectively. The scatter is also notable, reflecting differentiated strike of map-scale folds of the region. No regional variability of orientation of both these sets has been observed, although Bystrica subunit displays a wider scatter of dominant joint attitudes. The acute angle between the D_1 and D_2 joints is 50-60° in Raca, 30-80° in Bystrica, and 25-80° in Krynica subunits, averaging at 60-70°. The lowest figures (25-40°) have been encountered at individual stations in Krynica and Bystrica subunits, although average values for all the three units discussed tend to diminish northwards: from 61° and 60° in Krynica and Bystrica subunits, to 55° in Rača subunit (Figs. 6, 7).

Fold-parallel joints

Fold-parallel (longitudinal) joints (L, L') strike subparallel to the map-scale folds and comprise two sets of different orientation (Figs. 6-8). Set L comprises joints striking N65 °W, N30 °W and N55 °E in Rača, N75 °W, N55 °W and N60 °E in Bystrica, as well as N60 °W, W-E and N25 °W in Krynica subunits; those of set L' being orientated, respectively, W-E and N35 °E; N75 °E, N30 °W and N55 °W, as well as N65 °W, N35 °W and N85 °E. In general, the prevailing N65-75 °W strike of L joints in Rača and Bystrica subunits is locally overprinted by N30-35 °W and N55-60 °E orientations, whereas in Krynica subunit it is overprinted by W-E and, rarely, N25 °W orientations. The pattern of L' joints is even more chaotic. In most cases, the L joints are subparallel to the map-scale folds, usually occurring in hinges of large-scale structures and normal to the T joints (Figs. 8, 10). Joints of the L' set, in turn, strike under small angle (20-25°) to the map-scale fold axes and are nearly perpendicular to the acute bisector between the D_1 and D_2 sets.

Joint pattern: interpretation

Cross-fold joints

The morphology of *T joints* indicates that their development proceeded without the initial "shear" stage and

KRYNICA SUBUNIT

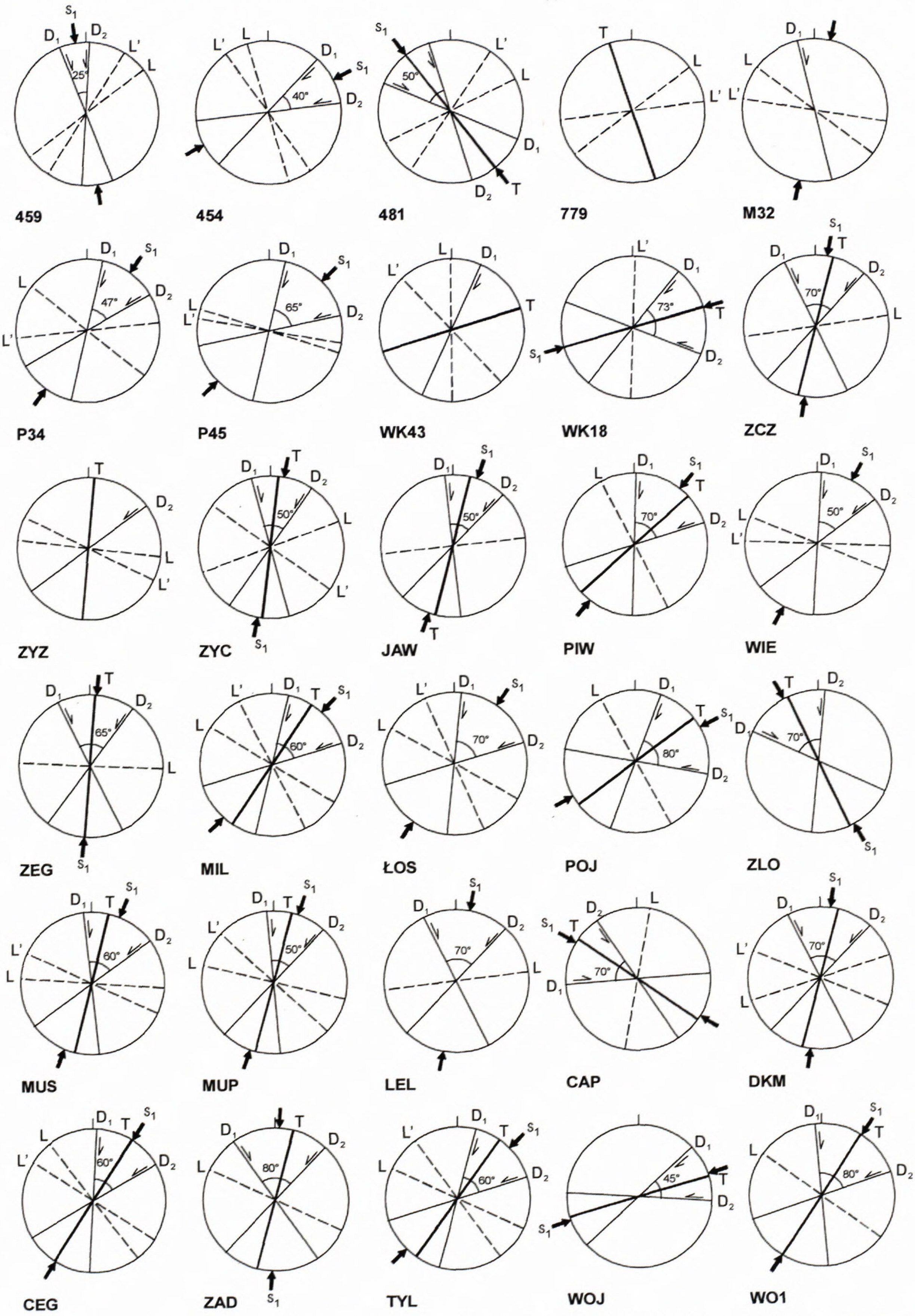

Fig. 6: Joint pattern at individual stations in the Krynica subunit. Cross-fold joints: T, D_1, D_2; fold-parallel joints: L, L'; s_1 - orientation of the maximum horizontal stress related to the cross-fold shear joint formation.

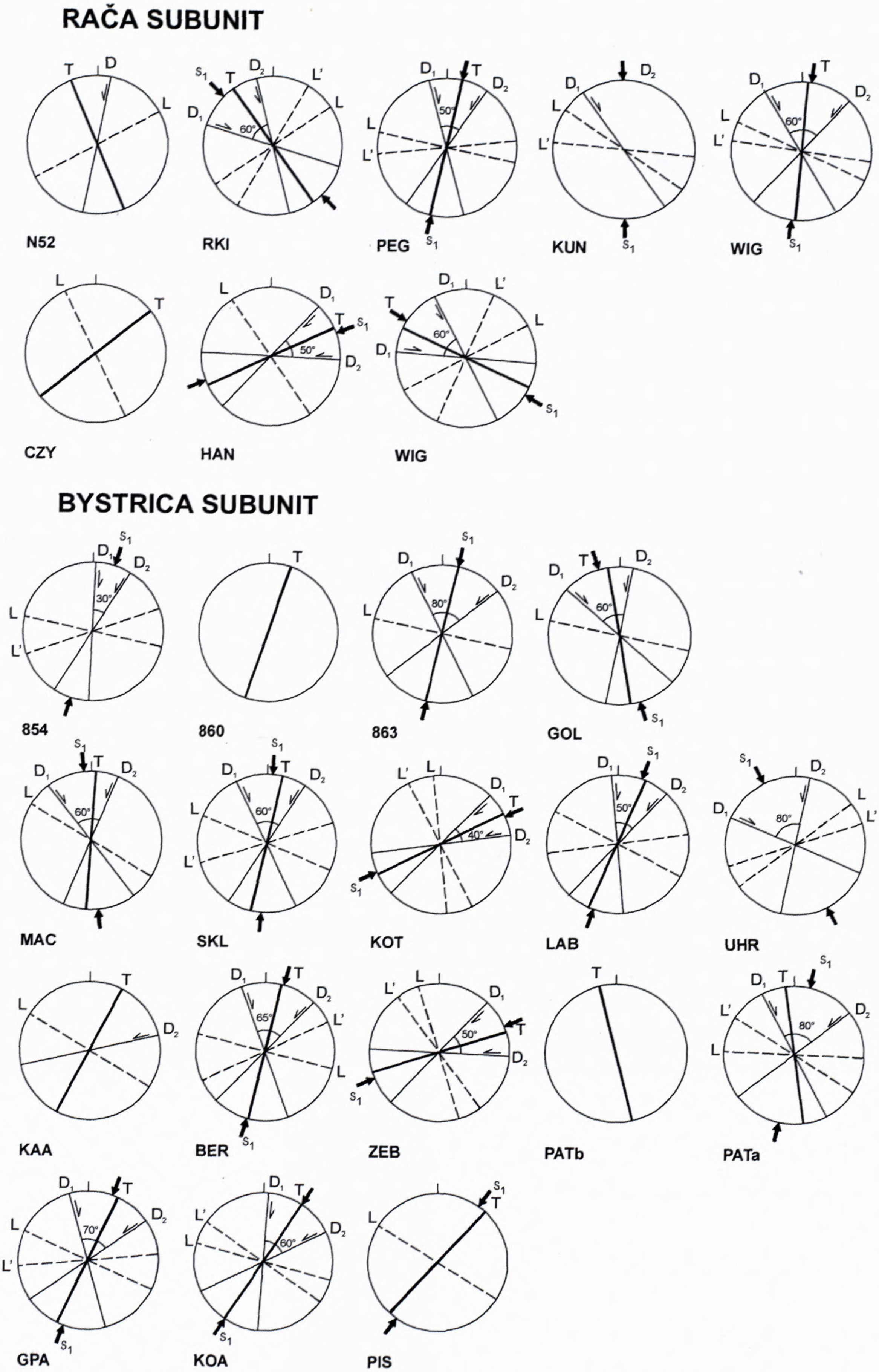

Fig. 7: Joint pattern at individual stations in the Bystrica and Rača subunits. For explanation - see Fig. 6.

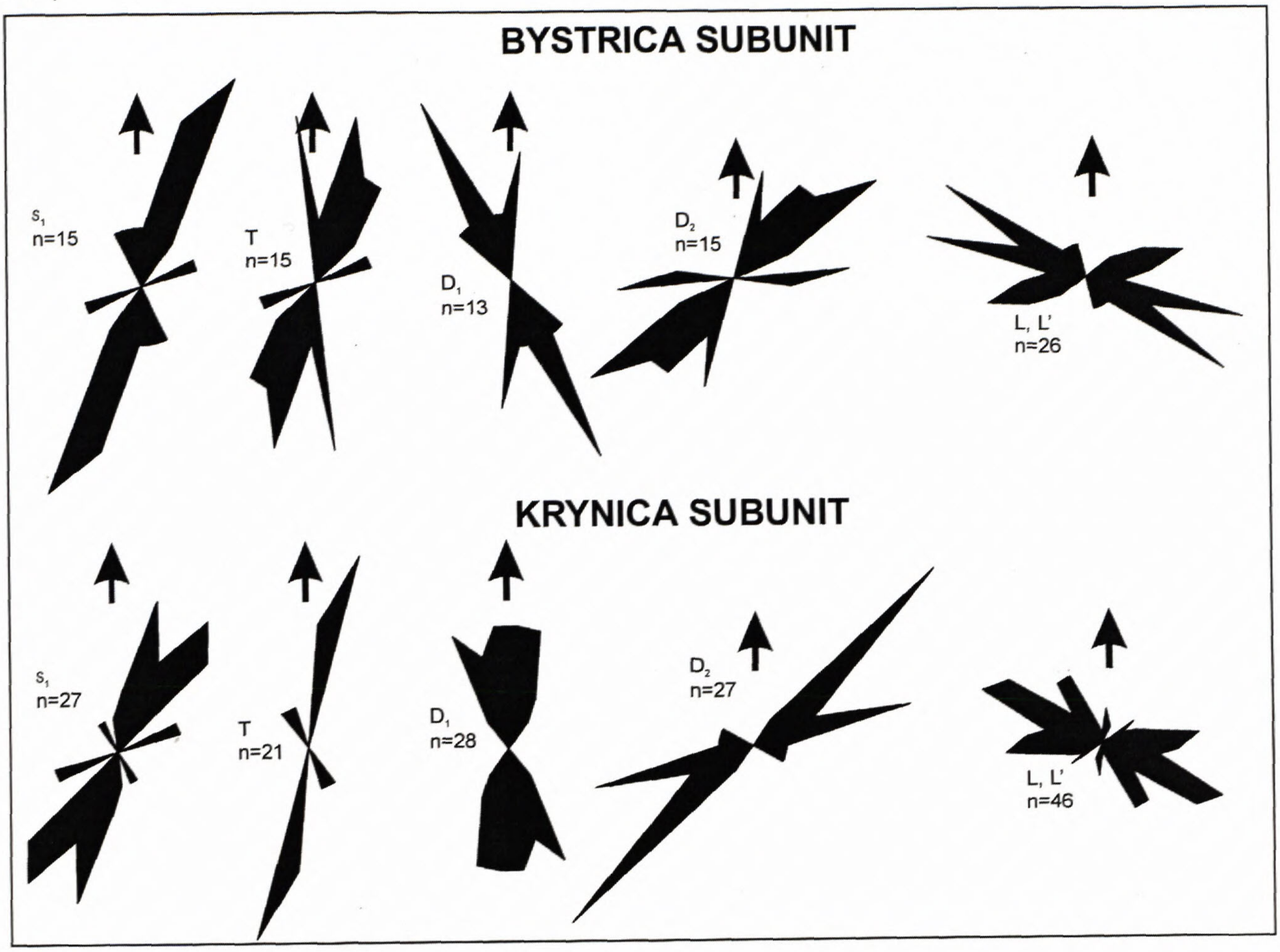

Fig. 8: Dominant orientations of principal joint sets in the Bystrica and Krynica subunits.

that they are extension (mode I) fractures (Price & Cosgrove, 1994).

Morphological properties of the *diagonal* (D_1, D_2) *joints* indicate that the incipient stage of their development was a shear one, whereas their further opening proceeded in extensional mode. 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, whose acute bisector is orientated differently throughout the mid-eastern Magura nappe: from N45 °W - N70 °E in Rača, through N55 °W- N70 °E in Bystrica, to N30 °W - N70 °E in Krynica subunits. The prevailing orientations are, however, N10 °E, N20 °E, and N35 °E, respectively. Deviations from these dominant trends areparticularly noticeable for stations located close to major strike-slip faults, like those associated with the Poprad and Dunajec river courses or situated shortly west of Krynica (Fig. 9).

Furthermore, abutting relationships suggest that the D_1 and D_2 joints are roughly coeval and were formed as "potential shear surfaces" in the triaxial stress field. The local occurrence of plumose structures, in turn, points to subsequent extensional opening of some of these joints.

We suppose that these joints are shear and, at some stations in Krynica and Bystrica subunits, hybrid fractures (Hancock, 1985) that form a conjugate system. Moreover, some of the joints were formed when the host strata were poorly lithified, as indicated by contamination of mineral veins that fill the joints by material derived from the host strata.

The acute angle comprised between the D_1 and D_2 sets (double value of the angle of shear, 2 ?) changes at individual exposures from 25° to 80° (Figs. 6, 7). Nearly 75 % of our data, however, fall into the interval of 60-70°. A regional tendency towards not very significant decrease of these values from the south to the north (61° to 55°) is to be noted.

The extensional T joints, in turn, appear to represent a younger episode of deformation closely associated with folding, particularly that related to extension in fold hinges. This set is probably coeval with fold-parallel L joints.

The above results concerning cross-fold joints in the mid-eastern Magura nappe appear to fulfill criteria listed by Hancock (1985) which lead to a conclusion that extension joints usually form single sets, and that conjugate hybrid joints enclose small dihedral angles (10-50°, commonly 35-45°), whereas conjugate shear joints enclose angles of 60° or greater.

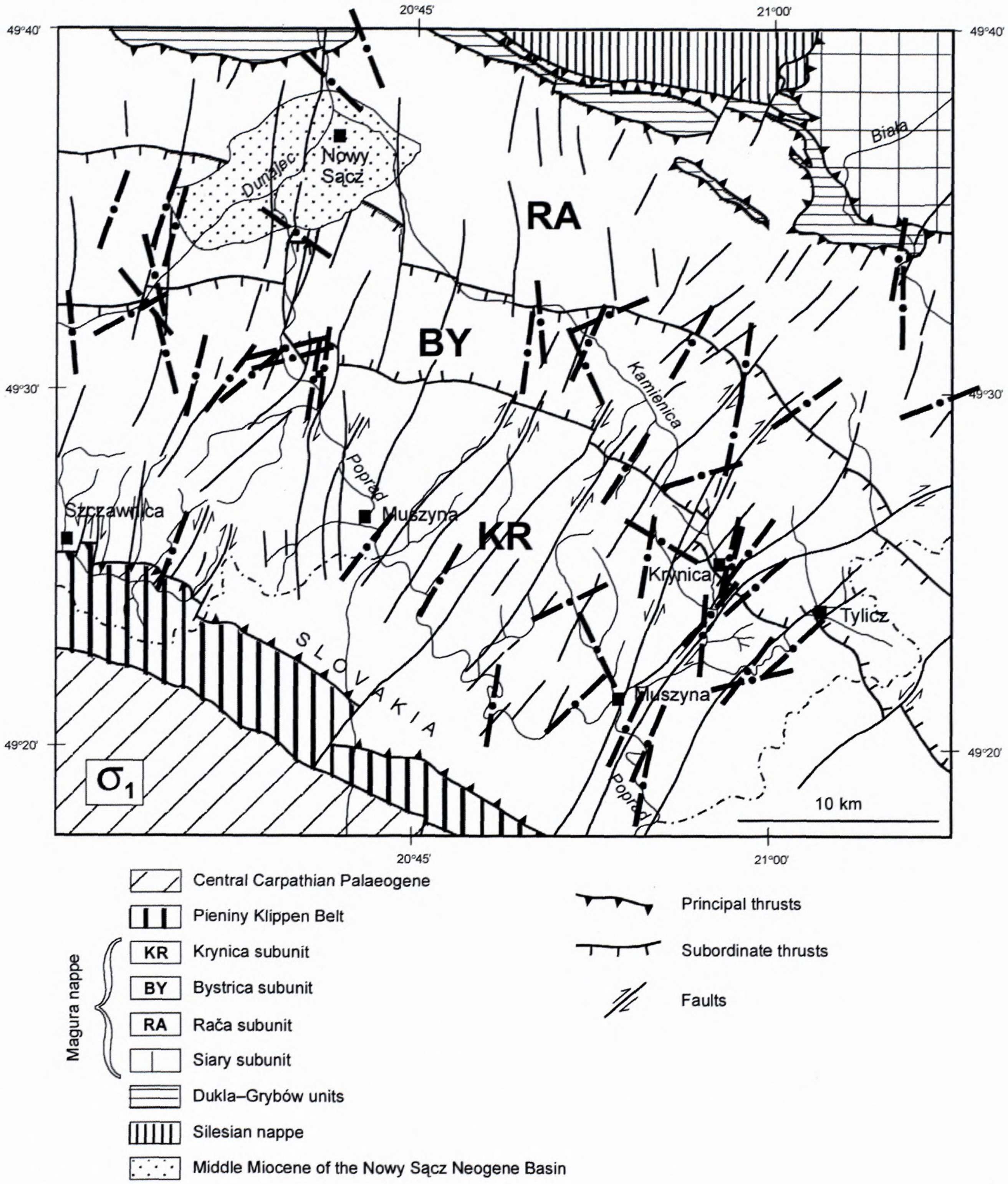

Fig. 9: Spatial distribution of cross-fold joint-related s_1 in the study area.

Fold-parallel joints

Both the L and L' sets are devoid of properties that would point to their shear origin. The morphology of joint surfaces, occurrence of plumose structures (particularly common in the L' set), and characteristic discontinuous or fading, at places nonlinear, traces of intersection with bedding planes appear to indicate extensional origin.

Discussion

Morphological properties of diagonal shear and hybrid joints imply that their formation occurred during early stages of syndepositional folding, when the host strata were not fully lithified. This is confirmed by the presence of calcite contamined by host rock-derived material within *en echelon* arranged veins related to the

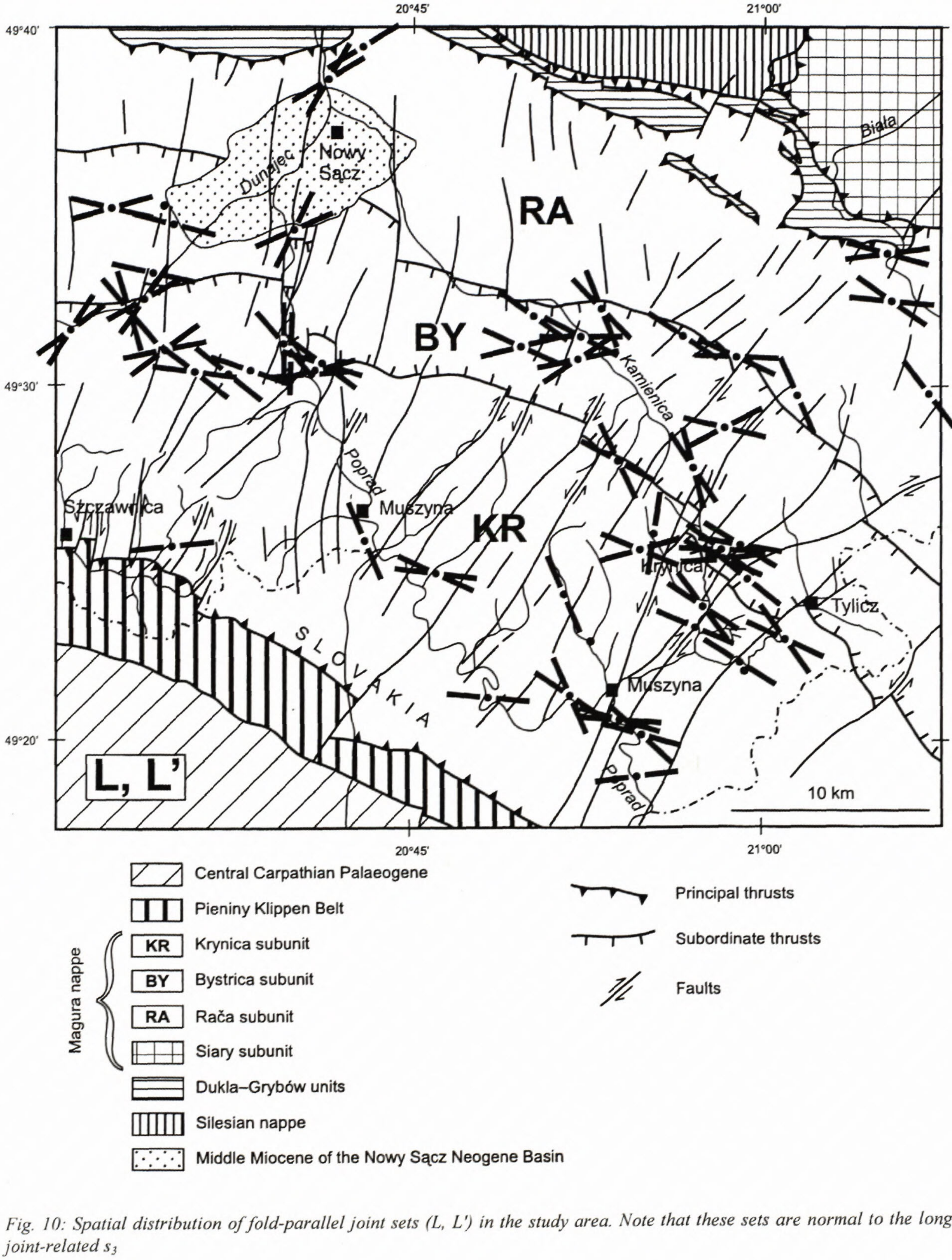

Fig. 10: Spatial distribution of fold-parallel joint sets (L, L') in the study area. Note that these sets are normal to the longitudinal joint-related s_3

cross-fold D_1 and D_2 sets. Fig. 11 shows the most frequently observed configuration of joint sets in the Magura nappe subunits, indicative of a minor anticlockwise rotation of the shear joint-related s_1 when proceeding from the south to the north, during the early through late Eocene folding. The acute angle comprised beween most frequently occurring diagonal joint sets appears to be changing from 40° in Krynica, through 80° in Bystrica to 65° in Rača subunits, whereas average values calculated for individual subunits tend to show another, northward-decreasing, trend. This apparent paradox results from diversified number of data available for each subunit and

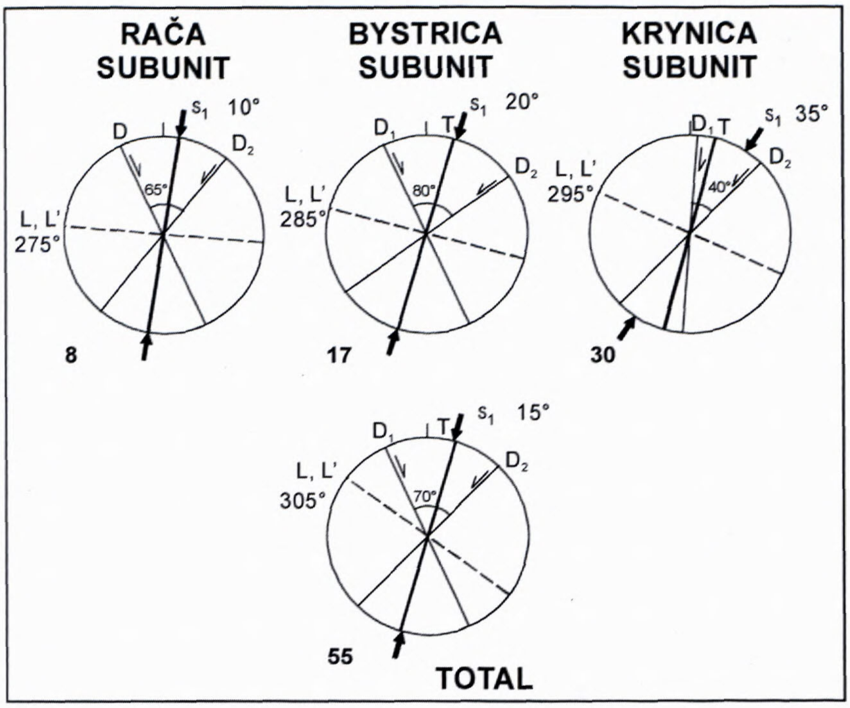

Fig. 11: Joint pattern in the mid-eastern segment of the Magura Nappe. Note anticlockwise rotation of the early joint-related principal compressive stress axis from the south to the north, i.e. from the Krynica, through Bystrica to Rača subunits.

their variable scatter. This contradiction makes it impossible - at this stage of research - to conclude about possible differentiation in overburden at the time of syndepositional folding and, consequently, shear jointing. The most frequently occurring pattern of cross-fold joints, however, points to relatively greater thickness of overlying strata in the Krynica subunit.

According to hitherto-published opinions, folding in the outer Carpathian basins took place several times: at the end of the Early Cretaceous, during the Laramian orogeny (Senonian - Paleocene), during the Eocene (synsedimentary folding in the Krynica subunit of the Magura nappe; cf. Żytko, 1977, 1999; Świerczewska & Tokarski, 1998), following the end of the Eocene and, predominantly, at the turn of the Oligocene/Miocene or during Miocene times (Książkiewicz, 1977; Oszczypko et al., 1991; Roca et al., 1995; Oszczypko, 1998; Ślączka & Kaminski, 1998).

The outer Carpathians are regarded as a remnant oceanic basin which developed between the colliding European continent and intra-oceanic arcs (cf. Oszczypko, 1999). Similarly to other orogenic belts, the outer Carpathians were progressively folded towards the continental margin. This process was initiated during the Paleocene by the formation of the Magura accretionary wedge. The first stage of basin shortening and coeval growing of the Magura accretionary wedge was probably completed before the Priabonian, being connected with submarine folding in the Bystrica and Krynica subbasins and development of the Krynica thrust. At the end of the Eocene, this part of the Magura basin was overlapped by the Globigerina Marls and then by flysch deposits of the Malcov Fm. (Oszczypko-Clowes, 1998). The northern part of the basin (Rača and Siary subbasins) was still occupied at that time by the deposition of the Magura Fm. and Wątkowa glauconitic sandstones, respectively. Deposition in the Magura basin persisted until the Late Oligocene (Oszczypko-Clowes, 1999). After the late Oligocene/early Miocene folding episode, the Magura nappe was thrust northwards onto the terminal Krosno flysch basin (Oszczypko, 1999). In the course of the Burdigalian transgression, the middle portion of the Magura nappe was invaded by the sea (Oszczypko et al., 1999 a). This transgression was followed by the intra-Burdigalian (late Ottnangian) folding, uplift, and thrusting of the marginal part of the Carpathians which overrode the European platform (Oszczypko, 1998). This episode of compression is manifested in the Magura nappe by thrusting of the Bystrica subunit onto the Burdigalian strata of the Nowy Sącz area. Subsequent shortening in the Magura nappe took place during the Late Badenian movements, leading to the steepening of the Bystrica and Krynica subunits. The last compressive event was postdated by formation of the Late Badenian/Early Sarmatian Nowy Sącz and Orava extensional basins.

According to Kovač et al. (1998), the maximum compressive stress in the Western Carpathians progressively rotated from NW-SE (Eggenburgian), through NW-SE (western segment) and NE-SW (eastern segment) during the Karpatian, to NE-SW in late Badenian and Sarmatian times.

The results of hitherto-conducted research into the history of jointing in the Polish outer Carpathians imply that the Palaeogene history of all the nappes was probably dominated by strike-slip stress regime, with more or less constant orientation of the maximum principal stress (Zuchiewicz et al., 1998). This regime has been active throughout the area since the Paleocene and, at least in the eastern segment of the Silesian nappe, since the Cretaceous (cf. Rubinkiewicz, 1998). The post-Palaeogene structural development of nappes located north of the Magura nappe was different from that of the Magura nappe (Zuchiewicz, 1998 a; Tokarski & Świerczewska, 1998; Zuchiewicz et al., 1998), in which the early joint pattern was disturbed by refolding, drag on cross-fold strike-slip faults, and/or by rotations of blocks bounded by gently-dipping shear zones (Aleksandrowski, 1985 b; Oszczypko et al., 1991; Decker et al., 1997; Zuchiewicz, 1998 a; Tokarski et al., 1999). The position of shear joints-related maximum stress axis was horizontal, its orientation changing from NW through NNE to NE in the western, medial and eastern portions of the outer Carpathians, respectively. Extension related to the formation of fold-parallel joints in the corresponding segments of the Carpathians was orientated NW, NW to N-S, and NE (cf. Zuchiewicz & Tokarski, 1999).

Deviations of the reconstructed cross-fold joint - related s_1 from the position normal to map-scale fold axes, observed at some places in the mid-eastern Magura nappe (Fig. 9), can be explained as a result of subsequent, i.e. post-Eocene episodes of folding and thrusting, as well as by rotation of some fault-bounded blocks, like those situated close to the Poprad and Dunajec river courses or west of Krynica.

Abutting relationships indicate that fold-parallel joints are younger features which originated during late stages of map-scale folding (L) or shortly after, during post-orogenic, mostly cross-fold extension (L').

Orientation of s_1 associated with the cross-fold shear joints coincides with that of recent horizontal stresses (NNE to NE) recorded by breakouts in the western and medial segments of the outer Carpathian flysch nappes (Jarosiński, 1998), but differ from those inferred from focal solutions of recent earthquakes (N to NNW) in the Krynica area (Wiejacz, 1994; Dębski et al., 1997).

Conclusions

The studied stations in the Krynica, Bystrica and Rača subunits represent northward-younging members of Eocene strata. Morphological properties of cross-fold shear or hybrid joints point to their formation at the time when host strata were not fully lithified, whereas their geometric relation to map-scale folds implies genetic relationship with early stages of syndepositional folding. The age of this folding was different in different subunits of the mid-eastern Magura nappe, migrating in time from the Early through Late Eocene times (cf. also Żytko, 1977, 1999). The regional stress field associated with these processes was probably characterised by a 15° counterclockwise rotation of shear joint-related s_1 from N35 °E in Krynica subunit to N10 °E in Rača subunit throughout the Eocene, possibly due to a change of the sense of subduction of the European plate under Alcapa (at present coordinates). Fold-parallel, extensional joints, represent younger episodes of deformation, related to post-orogenic, variably orientated extension. Local deviations observed throughout the area, and consisting in the position of shear joint-related s_1 different from normal to map-scale folds, are interpreted as a result of younger episodes of Miocene folding and thrusting that affected the whole studied portion of the Magura nappe, as well as due to still younger rotations of individual, fault-bounded blocks.

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