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THE INTERPLAY OF THE THERMAL AND STRUCTURAL HISTORIES OF THE MAGURA NAPPE (OUTER CARPATHIANS) IN POLAND AND SLOVAKIA

A b s t r a c t . X-ray diffraction studies of illite-smectite provide a tool for the reconstruction of the burial, thermal history and tectonic activity of the Magura Nappe in the Outer Carpathian arc. The observed thermal alteration of the rocks on the present-day erosion surface of the nappe reflects temperatures from < 75 to 200°C associated with tectonic burial to depths between < 4 and 11 km.

The present-day thermal structure of the Magura Nappe was largely established during the growth of an accretionary wedge. An outwardly directed decrease in thermal alteration across the nappe as well as a positive correlation between the age of rocks and the grade of their alteration are both related to the growth of this wedge. The thermal alteration of the Magura Nappe was accomplished before emplacement into its present-day structural position.

Two main stages of uplift and erosion can be identified. The first, which took place before Karpatian times, resulted in the removal of up to 4 km of strata. The second stage was related to the subsequent thrusting with co-eval internal deformation of the Magura Nappe over its foreland. The accretion-related thermal structure was greatly modified during this later event. Uplift was significantly influenced by the morphology of the Carpathian basement. The amount of erosion was greatest above and inward from the basement slope and involved exhumation of the most altered rocks. This stage, initiated in the Early Miocene, was still in progress in Early Sarmatian times.

Key-words: accretionary wedge, illite/smectite, thermal history, erosion, Outer Carpathians

INTRODUCTION

The Magura Nappe is the innermost part of the accretionary wedge of the Western Outer Carpathians (Fig. 1A). It formed during southward subduction of oceanic- or sub-oceanic crust intervening between the continental crust of the ALCAPA Unit and the European Platform and during the subsequent collision (review: Konečný et al. 2002). Migration of the accretion- and deformation front towards the descending plate should be expressed in spatial variations of burial history and in the amount of exhumation and erosion of the Magura Nappe as part of a thrust and fold belt (compare Molnar, Lyon-Caen 1988; Brandon 2004). Information about these processes is recorded in the

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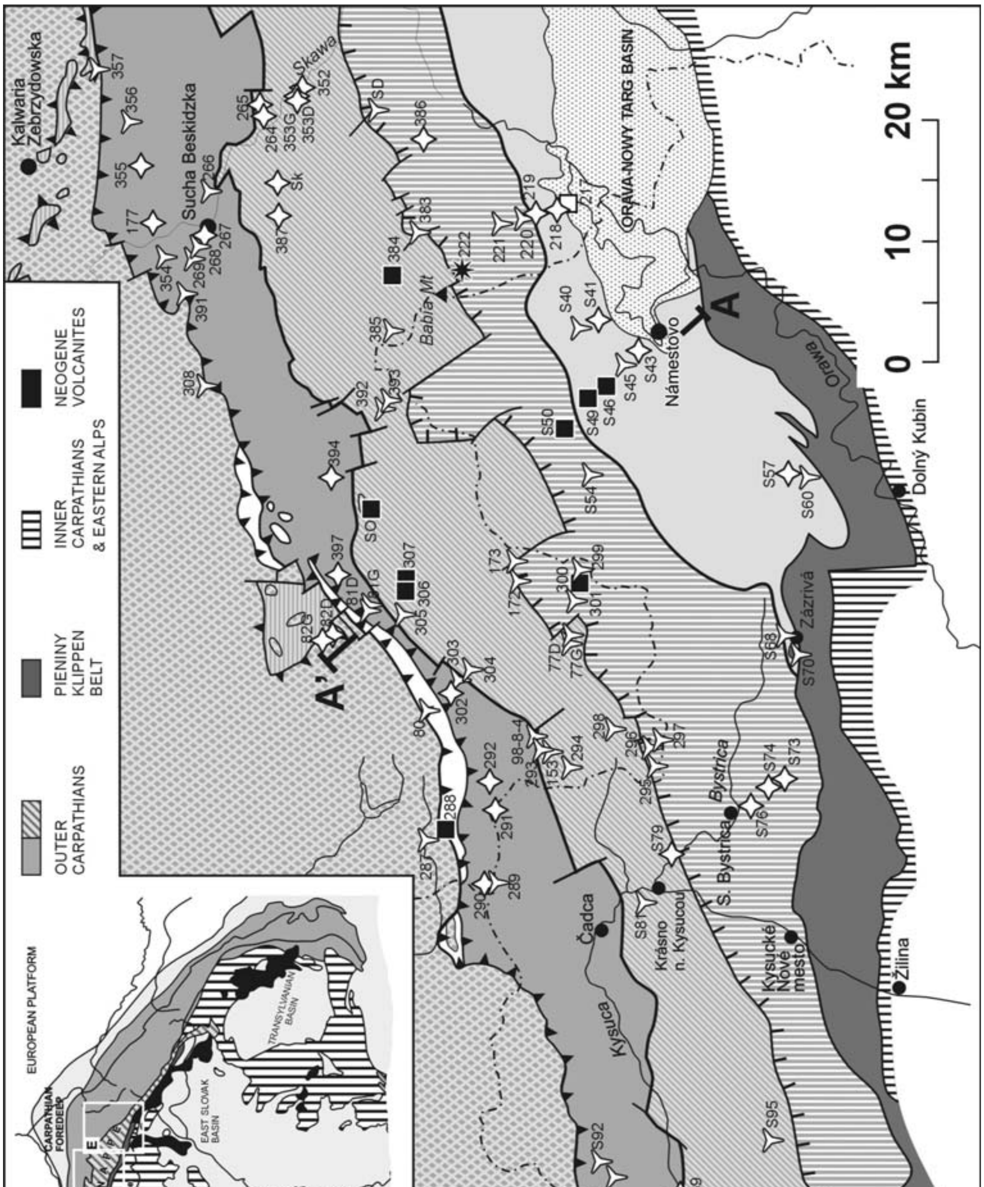
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Fig. 1. A–B

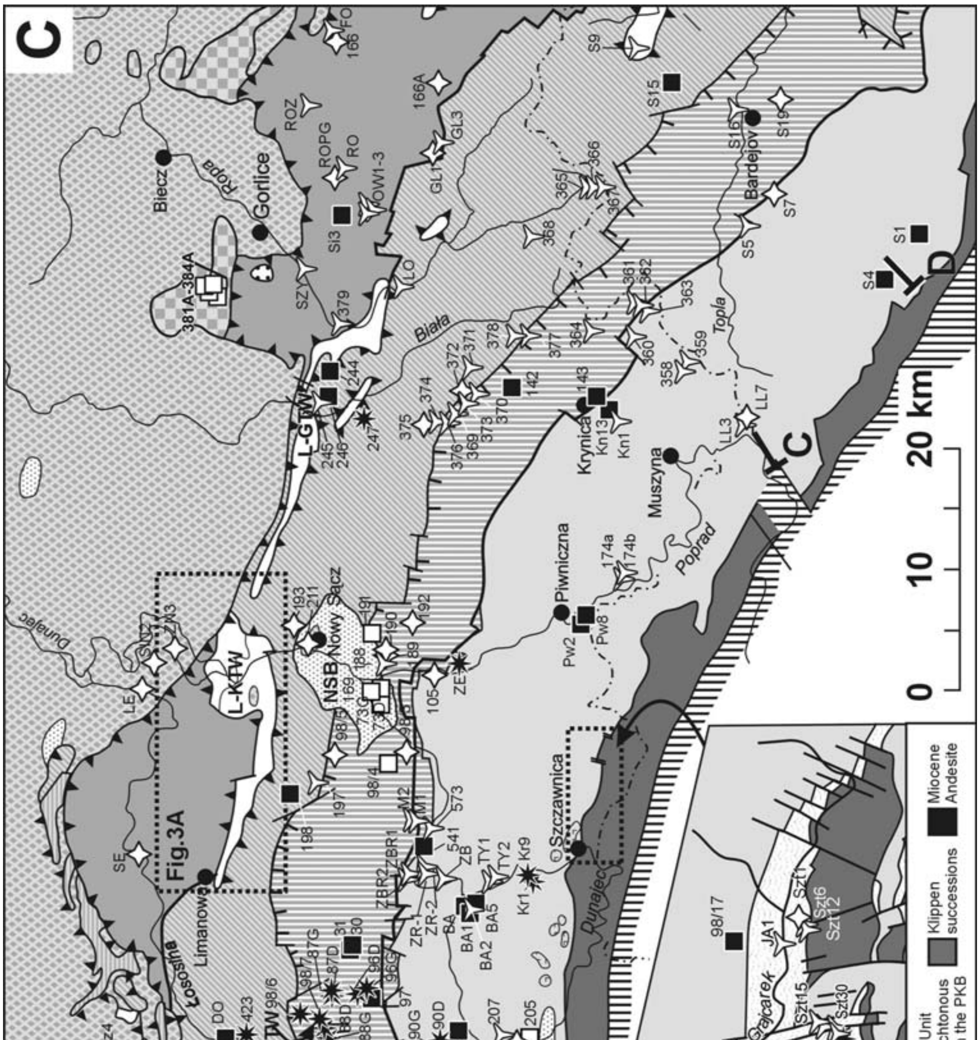
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Fig. 1. C–D

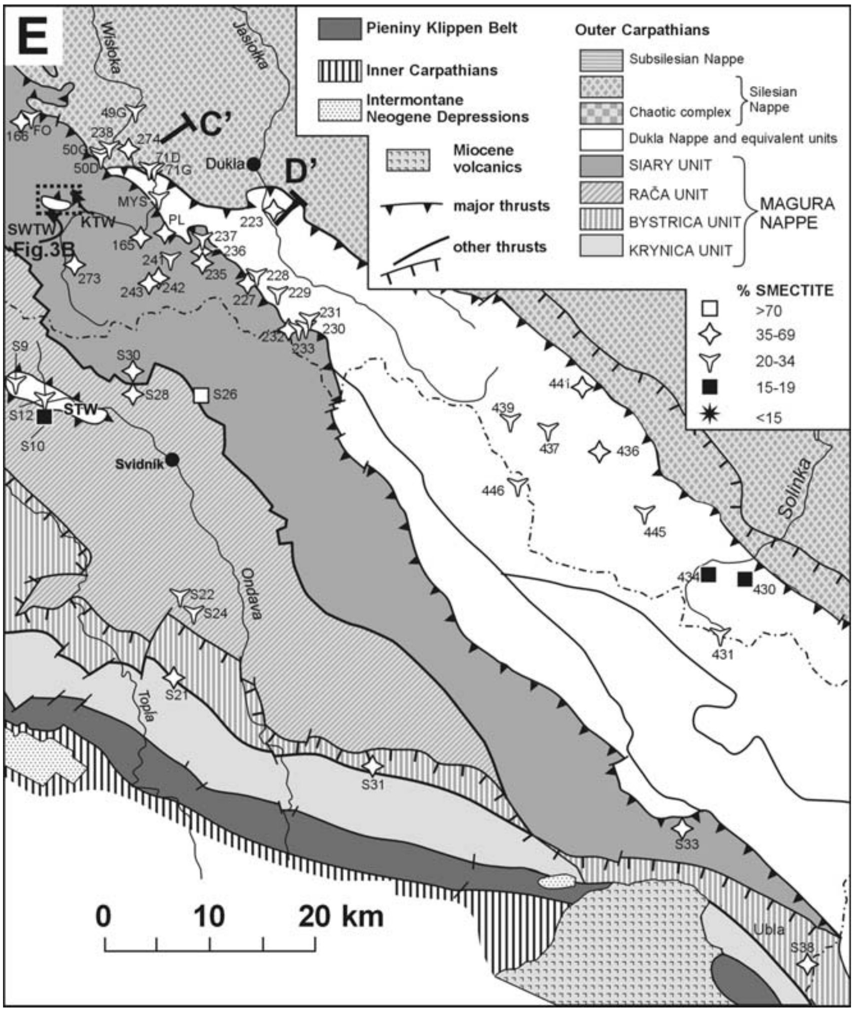

Fig. 1. A. Location of the study area (white rectangles) in the Carpathian arc (geology after Żytko 1999). B–E. Maps showing the locations of sampled sites and variations in I/S composition in the western (B), the central (C) and the eastern (E) parts of the studied segment of the Magura Nappe and adjoining areas and in the Pieniny Klippen Belt close to Szczawnica (D).
Sample numbers correspond to those in Appendices 1–4 where more data on the samples is provided. A–A′, B–B′, C–C′ and D–D′ are profiles used to estimate the amounts of erosion shown in Fig. 13. Abbreviations: KTW — Kotań tectonic window, L–GTW — Librantowa, Grybów and Ropa tectonic windows, L–KTW — Limanowa-Klęczany tectonic window, MDTW — Mszana Dolna tectonic window, NSB — Nowy Sącz Basin, STW — Smilno tectonic window, SZTW — Szczawa tectonic window, SWTW — Świątkowa tectonic window. Names of tectonic units and explanations of graphic symbols expressing ranges of S content in I/S are shown in E. The geology in B, C, and E was compiled from Jankowski et al. (2004); Ryłko and Tomaś (2003); Potfaj et al. (2002); Żytko et al. (1988).
The geology in D was compiled from Birkenmajer and Gedl 2004

thermal history of the sedimentary rocks. In this context, the mixed-layer illite-smectite (I/S) is potentially useful as a paleotemperature indicator due to its abundance in the sedimentary rocks.

The I/S is a product of the progressive transformation of smectite (S) to illite (I) controlled by temperature (Pollastro 1993) and by the physical and chemical properties of smectite-bearing rocks (Środoń 1979; Šucha et al. 1993; Harvey, Browne 1991; Honty et al. 2004). Illitization is a rapid and probably a time-independent process (Pollastro 1993, Środoń 1995) which results in a decreasing number of smectite particles and an increase in degree of structural ordering (Moore, Reynolds 1997). In argillaceous rocks, this transformation is mainly driven by increases in temperature (Pollastro 1993; Środoń 1995). The degree of smectite to illite conversion reflects equilibrium attained at the time of maximum paleotemperature (Pollastro 1993). In burial diagenetic settings, these paleotemperatures are usually correlated with burial depth (e.g., Šucha et al. 1993).

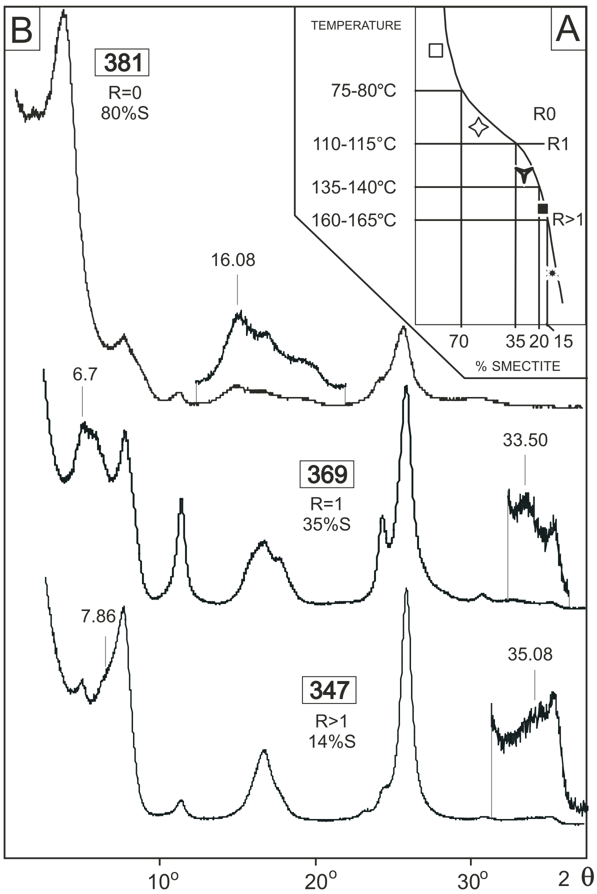

Fig. 2. A. Temperature versus %S in I/S from claystones (Šucha et al. 1993) including the 10°C correction of Clauer et al. (1997). Graphic symbols marking ranges of I/S composition are as in Figs 1B–D.
B. X-ray powder diffraction patterns of glycolated samples with different proportions of S and different ordering R. Diagnostic I/S peaks are marked with 2Θ values

Pure smectite and illite-smectite of detrital origin are stable up to about 70°C (Hoffman, Hower 1979; Jennings, Thompson 1986; Harvey, Browne 1991). Illitization begins at about 70–80°C with random interstratifications described as R0 (Fig. 2A). In the temperature range 110–120°C, transition from random- to ordered (R1) interstratifications occurs. At about 165°C, highly ordered structures appear (R>1). For claystones, these stages correspond to about 70%, 35% and 15% S in I/S, respectively (Fig. 2A; Šucha et al. 1993; Clauer et al. 1997). At a temperature of about 210°C, pure illite appears (Środoń 1999).

The results of earlier studies on I/S diagenesis in the Outer Carpathians show strong regional variations in the degree of smectite to illite transformation on the present-day surface. These variations, expressed by the **S content in I/S** (%S in the following text) and by the type of structural ordering (R), are a probable consequence of differential uplift and erosion (Dudek et al. 2000; Dudek, Świerczewska 2001; Świerczewska et al. 2003a,b; Dudek et al. 2004; Świerczewska 2005).

Moreover, it seems that the rocks of the Magura Nappe had been folded prior to deep burial (Kotarba 2003). The aim of this paper is to present an explanation for regional variations in thermal maturity and to reconstruct the burial and exhumation history of the Polish and Slovak segments of the Magura Nappe.

GEOLOGICAL SETTING

Outer Carpathians

The Western Outer Carpathians (Fig. 1A) are a thrust-and-fold belt, north verging in the Polish segment, north verging and south verging in Slovakia. South verging structures have been described within the eastern part of the Pieniny Klippen Belt (PKB) where the Inner Carpathians dip under the PKB and the PKB dips under the Magura Nappe (*fide* Żytko 1999; Jankowski et al. 2004). South verging structures have also been described near Zázrivá (Fig. 1B) in the central part of the PKB where high-angle, south verging thrusts occur (Marko et al. 2005). The main tectonic features of the Western Outer Carpathian belt were formed in Paleogene-Early Neogene times due to subduction of the European Platform below the ALCAPA Unit and subsequent collision. The Polish and Slovak segments of the Outer Carpathians comprise a strongly deformed accretionary wedge composed of Upper Jurassic-Lower Miocene rocks thrust over the Miocene strata of the Carpathian Foredeep.

The belt is composed of several nappes (from S to N): Magura, Dukla (Fore-Magura group of nappes, *sensu* Cieszkowski, Ślączka 2001), Silesian, Sub-Silesian and Skole nappes (Figs 1B, C, E). The PKB separates the accretionary wedge from the fore-arc area. The Outer Carpathian belt is thrust at least 30–40 km, probably up to 100 km, over the authochtonous Miocene of the foredeep (Oszczypko 1998, 2001 and references therein). In several intramontane depressions, unfolded Neogene rocks discordantly overlie the folded and sliced older Outer Carpathian strata (Oszczypko 1999). There are suggestions that within the Outer Carpathians, only the Magura basin was formed on oceanic crust (Birkenmajer 1986, Oszczypko 1999).

Magura Nappe

The Magura Nappe occupies the highest structural position in that part of the Western Outer Carpathian stack of nappes that is discussed here. To the west, along the northern front of the Eastern Alps, the Magura Nappe links with the Rhenodanubian flysch zone. To the southeast, the nappe terminates in the Eastern Carpathians (Fig. 1A).

The Magura Nappe is subdivided into five units: Biele Karpaty, Krynica (Oravska Magura), Bystrica, Rača (internal Rača, southern Rača) and Siary (external Rača, northern Rača) units. The units are separated by thrusts or reverse faults, which in the following text will be termed "thrusts". The Krynica Unit is thrust over the Bystrica Unit along the Krynica thrust, the Bystrica Unit over the Rača Unit along the Bystrica thrust and the Rača Unit over the Siary Unit along the Rača thrust.

In addition, within the PKB, a succession (Grajcarek Unit) occurs which was deposited in the Magura basin during Jurassic-Cretaceous times, but which was afterwards incorporated into the PKB. The Grajcarek Unit has been interpreted to be a back--thrusted, tectonic outlier (Birkenmajer 1977) or a tectonic window (Jurewicz 1997).

The units of the Magura Nappe have been variously classified, on facies and/or tectonic grounds, as zones (Książkiewicz 1977), tectonic units (Matejka, Roth 1950; *fide* Książkiewicz 1977), slices (e.g., Świerczewska, Tokarski 1998) or facies tectonic sub-units (e.g., Oszczypko 1999). Due to facies similarities, the boundary between the Rača and Siary units is, in places, difficult to localize; both are presented as one tectonic body on geological maps as a result (compare Żytko et al.1988, Lexa et al. 2000).

In the stratigraphic profile of the Magura Nappe, Upper Cretaceous-Eocene rocks predominate. In the area studied, older rocks (Jurassic-Cretaceous Grajcarek Unit, Birkenmajer 1977) related to the Magura Nappe are known from the Pieniny Klippen Belt (Fig. 1D). Older sequences (Albian-Cenomanian, Jasień Formation; Oszczypko et al. 2005) are also known from the southern rim of the Mszana Górna tectonic window (Fig. 1C). In the Krynica Unit, the Upper Eocene-Lower Oligocene rocks of the Malcov Formation are exposed in the vicinity of the intermontane depression called the Orava--Nowy Targ Basin (Cieszkowski, Olszewska 1986 and Figs 1B, C) and in other places close to the Pieniny Klipen Belt (Oszczypko 1996; Lexa et al. 2000). In the Bardejov region, the tectonic setting of the Malcov Formation (beds) is unclear. According to different authors, the Malcov beds there are located either in the frontal part of the Krynica Unit (Jankowski et al. 2004) or in the innermost part of the Bystrica Unit (Lexa et al. 2000). In the Polish part of the Bystrica Unit, the youngest rocks are of Late Eocene age. In the Rača Unit and especially in the Siary Unit, Oligocene rocks are common. The youngest rocks of the Magura Nappe (Rača Unit, Zawada Formation, Lower Miocene, Burdigalian; Oszczypko et al. 1999; Oszczypko, Oszczypko-Clowes, 2002) occur close to the intermontane Nowy Sącz Basin (Fig. 1C) and in the Nowy Targ region (Krynica Unit, Stare Bystre Beds, Lower-Middle Miocene; Cieszkowski 1992b). The majority of the lithostratigraphic units in the Magura basin display diachronous boundaries (e.g. Oszczypko, Oszczypko-Clowes 2002).

In the Magura Nappe, the stratigraphic thickness of the Upper Cretaceous-Paleogene sediment pile is approximately 2300–2500 m in the northern part and 3000–3500 m in the southern part (Poprawa et. al. 2002). The thickness of the Lower Miocene strata of the Zawada Formation is about 500 m (Oszczypko, Oszczypko-Clowes 2002).

The Magura Nappe is uprooted from its substratum along ductile Upper Cretaceous rocks (Birkenmajer 1986). In the Polish segment, the Magura Nappe is flatly thrust over both the Fore-Magura group of nappes and the Silesian Nappe (Figs 1B, C, E). The amplitude of the overthrust is at least 50 km (Oszczypko 2004). The strikes of the major thrusts separating units of the Magura Nappe change from SW-NE in the west to W-E in the central segment of the nappe and to NW-SE in the east. The strike of the frontal overthrust of the Magura Nappe is parallel to that of the internal thrusts, changing from SW-NE in the west to NW-SE in the east. In the central part, the strike of the frontal overthrust varies but the W-E strike predominates. The original northern extent of the Magura Nappe has been reduced by erosion (e.g., Roca et al. 1995).

In the west, the Magura Nappe (Siary Unit) is underlain by the Silesian Nappe or by the Fore-Magura group of nappes (Fig. 1 B). In the east, the Siary Unit is thrust over the Silesian and Dukla nappes (Fig. 1E). In the central part, the tectonic setting is more complicated. In the region of the Limanowa-Kłęczany tectonic window (Figs 1C, 3A), the frontal overthrust of the Magura Nappe dips 30–50° to the south (Cieszkowski 1992a) and the Rača and Siary units occur in the hanging wall of the overthrust (Cieszkowski 1992a; Ryłko, Tomaś 2003). These units are thrust over the Silesian and Sub-Silesian nappes, over the Fore-Magura group of nappes and over the transgressive marine Miocene deposits which cover the Silesian Nappe. The chaotic complex of the Silesian Nappe (olistostromes, Gorlice beds, Oligocene-Lower Miocene) occurs in front of the Magura frontal overthrust (Fig. 1C).

Along the entire segment of the Magura Nappe studied, the Pieniny Klippen Belt adjoins the nappe to the south (Figs 1B, C, E). In the Polish segment of the Carpathians, the contact between the Magura Nappe and the PKB occurs along subvertical faults (Birkenmajer 1985). The PKB also contains other than klippen successions. The Jurassic--Cretaceous Magura succession (Grajcarek Unit) is one of such. This unit was probably incorporated into the PKB during Early Paleocene times (Birkenmajer 1986). Two post--tectonic covers (Maastrichtian-Paleocene Jarmuta Formation and Paleogene) occur in the PKB.

The basement of the Magura Nappe is exposed in tectonic windows (Figs 1B, C, E, 3A, B). In the majority of the windows, this basement comprises the Dukla Nappe and its equivalents (Fore-Magura group of nappes *sensu* Cieszkowski, Ślączka 2001). The rocks of the Silesian Nappe appear only in the Limanowa-Kłęczany and Kotań windows (Burtan et al. 1992; Kopciowski et al. 1997a, b).

According to Oszczypko (2004), the Magura Nappe corresponds to a Late Oligocene/Early Miocene accretionary wedge. The nappe is thrust over more external nappes of the Outer Carpathians. The latter correspond to an Early/Midlle Miocene accretionary wedge. In some interpretations, however, the ages of the wedges are Eocene-Middle Miocene for the wedge of the Magura Nappe (Świerczewska, Tokarski 1998; Nemčok et al. 2000), and Oligocene-Middle Miocene for the external wedge (Nemčok et al. 2000).

During Paleogene and Neogene times, the rocks of the Magura Nappe suffered three phases of deformation. Initially, the nappe was formed as an accretionary wedge related to south-directed subduction (Tomek, Hall 1993) resulting in north-verging synsedimentary folding and thrusting (Świerczewska, Tokarski 1998; Tokarski, Świerczewska 1998). This was followed either by major clockwise rotation of the regional stress field (Aleksandrowski 1985; Decker et al. 1997) or by major anticlockwise ro-

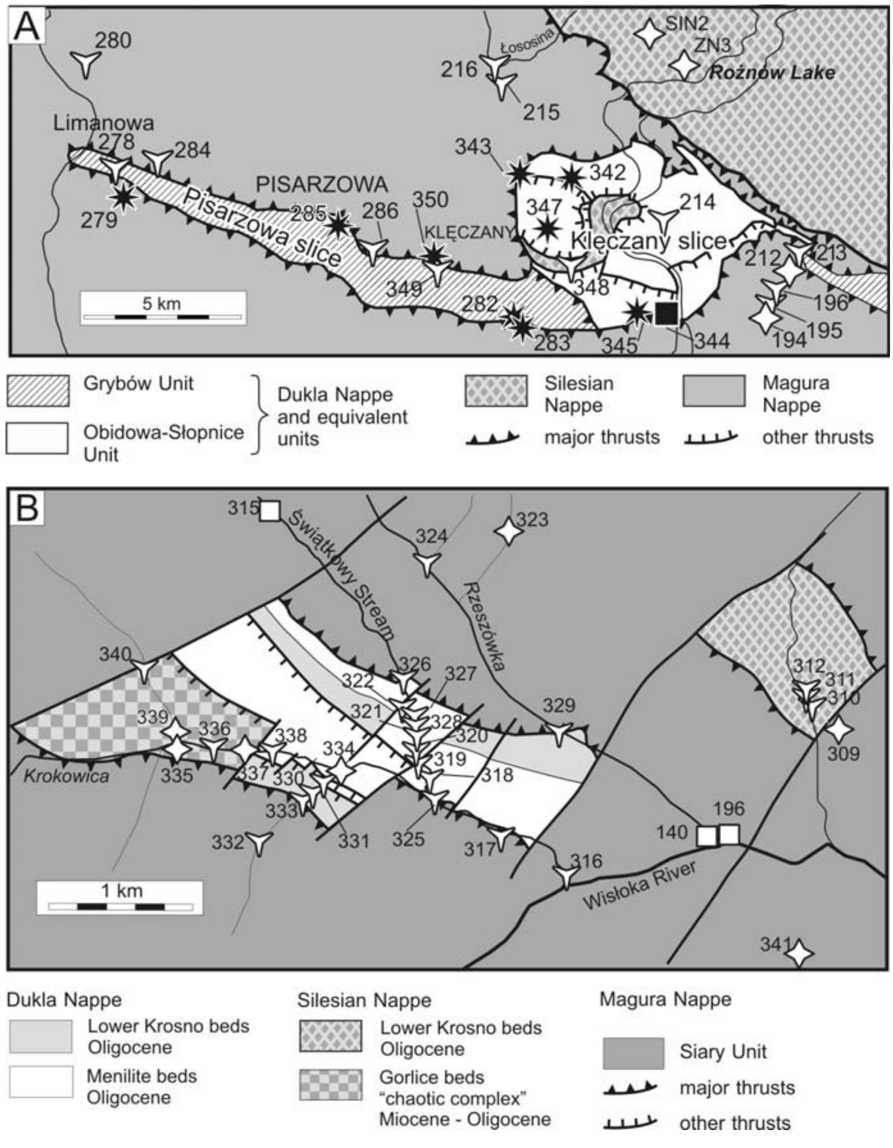

Fig. 3. Sketch maps showing locations of sampled sites and variation in I/S composition. A. Limanowa-Klęczany teconic window and adjoining area. Ranges of I/S composition in samples 194–196, 213, 215, 216, 282 and 344 after Świerczewska et al. (2003). B. Świątkowa and Kotań tectonic windows and an adjoining area. Ranges of I/S composition in samples 140, 196 and 323 after Świerczewska et al. (2003). Graphic symbols in A and B show the same ranges of I/S composition as in Figs 1B–D. Geology in A was compiled from Cieszkowski (1992a), and that in B from Kopciowski et al. (1997a)

tation of the Magura Nappe (cf. Márton et al. 2004), resulting in widespread fold--parallel strike-slip faulting (cf. Decker et al. 1997). Finally, regional collapse of the nappe was marked by normal faulting (Decker et al. 1997; Zuchiewicz et al. 2002).

Basement exposed in tectonic windows

Several tectonic windows of different sizes crop out on the erosion surface of the Magura Nappe. Most are located in the outer part of the nappe (Figs 1B, C, E). There are none in the Krynica Unit. The Mszana Dolna tectonic window in the central segment of the nappe (Fig. 1C) is the largest in the Magura Nappe. Two tectonic units of the Fore Magura group are exposed in this window. The first comprises slightly deformed Oligocene strata of the Obidowa-Słopnice Unit, the Mszana Dolna Unit of Mastella (1988), exposed in the central, most uplifted part of the window. This unit is the westernmost prolongation of the Dukla Nappe (Cieszkowski et al. 1985). The second and structurally higher tectonic unit comprises strongly deformed Cretaceous-Oligocene strata of the Grybów Unit preserved for the most part at the margins of the window (Mastella 1988; Oszczypko-Clowes, Oszczypko 2004). Cretaceous-Paleocene rocks of the Bystrica and Rača units crop out on the rim of the Mszana Dolna tectonic window. On the southern rim of the window, the Magura Nappe is segmented into three sheets. One sheet, exclusively of Upper Cretaceous rocks, occurs close to the window. The others comprise Upper Cretaceous-Eocene rocks (Oszczypko-Clowes, Oszczypko 2004).

The Szczawa tectonic window occurs inside the Bystrica Unit, about 15 km SE of the Mszana Dolna tectonic window (Fig. 1C). Oligocene strata of the Grybów Unit are exposed in this window (Oszczypko-Clowes, Oszczypko 2004). It is surrounded by Upper Cretaceous-Paleocene rocks.

The Limanowa-Klęczany tectonic window occurs in the frontal part of the Magura Nappe (Fig. 3A), probably within the Siary and Rača units (Ryłko, Tomaś 2003). However, according to Cieszkowski (1992a), it occurs in the Rača Unit. Two main slices, the Klęczany- and Pisarzowa slices, are exposed in this window. The thrust separating the slices strikes NW-SE. The Pisarzowa Slice mainly comprises Oligocene strata of the Grybów Unit (Southern Grybów Unit, Cieszkowski 1992a; Southern Fore-Magura Unit, Burtan et al. 1992). Oligocene rocks of the Dukla Nappe (Obidowa-Słopnice Unit) occur in the Klęczany Slice (Northern Grybów Unit, Cieszkowski 1992a). Cretaceous rocks of the Silesian Nappe (“kreda kurowska”) only crop out in the eastern part of the Klęczany-Limanowa tectonic window; their tectonic position is, however, not clear (Burtan et al. 1992). Upper Cretaceous-Paleocene rocks surround the Limanowa-Klęczany tectonic window. Eocene rocks occur only close to the northern boundary of the Klęczany Slice (Burtan et al. 1992; Cieszkowski 1992a).

The Świątkowa and Kotań tectonic windows are located in the eastern part of the Siary Unit (Figs 1E, 3B). Rocks in the Świątkowa tectonic window belong to several thrust-sheets. However, the outline of the window, the number of thrust sheets and the identity of the unit exposed in the window are still the subject of debate (Koszarski, Tokarski 1968; Kopciowski et al. 1997a; Mastella, Rubinkiewicz 1998). According to

Kopciowski et al. (1997a, b), Oligocene rocks of the Dukla Unit and Oligocene-Miocene olistostromes (chaotic complex) crop out within the window. This interpretation is adopted here.

The Kotań tectonic window is a small window about 5 km northeast of the Świątkowa window. In the Kotań window, Oligocene Lower Krosno beds of the Silesian Nappe are exposed. Both of these windows are surrounded by Late Cretaceous--Oligocene strata of the Magura Nappe (Kopciowski et al. 1997a).

The Smilno tectonic window occurs in the eastern part of the Rača Unit in Slovakia (Fig. 1E). Middle Eocene-Lower Oligocene rocks crop out in the window. This window is surrounded mainly by Eocene rocks, except on the southern boundary where Upper--Cretaceous-Paleocene rocks occur (Nemčok et al. 2000). The Smilno, Mszana Dolna and Świątkowa tectonic windows are considered to be duplexes (Mastella, Rubinkiewicz 1998; Nemčok et al. 2000; Oszczypko et al. 2004) formed during the overthrusting of the Magura Nappe.

Neogene depressions

The Orava-Nowy Targ Basin is located in the innermost part of the Magura Nappe along the boundary between the Outer and the Inner Carpathians (Figs 1B, C). Towards the south, the basin covers the Pieniny Klippen Belt and the northern rim of the Podhale Basin. To the north, the basin adjoins the Late Cretaceous-Early Oligocene strata of the Krynica Unit. The oldest Neogene strata in the basin are probably Badenian or Karpatian-Badenian (Worobiec 1994).

The Nowy Sącz Basin is located in the centre of the Magura Nappe (Fig. 1C). The thrust separating the Bystrica and Rača units is hidden under the Neogene fill of the basin. Badenian-Sarmatian strata fill the basin (Oszczypko et al. 1992) which is surrounded by Late Cretaceous-Early Miocene strata of the Magura Nappe.

The present day boundaries of both the Orava-Nowy Targ Basin and the Nowy Sącz Basin essentially correspond to the extent of their Neogene fill. The origin of both basins was related to faulting (Oszczypko 1973; Pomianowski 1996; Baumgart-Kotarba 1996).

MATERIALS AND METHODS

Studies on the smectite to illite transformation were performed on 365 claystone samples collected in 1996–2004 from natural exposures in stream valleys and quarries (Fig. 1). The sampled sites differ in altitude by less than 500 meters. Lithostratigraphic positions and ages were inferred from the Geological Map of Poland (1 : 50000) and other published maps. The formal names used for lithostratigraphic units are as given in Oszczypko, Oszczypko-Clowes (2002) and Oszczypko et al. (2005). As the lithostratigraphic status of some of the sampled strata in the Polish part of the Magura Nappe is unclear, and as lithostratigraphic correlation into Slovakia is problematic, informal and traditional lithostratigraphic names are used (Fig. 4, Appendices 1–4). The age control on these is rather poor; hence the simplified time scale adopted covering Late Cretaceous-Paleocene, Paleocene-Eocene, Eocene, Late Eocene-Oligocene, Oligocene and Early Miocene time ranges.

I/S studies were performed on 269 samples of Upper Cretaceous-Lower Miocene claystones that, excluding the Biele Karpaty Unit (Slovakia), were collected over the entire area of the Polish and Slovak parts of the Magura Nappe. In order to define relationships between the Magura Nappe and adjoining tectonic units, 19 samples were

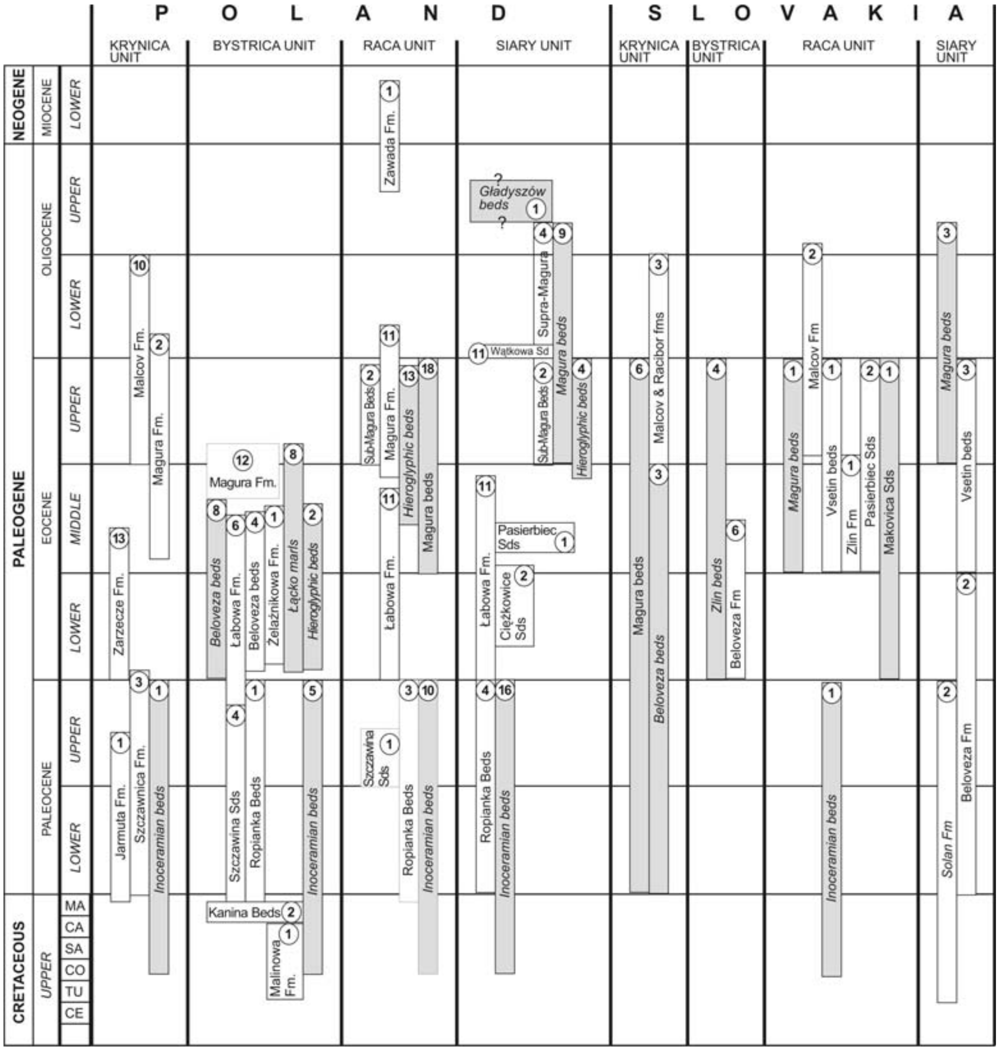

Fig. 4. Scheme illustrating the lithostratigraphic positions of the strata sampled in the Krynica, Bystrica, Rača and Siary units. Numbers of samples studied are circled. Position of formal lithostratigraphic units (white rectangles) are after Oszczypko et al. (2002) for the Polish part of the Magura Nappe and after Lexa et al. (2000) for the Slovak part. Positions of informal lithostratigraphic units (grey rectangles) are from Korab (1983), Potfaj et al. (2002), Nemčok (1990), Ryłko (2004) and the 1 : 50 000 Geological Map of Poland. CA — Campanian, CE — Cenomanian, CO — Coniacian, MA — Maastrichtian, SA — Santonian, TU — Turonian

collected from the Cretaceous-Lower Miocene rocks of the Silesian Nappe, 14 samples from the Upper Cretaceous-Oligocene rocks of the Dukla Nappe and 5 samples from the Neogene depressions. In the Pieniny Klippen Belt, 11 samples were collected from Jurassic and Cretaceous strata of the Grajcarek Unit near Szczawnica, one sample from the Paleocene-Maastrichtian molasse (Jarmuta Formation) and one sample from the Klippen succession near Zázrivá (Skrzypne Formation, Aalenian; Aubrecht et al. 2004).

Variation in the I/S across the frontal Magura overthrust was examined only in the Polish segment of the Magura Nappe. Samples were collected up to 5 km outwards from the overthrust. The effect of thrusting on smectite contents was examined in profiles across the Krynica, Bystrica and Rača thrusts. I/S compositions in different units up to 2 km from the thrust were compared.

Forty-two samples were collected from the basement of the Magura Nappe exposed in the tectonic windows — from the Dukla Nappe and equivalent units and from the Silesian Nappe. These were collected from Oligocene strata in the main.

Smectite illitization in the clay fraction (< 0.2 μm) separated from claystones using the method of Jackson (1975) was studied by X-ray diffraction. Sedimented air-dry and glycolated preparations were analysed in the Cracov Research Center (Institute of Geological Sciences, Polish Academy of Sciences) using a Phillips diffractometer equipped with a Cu tube and a graphite monochromator and an ARL X'TRA diffractometer equipped with a Si(Li) solid state detector (samples 419–446). The preparations were scanned from 2–36°2Θ in 0.02°2Θ steps with a counting time of 5 sec./step at 45 mA and 60 kV (Phillips diffractometer) and 40 mA and 45 kV (ARL X'TRA diffractometer).

The degree of smectite to illite transformation is expressed as the percentage of smectite in the mixed-layer illite-smectite structure (%S) and as the type of structural ordering (R). Both parameters were identified by the author using X-ray powder diffraction techniques (Środoń 1980, 1981, 1984; Dudek, Środoń 1996) based on the measurement of the positions of diagnostic reflections (6–8, 15–17 and 33–35°2Θ) in glycolated samples (Fig. 2B). Due to the abundance of discrete illite, the presence of the illite-smectite-diagnostic reflections was verified using air-dry preparations. No systematic investigation of the detrital clay minerals was attempted. In cases where two I/S populations were found in a particular sample, the more smectitic mineral was deemed to be the product of diagenesis in the Magura Nappe. All results are presented in Appendices 1–4 together with details of sample locations and stratigraphic ages. Maximum paleotemperatures were estimated using the plot of Šucha et al. (1993) based on data from the East Slovakian Basin (Fig. 2A) with a 10°C correction as suggested by Clauer et al. (1997).

RESULTS

Magura Nappe

Within the Magura Nappe, the claystones show a full spectrum of %S from <5 to 90% (Figs 1B–E; 3A, B; 5; Appendix 1). I/S structural ordering varies from R>1 (higher ordered structures) to R1 to random structures (R0). The ranges of %S, mean values of %S, and I/S structural ordering for individual units are summarized in Table 1.

TABLE 1

Ranges of S contents in I/S (S%), mean values of %S and ordering R of I/S for rocks from the Magura Nappe and the Dukla Nappe in the Magura Nappe foreland

Age	MAGURA NAPPE												DUKLA NAPPE		
	Krynica Unit			Bystrica Unit			Rača Unit			Siary Unit					
	%S	mean %S	R	%S	mean %S	R	%S	mean %S	R	%S	mean %S	R	%S	mean %S	R
Miocene							85		R0						
Oligocene										40–67	55	R0	24–35	29	R1
Upper Eocene--Oligocene	28–60	41	R0, R1				17–40	25	R1	28–80	51	R0, R1, R>1			
Eocene	8–55	24	R0, R1, R>1	8–70	30	R0, R1, R>1	15–55	30	R0, R1, R>1	19–55	35	R0, R1, R>1	40–60	50	R0
Paleocene--Eocene	15–40	27	R1 R>1	9–35	24	R1, R>1	17		R>1	28–34	31	R0, R>1	9		R>1
Upper Cretaceous--Paleocene	8–13	11	R>1	1–18	9	R>1	8–37	17	R1, R>1	10–36	27	R0, R1, R>1	7–31	14	R1, R>1

In all units, I/S from Upper Cretaceous-Paleogene rocks contain less than 37%S (Fig. 5). Eocene rocks are characterized by the largest fluctuations in S contents (up to 60%). The highest S content occurs in the Late Eocene-Oligocene and Miocene rocks (80 and 85%, respectively). Mean %S values calculated for rocks of different ages in each unit show a progressive increase from Upper Cretaceous to Miocene rocks (Fig. 5E). This increase is accompanied by a decrease of structural ordering (R). For all age ranges, the rocks of the Krynica Unit are more altered than are those of the Siary Unit. Alteration in the Bystrica and Rača units is intermediate between that of the Krynica and Siary units, except for the Late Eocene-Oligocene rocks in the Rača Unit which display the highest degree of alteration. However, rocks were sampled at only one site (SN, Fig. 1C) in the Rača Unit.

In the following, the degree of rock alteration is expressed in terms of five S content ranges, corresponding to major stages of smectite to illite transition (Figs 1B–E, 3A, B).

Within all units, changes in I/S compositions are not systematic. Some areas up to a few hundred square kilometres in size show similar ranges of %S (Figs 1B, C, E; 3A, B). Transitions from areas displaying the highest alteration to areas displaying the lowest are continuous. Gradual changes in the I/S composition are best seen around the Neogene intermontane depressions where the %S decreases outwards.

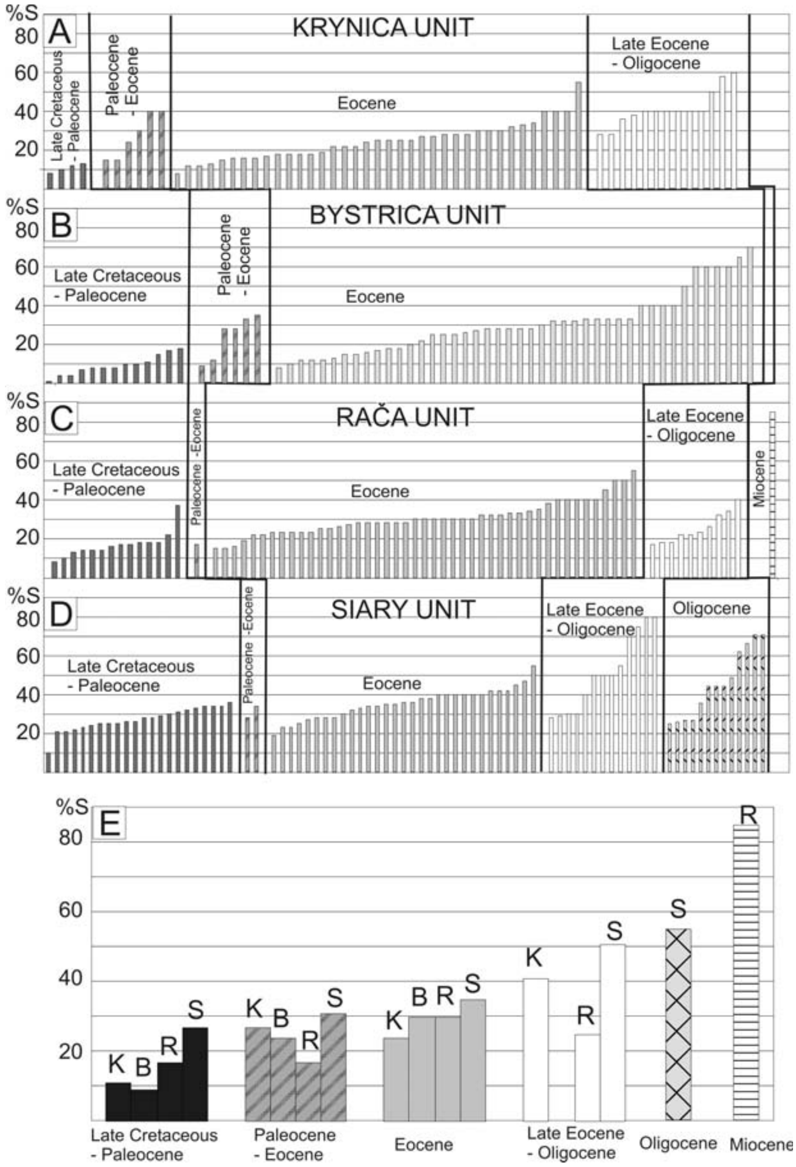

Fig. 5 . Variation of %S in I/S versus age of the rocks sampled. A — Krynica Unit; B — Bystrica Unit, C — Rača Unit, D — Siary Unit; E — mean contents of S in all units (Late Cretaceous-Palaeocene, Palaeocene-Eocene, Eocene, Late Eocene-Oligocene, Oligocene and Miocene). In A–D, samples in each age range are ordered according to increasing S contents

Zones of internal thrusts

Krynica thrust

Along the western and eastern segments of this thrust, the difference between the %S of the Krynica and Bystrica units is insignificant (Fig. 6A). The %S in the Krynica Unit close to the thrust varies from 15 to 40%. In the Bystrica Unit, values between

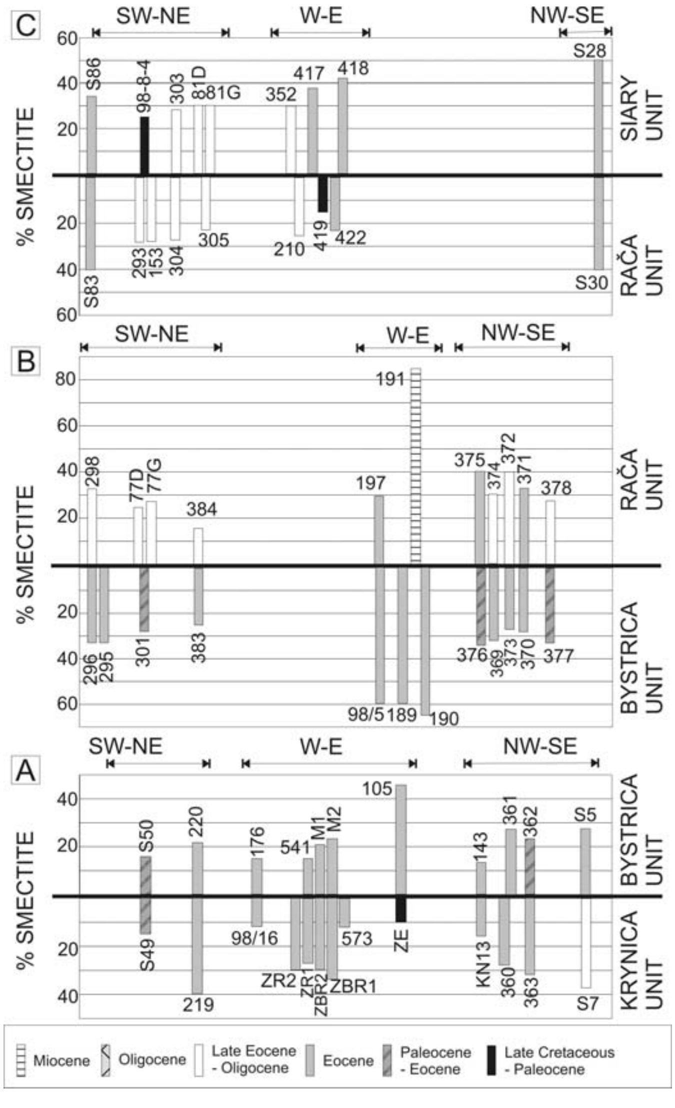

Fig. 6. Percentage of smectite in mixed-layer illite-smectite structure across:
A — Krynica thrust, B — Bystrica thrust and C — Rača thrust. In A–C, individual segments of the Magura nappe are marked as SW-NE (western part), W-E (middle part) and NW-SE (eastern part).
For locations of sites sampled see Figs 1B, C, and E

16 and 36% are observed. Samples from opposite walls of the thrust, in individual sections oriented perpendicular to the thrust, show the same ranges in %S.

Greater differences in the %S across the Krynica thrust are seen in the central part of the Magura Nappe — in the Dunajec and Poprad river valleys (Fig. 1C). Different ranges of S contents, 10–34% and 18–55%, characterize the adjoining Krynica and Bystrica units respectively. The greatest difference (45%) is found in the Poprad river valley: 55%S in sample 105 as against 10%S in sample Ze.

Bystrica thrust

Samples collected in the Krynica and Rača units along the western and eastern segments of the Bystrica thrust (Fig. 6B) show similar ranges of the S content (23–40%). Differences in I/S composition across the thrust range up to 15%S. Samples from the central segment of the thrust are more smectitic and display larger differences between the units (up to 30%S). All samples from the Bystrica Unit contain about 60%S. Samples from the Rača Unit show either higher (85%) or lower (30%) smectite contents.

Rača thrust

There is no difference in the I/S composition among samples collected in both walls of the thrust in the western and eastern segments (Fig. 6C). Claystones from the Rača and Siary units contain 16–40%S and 23–50%S, respectively. However, samples from the opposite walls of the thrust, especially in the sections oriented perpendicular to the thrust, show differences of up to 10%S. In the central segment of the thrust, I/S from the Siary Unit is enriched in S (30–42%) compared to that of the Rača Unit (16–23%).

I/S compositional differences across the Krynica, Bystrica and Rača thrusts define two broad patterns. Firstly, in the western and eastern segments of the Magura Nappe, the thrusts are not marked by any difference in the I/S composition. Secondly, in the central segment of the nappe, there are significant differences in the I/S composition across the thrusts though, with the exception of the Rača thrust, no systematic changes in smectite contents characterize individual units.

Polish segment of the frontal Magura overthrust

The western segment. As shown in Figure 7, the Silesian and the Magura nappes are either characterized by the same range of S contents (~ 30–35%) or the rocks of Magura Nappe contain more %S (up to 20% more) than those of the Silesian and Sub-Silesian nappes. The rocks of the Fore-Magura group of nappes are more altered (15–22%S) than those of the Magura Nappe (32–35%S).

The central segment. There is large variation in S contents between the Silesian and Magura nappes (Fig. 7). I/S from the Magura Nappe contain 14–40%S, whereas in the Silesian Nappe the content is typically 22–85%S. The most smectitic I/S values are found in the clasts and matrix of Miocene olistostromes (samples 381A–384A).

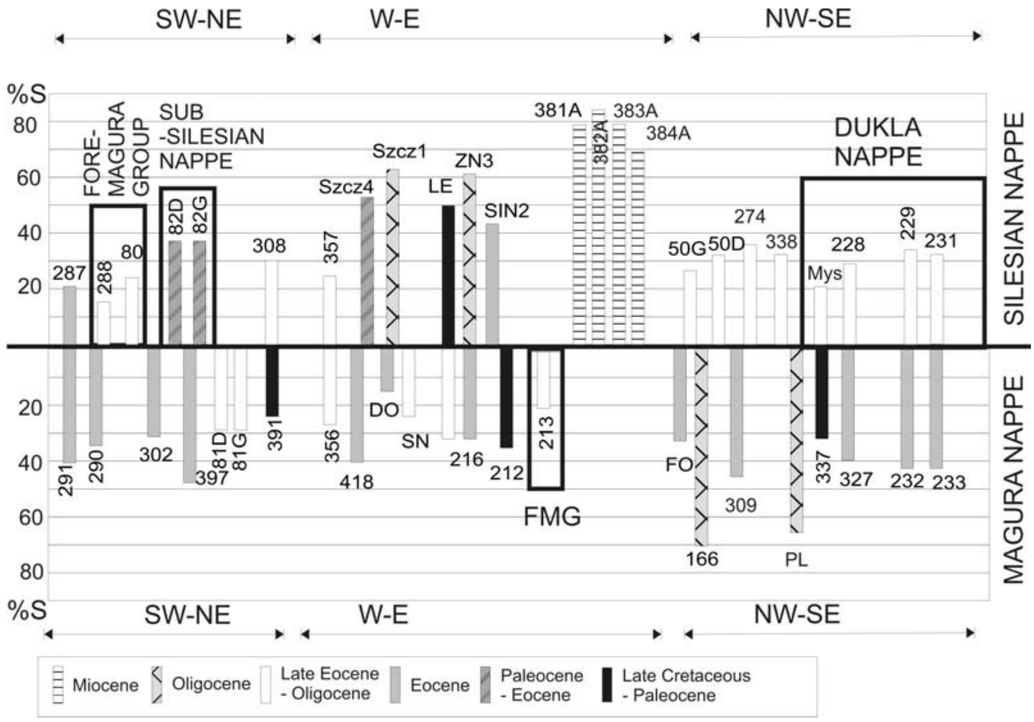

Fig. 7. Percentage of smectite in mixed-layer illite-smectite structure across the frontal Magura overthrust. Individual segments of the Magura Nappe are marked as SW-NE (western part), W-E (middle part) and NW-SE (eastern part). For locations of the sites sampled see Figs 1B, C, and E

The eastern segment. Close to the frontal overthrust, the Dukla Nappe shows the same degree of transformation (21–32%S) as the Silesian Nappe (Fig. 7). In comparison to basement rocks, those of the Magura Nappe contain more smectitic I/S (32–70%). The contrast between the Magura and Silesian nappes (up to 45%S) is greater than that between the Magura and Dukla nappes (up to 10%S).

Differences in %S show that the rocks of the Dukla and Fore-Magura group of nappes and those of the Silesian Nappe below the western and eastern part of frontal overthrust are, excepting the Silesian Nappe in the western segment, more altered than those of Magura Nappe. In contrast, in the central part of the area, more altered rocks in the Magura Nappe overlie less altered rocks in the Silesian Nappe.

Dukla Nappe

Samples collected between the Solinka and Jasiołka rivers in the external part of the Dukla Nappe in Poland (Fig. 1E, Appendix 2) show a wide variation of the I/S composition (7–60%S). Values from Oligocene strata in that area are similar to those from rocks cropping out close to the Magura frontal overthrust (20–33%S; R0, R1). In that part of the Dukla Nappe studied, there are areas up to hundreds of km^2 that show similar ranges of %S.

Pieniny Klippen Belt

Samples collected in the Grajcarek Unit (Figs 1D, 8, Appendix 3) contain 10–37%S. Those from Jurrassic and Cretaceous outcrops in the Sztolnia creek contain 28–37%S, and 10–22%S respectively. Jurassic-Cretaceous rocks in the Szczawnica region are characterized by 23–30%S. Sample JA1 from the Jarmuta Formation contains 23%S. These values are the same as, or higher than, those from the Magura Nappe close to the Pieniny Belt in the Szczawnica region (8–19%S). In the Zázrivá region, there is no difference in alteration between the Eocene rocks of the Magura Nappe (33%S) and the Aalenian rocks of the PKB (36%S).

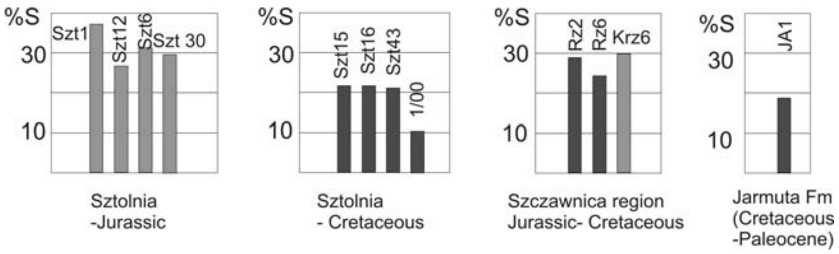

Fig. 8. Graphs showing percentage of smectite in mixed-layer illite-smectite structure in the rocks of the Grajcarek Unit and in authochtonous mollase (Jarmuta Formation) in the PKB region. Ages of Sztolnia samples are from Birkenmajer and Gedl (2004). For locations of the sites sampled see Fig. 1D

Tectonic windows

Mszana Dolna tectonic window (Figs 1C, 9A, Appendix 4). I/S in the Oligocene rocks of the Grybów and Obidowa-Słopnice units contain <5–16%S and 8–12%S, respectively. The lowest content was recorded from the Oligocene-Cretaceous rocks close to the basal Magura overthrust. In NNW-SSE and N-S profiles across the window, samples from the northern margin are slightly less altered compared to those from the central part. The former (Upper Cretaceous-Eocene) contain 16–22%S. These values contrast with those from the southern rim of the window (<<5–12%S). In the profiles mentioned, the I/S with the lowest S content (<<5%) occur in Cretaceous rocks some 2–3 km south of the window.

Szczawa tectonic window (Figs 1B, 9B, Appendix 4). Oligocene rocks in the Grybów Unit contain about 10%S in ordered I/S (R>1). Over the window rim to the west, the lowest S% values (<5–12%S, R>1) occur in the Upper Cretaceous-Paleocene rocks. The zone of lowest %S extends westwards to the southern rim of the Mszana Dolna tectonic window. On the southern rim of the Szczawa tectonic window, the Upper Cretaceous-Eocene rocks contain 8–18%S (R>1).

Limanowa-Kłęczany tectonic window (Figs 3A, 9C, Appendix 4). There are differences in %S and I/S ordering between the Grybów and Obidowa-Słopnice units. In the Grybów Unit, S contents range from 12 to 30%S (R1 and R>1) and, in the Obidowa-Słopnice Unit, from 13 to 15%S (R>1). Lower Cretaceous rocks from the

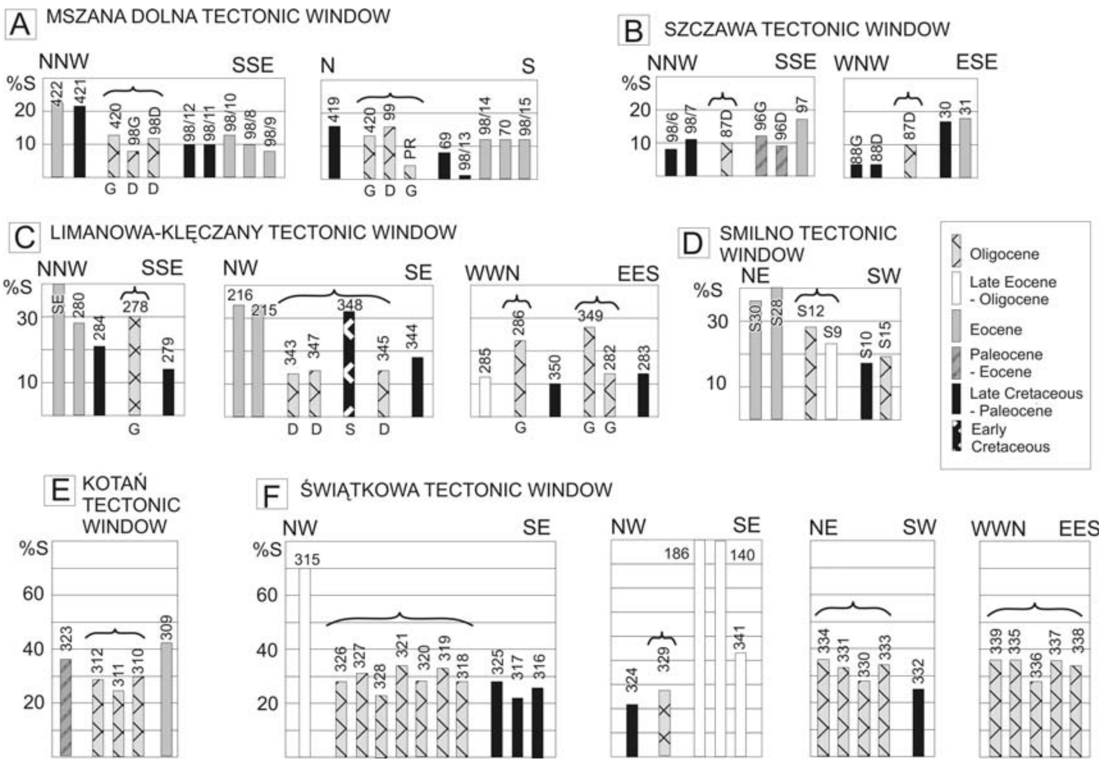

Fig. 9. Variation in I/S composition along selected profiles in tectonic windows (braces) and in adjoining areas. For locations of the sites sampled see Fig. 1 C (profiles A, B, D), Fig. 1E (profile D), Fig. 2A (profile C) and Fig. 2B (profiles E, F)

Klęczany Slice in the Silesian Nappe contain 32%S (R1), a value is considerably higher then values from the surrounding rocks of the Obidowa-Słopnice Unit. Samples collected from the Magura Nappe at the rim of the window show either the same or lower degrees of smectite to illite transformation than do the window rocks. Outside, up to 5 km out from the window margin, %S varies from 25 to 40% with I/S showing both random and ordered interstratification (R1).

Świątkowa and Kotań tectonic windows (Figs 3B, 9E, 9F). The samples collected within the Świątkowa window are characterized by ordered I/S (R1) containing 25–37%S. The samples from the chaotic complex contain slightly more smectitic I/S (mean 32%S) than do samples of older rocks (mean 29%S). The Lower Krosno beds (Silesian Nappe) exposed in the Kotań tectonic window contain ordered I/S (R1) with 28–34%S.

The oldest rocks of the Magura Nappe (Inoceramian beds), sampled at the rims and up to 1 km from the windows, contain 22–28%S (R1, R>1). These values match or are lower than those in the windows. The Eocene-Oligocene strata exposed in the vicinity of the windows contain 40–80%S in random I/S.

Smilno tectonic window (Figs 1C, 1E, 9D, Appendix 4). Along the NE-SW profile, I/S progressively changes (Fig. 9D). In the NE, the Eocene rocks of the Rača Unit contain 38–40%S (R0, R1). Further to the SW, the Oligocene-Upper Eocene rocks of the window are characterized by I/S containing 22–28%S with R1 and R>1. I/S with the lowest smectite content (17–19%) occurs in the Cretaceous rocks about 2–5 km SW of the window.

Neogene depressions and adjoining area

Orava-Nowy Targ Basin (Figs 1B, C, Appendix 2). Neogene strata in this basin contain random I/S with 70–90%S. For up to 2 km northward from the boundary of the basin, the Paleocene-Lower Oligocene rocks of the Magura Nappe display rather uniform S contents (40–60%S) in random I/S (Fig. 10A). The observed S contents, 40% (Paleocene-Eocene), 42% (Eocene) and 40–60% (Eocene-Lower Oligocene) do not exceed those in the basin. Further northward, 2–5 km from the northern basin margin (Fig. 10B), the %S in the Paleocene- Eocene rocks varies from 25 to 40% as the I/S ordering changes from R>1 to R0. Upper Cretaceous to Eocene rocks from further north and northwest in the Magura Nappe, i. e. 5–12 km out from the basin (Fig. 10C), are characterized by values of 8–12%S (Upper Cretaceous), 24–30%S (Paleocene-Eo- cene) and 8–26%S (Eocene) and by highly ordered structure (R>1).

Nowy Sącz Basin (Fig. 1C, Appendix 2). The Neogene infilling of this basin contains random I/S with 75–90%S (Figs 11A–C). In the Magura Nappe, samples collected near

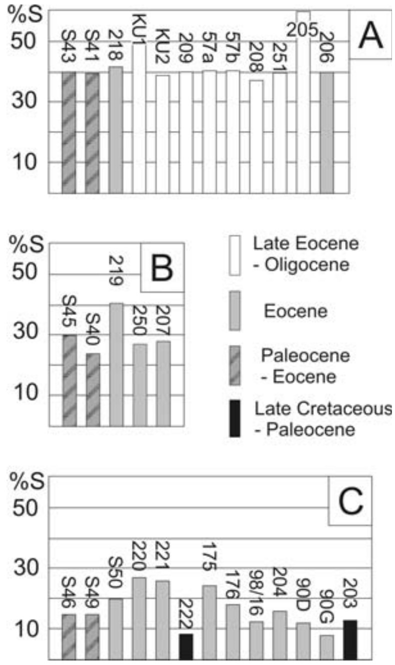

Fig. 10. Variation in I/S composition in the Krynica Unit in various areas north of the Orava-Nowy Targ Basin. A — up to 2 km north of the basin, B — 2–5 km north of the basin, C — 5–12 km north of the basin. For locations of the sites sampled see Figs 1 B, C

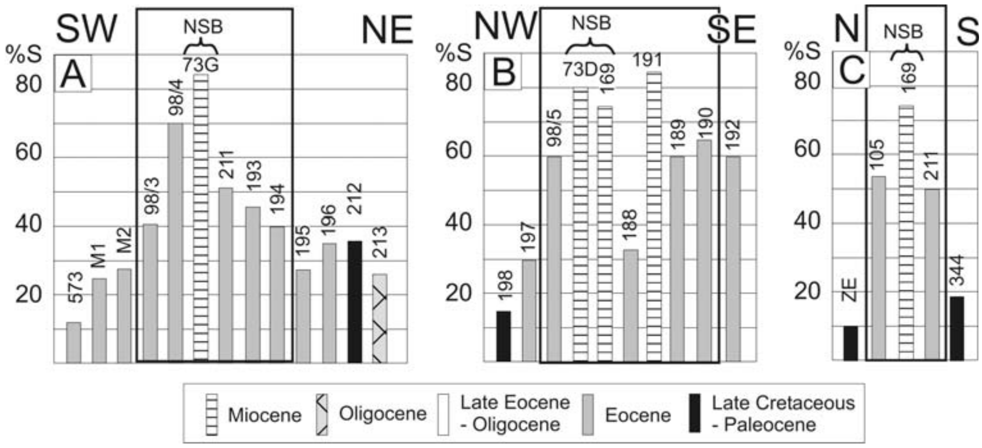

Fig. 11. Variation in I/S composition along selected profiles in the Nowy Sącz Basin (NSB) and in the adjoining area. A — profiles oriented SW-NE, B — NW-SE and C — N-S. Data from samples collected up to 5 km outside the basin are in rectangles. For locations of the sites sampled see Figs 1C, 2A

to, and up to 5 km from, the basin boundary (Figs 1C, 11A–C) are characterised by either the same diagenetic grade as Neogene rocks from within the basin (sample 191, Zawada Formation, Lower Miocene) or by less smectitic I/S (Eocene; 35–60%S, R0, R1). In contrast, the degree of smectite to illite transformation in more distant rocks is much higher. These rocks are characterised by ordered I/S structure and values of 10–37%S (Upper Cretaceous-Paleocene) and 12–35%S (Eocene). The SW-NE-oriented profile (Fig. 11A) reveals a progressive decrease in %S contents towards the NE and SW for up to 12 km from the basin. These external changes in I/S are less pronounced in the SE part of the NW-SE-oriented profile where the Zawada Formation was sampled (Fig. 11B). Along the N-S profile (Fig. 11C), the degree of smectite to illite transformation increases sharply outside the basin, both southward [from 55%S (Eocene) to 10%S (Upper Cretaceous-Paleogene)] and northward [from 50%S (Eocene) to 13%S (Upper Cretaceous-Paleogene)].

THERMAL ALTERATION

Magura Nappe

The part of the Magura Nappe discussed here experienced maximum paleotemperatures ranging from <75°C to >165°C (possibly up to 200°C). The maximum thermal overprint, corresponding to 160–165°C, is registered in the central part of the nappe (southward and south-eastward of the Mszana Dolna tectonic window), in the southern rims of the Limanowa-Klęczany, Librantowa, Grybów and Ropa tectonic windows and in scattered places near Szczawnica and Babia Góra Mt (Fig. 12). Heating up to 135–165°C affected most of the central part of the Magura Nappe between the Raba and

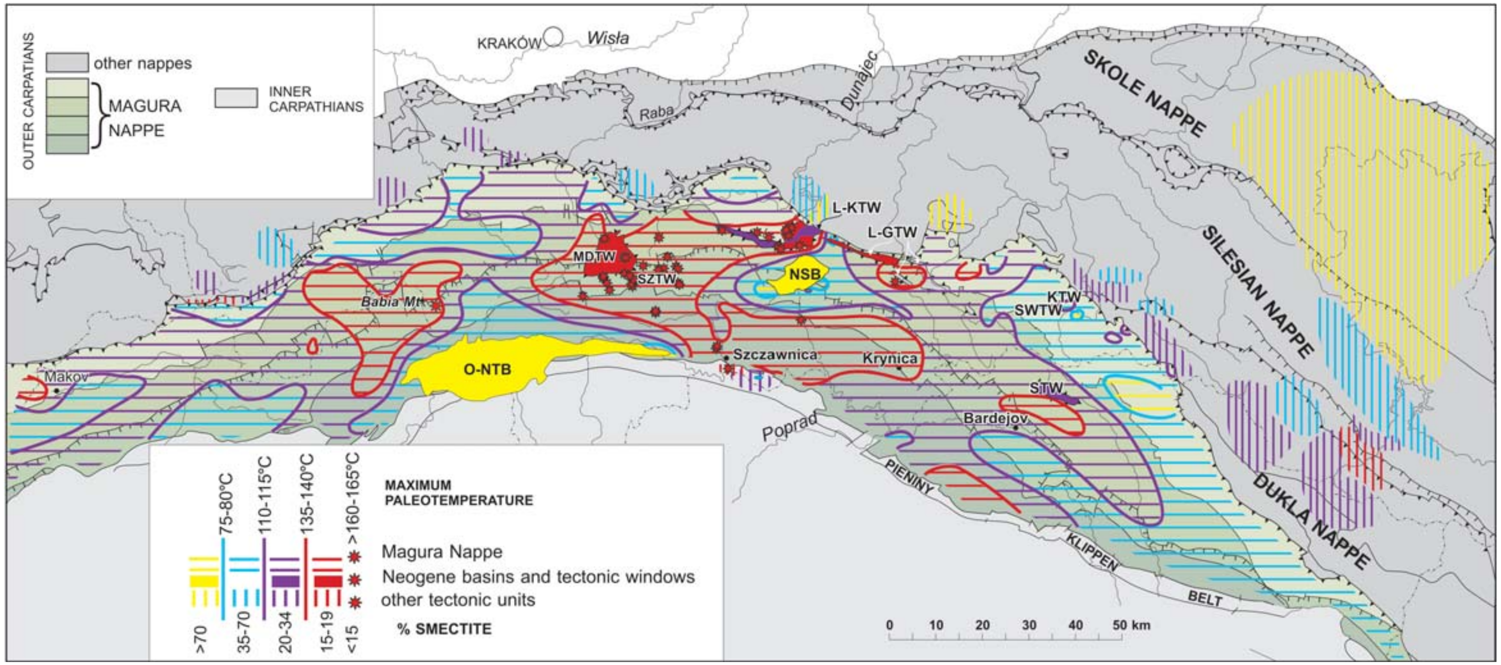

Fig. 12. Paleoisotherms on the present-day erosion surface in the Outer Carpathians. Data for the Skole and Silesian nappes are after Dudek, Świerczewska (2001), Dudek et al. (2000) and Dudek et al. (2004). Abbreviations of names of tectonic windows are KTW — Kotań, L-GTW — Librantowa, Grybów and Ropa, L-KTW — Limanowa-Klęczany, MDTW — Mszana Dolna, STW — Smilno, SZTW — Szczawa, SWTW — Świątkowa. Other abbreviations used are NSB — Nowy Sącz Basin, O-NTB — Orava-Nowy Targ Basin

Dunajec-Poprad rivers except for the Neogene depressions and their surroundings and the outermost part of the nappe. Parts of the Krynica and Bystrica units in the area between the towns of Szczawnica and Krynica as well as the part of the Rača Unit sited along the Librantowa, Grybów and Ropa tectonic windows were similarly affected. Evidence for comparable paleotemperatures is seen locally to the south of the Smilno tectonic window, further south close to the PKB (eastern part of the nappe) and in areas close to Babia Góra Mt and Makov (western part of the nappe). All are shown in Figure 12.

Within the Magura Nappe, rocks affected by the lowest paleotemperatures (<75°C, possibly <70°C) occur only on the edge of the Nowy Sącz Basin, and in scattered localities in the eastern part of the Siary Unit (Fig. 12). These temperatures correspond to those that affected the Neogene infilling of the Nowy Sącz and Orava-Nowy Targ basins.

Within the Magura Nappe, there is a clear general decrease in thermal alteration from the inner part outwards (Fig. 12). A similar trend is seen in the Silesian and Skole nappes in the eastern part of the Polish Outer Carpathians where the degree of thermal alteration decreases towards the Carpathian Foredeep (Dudek, Świerczewska 2001; Dudek et al. 2000; Dudek et al. 2004). The data from the Dukla Nappe presented here conform to this pattern. Small patches of higher thermal alteration occurring within the eastern segment of the Siary Unit relate to outcrops of Upper Cretaceous-Paleocene rocks or Lower-Middle Eocene rocks; these are anomalies in the general outward decrease of thermal alteration. Finally, a local and less distinct trend of decreasing thermal alteration inward towards the Inner Carpathians is apparent in the innermost part of the Magura Nappe.

In general, the internal thrusts of the Magura Nappe (Krynica, Bystrica and Rača thrusts) do not modify the pattern of progressive change in thermal alteration. The paleoisotherms are not disturbed by the thrusts though, in some places, they run parallel to them (Fig. 12). However, in most cases, this parallelism may be an artefact resulting from the relatively sparse sampling of the Slovak part of the Magura Nappe. Examination of profiles crossing the thrusts show that only short segments of the Krynica thrust in the Dunajec River valley and of the Rača thrust north from the Mszana Dolna tectonic window actually separate bodies of rock affected by different paleotemperatures. Across the Krynica thrust, the calculated paleotemperatures may differ by up to 65°C with more altered rocks occurring in the hanging wall of the thrust in some places and in the down-thrown foot wall in others. A somewhat different situation exists across the Rača thrust where the more altered rocks of the Rača Unit (maximum paleotemperatures 130–150°C) consistently overlie less altered rocks of the Siary Unit (90–120°C).

Foreland of the Magura Nappe

Unlike the internal thrusts, the frontal overthrust of the Magura Nappe disturbs the regional paleotemperature trend observed in the Outer Carpathians (Figs 1B, C, E, 12). This disturbance is most obvious along the central segment of the overthrust where the

Magura Nappe is thrust over significantly less altered rocks in the Silesian Nappe. The maximum thermal jump across the overthrust is about 50°C.

The Dukla Nappe provides evidence of maximum paleotemperatures between 110 and 135°C. Close to the frontal Magura overthrust, these paleotemperatures are the same as or slightly higher than those recorded in the Magura Nappe.

Hinterland of the Magura nappe

In the Szczawnica region (Fig. 1D), the rocks in the Grajcarek Unit are less thermally altered than are those of the Magura Nappe. The observed %S variation suggests temperatures between 110–135°C except for one place (sample 1/00) where the Upper Cretaceus rocks reached temperatures >165°C. It is notable that all sampled rocks from the Magura Nappe in that same region record temperatures >135°C, mostly >165°C.

There are few paleotemperature data for the PKB. I/S data from the Maruszyna IG1 borehole close to Nowy Targ on the southern rim of the Orava-Nowy Targ Basin show a progressive decrease from about 30%S at 500 m depth to less than 10%S at 4500 m (Kotarba 2003). The range of %S contents is similar to that observed in the Grajcarek Unit of the Szczawnica region.

In the Zázrivá region (Fig. 1B), the Klippen succession and the Magura Nappe were subjected to the same temperatures (110–135°C). However, illite crystallinity data (Wójcik-Tabol 2003) suggest that, at least in some localities, rocks of the Klippen succession show more intense alteration. These results indicate that Cenomanian--Turonian rocks sampled about 6 km SW of Szczawnica are anchimetamorphic having experienced temperatures >200°C (illite crystalinity <0.45).

Tectonic windows

The rocks of the Mszana Dolna tectonic window (Fig. 1C) reached temperatures of >135°C, in places >165°C, and those of the Szczawa tectonic window (Fig. 1C) temperatures >165°C. The alteration of the rocks within the Mszana Dolna tectonic window is intermediate between the alteration of the Magura Nappe rocks on the northern rim of the window (lower alteration) and that on the southern rim of the window (greater alteration). The rocks of the Magura Nappe in the rim of the Szczawa tectonic window show greater alteration than do the rocks within the window.

The thermal alteration of rocks exposed in the Limanowa-Kłęczany tectonic window is variable (Figs 3A, 12). In the Pisarzowa Slice, the rocks of the Grybów Unit reflect paleotemperatures increasing eastwards towards the Kłęczany Slice from 110–140°C to >165°C. In most sampled locations, the Magura Nappe adjacent to the window was affected by temperatures >165°C. However, in the NW part of the rim, no contrast exists between the Pisarzowa Slice and the Magura Nappe (110–140°C). In the western part of the Kłęczany Slice, the Obidowa-Słopnice Unit reached temperatures >165°C. In contrast, rocks of this unit in the eastern part of the slice experienced, as did the Silesian Nappe within the window, lower temperatures between 110 and 140°C. The rocks in the Magura Nappe situated a few kilometres to the NW and SE of the Klęczany Slice reached temperatures from <100 to 140°C.

The window series exposed in the Smilno (Fig. 1C, E), Kotań and Świątkowa (Fig. 3B) tectonic windows were altered at temperatures between 110 and 140°C. These rocks are less altered than are those in the windows within the central segment of the Magura Nappe.

The Upper Cretaceous-Paleocene rocks of the Magura Nappe show, in the rim of the Świątkowa tectonic window, the same degree of alteration or are slightly more altered than those exposed within the window. The Paleocene-Eocene rocks of the Magura Nappe in the vicinity of the Kotań and Świątkowa tectonic windows are essentially no more altered than those exposed within the windows. On the other hand, the Late Eocene-Oligocene rocks sampled about 1km from both windows were altered at temperatures <75°C as against 110–140°C within the windows.

The paleotemperature pattern at the rim of the Smilno tectonic window matches that at the rim of the Mszana Dolna tectonic window. In the former case, the rocks of the Magura Nappe sampled SW from the window, i.e., toward the internal part of the nappe, were altered at temperatures between 140 and 165°C. Those sampled NE from the window were heated to 90–115°C.

Neogene basins and their rims

There is a gradual northward increase in maximum calculated paleotemperatures in the northern rim of the Orava-Nowy Targ Basin; these temperatures range from about 80°C (mostly 105°C) close to the basin to >165°C (mostly 135–165°C) some 12 km distant. In this region, rocks of different ages display similar thermal alteration in zones parallel to the basin boundary. The paleotemperature difference between the Neogene fill of the basin and the rocks of the Magura Nappe nearby is usually more than 30°C.

The paleotemperatures calculated for the Miocene rocks in the Nowy Sącz Basin are the same as those for the Lower Miocene rocks of the Zawada Formation in the vicinity of the basin (<75°C). They are only marginally lower than those (85°C) for the Eocene rocks that are close to the basin too. The Nowy Sącz Basin is surrounded by a <5 km wide zone in which alteration of the Magura Nappe rocks reflects temperatures <115°C.

DISCUSSION

Source of heating

Deep-borehole I/S studies of folded rocks in the Skole and Silesian nappes show a progressive increase in the degree of diagenetic change with depth (Świerczewska et al. 2003). I/S studies in the Nowy Targ IG-1 well (Kotarba 2003) reveal a similar trend in the Magura Nappe that reflects burial-induced heating of folded strata. Thus, earlier suggestions of a regional thermal event related to post-orogenic collapse in the central segment of the Magura Nappe (Dudek, Świerczewska 2001) are open to discussion. Maximum diagenetic alteration is more likely keyed to a burial-related, cross cutting 165°C paleoisotherm (compare Fig. 12).

Correlation with other paleotemperature indicators

The maximum calculated I/S paleotemperatures do not agree with those inferred from random reflectance studies of telocollinite (reflectance R_o: 0.38–0.40%) in autochthonous detrital coals from the Magura Nappe (Wagner 1996). The coals are of sub-bituminous type and correspond to the initial oil generation stage. This type of coal should correspond to temperatures below 65°C (Nowak 1999). Moreover, Kotarba (2003) also noted a low degree of alteration of the organic matter in the rocks of the Magura Nappe.

Analyses of claystones from the same region as the coals suggest maximum paleotemperatures of 80–140°C. Moreover, in contrast to coalification, illitization is a time--independent process (Pollastro 1993; Środoń 1995). According to Środoń (1979) and Velde, Espitalie (1989), illitization progrades more slowly then coalification and is much less temperature-sensitive than organic matter diagenesis. Therefore, the lack of correlation between the smectite to illite transformation results and the coal-reflectance data cannot be explained in terms of a short-lived heating event. Resolution of the disagreement probably requires further I/S and organic maturity studies.

Any possible influence of detrital I/S on the interpreted maximum temperatures may also be excluded as different samples from individual lithostratigraphic units show different %S. Moreover, only moderately or highly altered clastic and pyroclastic rocks might have been possible sources of detrital I/S. Provenance studies on the Magura basin indicate northern and south-eastern source areas of clastic material (Oszczypko 1992 and references therein). However, these studies have also shown that I/S-bearing rocks were rare in the source areas; crystalline rocks predominated there and limestone was the most common sedimentary rock (Oszczypko, Salata 2005 and references therein).

Paleothermal gradient and paleodepth of burial

Present-day data from boreholes show variation in the thermal gradient from place to place in the Magura Nappe. In the central part of the nappe, borehole gradients of 22.7°C/km for Poręba Wielka IG-1 and 21°C/km for Obidowa IG-1 have been determined (N. Oszczypko and W. Zuchiewicz, personal communication). In the Smilno window region, values from the Smilno-1 borehole range between 26.1 and 32.0°C/km (Leško et al. 1987). In boreholes located close to the PKB, measured thermal gradients are variable. The thermal gradient in the central segment of the Magura Nappe is 19.4°C/km (Maruszyna IG-1; N. Oszczypko and W. Zuchiewicz, personal communication) whereas, in the eastern segment of the nappe, the gradient in the Hanusovce-1 borehole is 29.18°C/km (Leško et al. 1985). These data suggest that paleothermal gradients might well have been variable in the past, too.

Geothermal grade in an accretionary wedge depends on the thermal structure of the associated subduction zone (Sakaguchi 1999). Due to subduction of cool oceanic lithosphere, accretionary wedges are usually associated with low geothermal gradients (e.g., Peacock 1996). The geothermal gradient decreases inwards in the wedge due to addition of accreted cold sediments (Francù et al. 2002). Hydrothermal activity may locally increase the geothermal gradient.

For a Magura basin located above oceanic or sub-oceanic crust, a paleogradient higher than that in the wedge but lower than the present-day gradient of 26°C/km in the Paleozoic basement of the Outer Carpathians is plausible (Poprawa et al. 2001). Approximate paleogeothermal gradients inferred from methane-water fluid inclusions in quartz-calcite veins present in for the Magura Nappe (Krynica Unit), and in the equivalents of the Dukla Nappe exposed in the Mszana Dolna and Szczawa tectonic windows, are 20°C/km and 17°C/km respectively (Hurai et al. 2004). The fluid inclusions were related to regional collapse — the final stage in the structural evolution of the Outer Carpathian accretionary wedge (Świerczewska et al. 1999). The thermal gradients inferred from fluid inclusions are similar to the present day gradient of 16.5°/km in the frontal part of the Outer Carpathians (Poprawa et al. 2001).

Assuming a mean value of 18°C/km for the paleogeothermal gradient, paleodepths of burial have been calculated from the I/S compositions. These are 11 km (maximum), 7.8–9.2 km, 6.1–7.8 km and 4.1–6.1 km for areas that experienced thermal overprints of 165–200°C, 140–165°C 110–140°C and 75–110°C, respectively. These calculated values are a measure of the maximum thicknesses of cover rocks eroded. These calculations do not take into account surface temperature (+4°C for a deep basin or 10–15°C for a shallow warm sea) or sample-site altitude (±0.5 km). Including the maximum surface temperature decreases any calculated erosion thickness by no more than about 0.8 km.

It is not possible to ignore paleogradient variation in the wedge. Any increase in that gradient will lower the calculated paleodepth of burial. For example, with a paleogradient of 25°C/km (mean present-day thermal gradient in the Magura Nappe), the thickness of cover rocks eroded in the area examined here may be estimated. These estimates are 8 km (maximum), 5.6–6.6 km, 4.4–5.6 km, and 3.0–1.4 km for the areas that experienced thermal overprints of 165–200°C, 140–165°C, 110–140°C and 75–110°C, respectively. However, based on the general pattern of gradients in accretionary wedges (e.g., Sakaguchi 1999), the lowest paleogradient estimates are the most plausible for the actual amount of erosion. Therefore, in the following discussion, a paleogradient of 18°C/km is used.

The potential role of hot fluids must be considered. For those exposures where low paleogradients are constrained by fluid inclusion data, burial depths calculated using I/S data agree with those based on fluid inclusions (compare Hurai et al. 2004). This coincidence indicates that the influx of the water-methane fluids and the maximum thermal alteration were coeval. The occurrence of water-methane fluid inclusions related to high-temperature (<210°C) quartz mineralization was documented at only at a few localities in the Magura Nappe and its basement (Świerczewska et al. 1999; Świerczewska et al. 2000; Hurai et al. 2004). In contrast, the area showing high degrees of smectite to illite transformation is more extensive; the observed %S variability is regional. Thus, any extensive influence of hot fluids (a short-lived heat source) as an agent of thermal alteration of the Magura Nappe rocks is discounted.

Both the Miocene rocks of the Zawada Formation and the Miocene rocks filling the Nowy Sącz Basin show very low grades of alteration (<<75°C). Thus, the amount of erosion in the Magura Nappe prior to sedimentation of the Badenian strata in the Nowy Sącz Basin cannot be estimated by the I/S method. However, close to the basin, about 4 km of Magura Nappe rocks were eroded. Geological cross-sections of the basin (e.g., Oszczypko, Oszczypko -Clowes 2002) show that this erosion predated deposition of the Badenian strata.

In the Orava-Nowy Targ Basin and its immediate surroundings, uplift was insignificant. In the Nowy Targ PIG 1 borehole, Badenian strata are only about one hundred meters thick (Paul, Poprawa 1992). Below the Badenian strata, the thermal alteration of the Magura Nappe rocks is the same as the minimal alteration recorded in the Magura Nappe rocks in the vicinity of the basin and indicates a temperature of about 80°C (based on Kotarba 2003). It is probable, these data show, that up to 4.4 km of Magura Nappe rocks were eroded before sedimentation of the Neogene strata in this area. In the Orava part of the basin, the Neogene strata are about 1000 m thick and discordantly overlie the Magura Nappe (e.g., Baumgart-Kotarba 1996). Close to this part of the basin, most Magura Nappe rocks were altered at temperatures of about 105°C corresponding to 5.8 km of overburden. Consequently, it appears that folded Magura Nappe rocks close to the Orava part of the basin were uplifted about 1.4 km above the depth of the present-day basement there. This conclusion corroborates other evidence for the tectonic origin of the basin boundary (Pomianowski 1996; Baumgart-Kotarba 1996). The uplift and concomitant erosion evidently occurred after sedimentation of the Neogene strata.

Four profiles show the maximum amount of erosion in different parts of the Magura Nappe, in its basement, in tectonic windows, and in the foreland of the nappe (Figs 1A, C, E, 13). The southern parts of the profiles AA′, BB′ and CC′ oriented perpendicular to the Magura frontal thrust (Fig. 13) show a lessening degree of erosion towards the PKB. However, the amount of erosion is the greatest in the southern part of the DD′ profile. In all profiles, the least erosion is shown to have occurred in the marginal part of the Magura Nappe. The BB′ profile across the central segment of the nappe shows a single maximum, whereas other profiles crossing the western and eastern segments reveal several less pronounced maxima (Fig. 13). Notably, the area of maximum erosion overlaps the area in the central segment of the Magura Nappe on the profile between the Szczawa and Limanowa-Kłęczany windows which, according to Nemčok et al. (2000), underwent maximum (50%) shortening. Box-sand models support a correlation between an amount of uplift and an amount of shortening (Souza Gomes, Ferreira 2000).

The tectonic windows and the adjoining areas of the Magura Nappe are places of enhanced erosion (profiles BB′, CC′ and DD′). However, the areas of maximum erosion do not geographically correspond to the windows but occur southward from them. Erosion of the Dukla Nappe and of equivalent units in the Magura Nappe foreland was either considerably greater at up to 2 km (profiles AA′, CC′) than that of the frontal part of the Magura Nappe, or only marginally so (profile DD′). Erosion of the Dukla Nappe was greater than that of the Silesian Nappe (profiles AA′, CC′). Comparison of profiles CC′ and DD′ shows that the degree of erosion of the Magura Nappe and its foreland changed considerably over a very short distance along strike. In the central segment of the region examined (profile BB′), there is a marked contrast in amount of erosion between the Magura and Silesian nappes; the estimated thickness of removed overburden corresponds to 6.2 and 4.8 km, respectively.

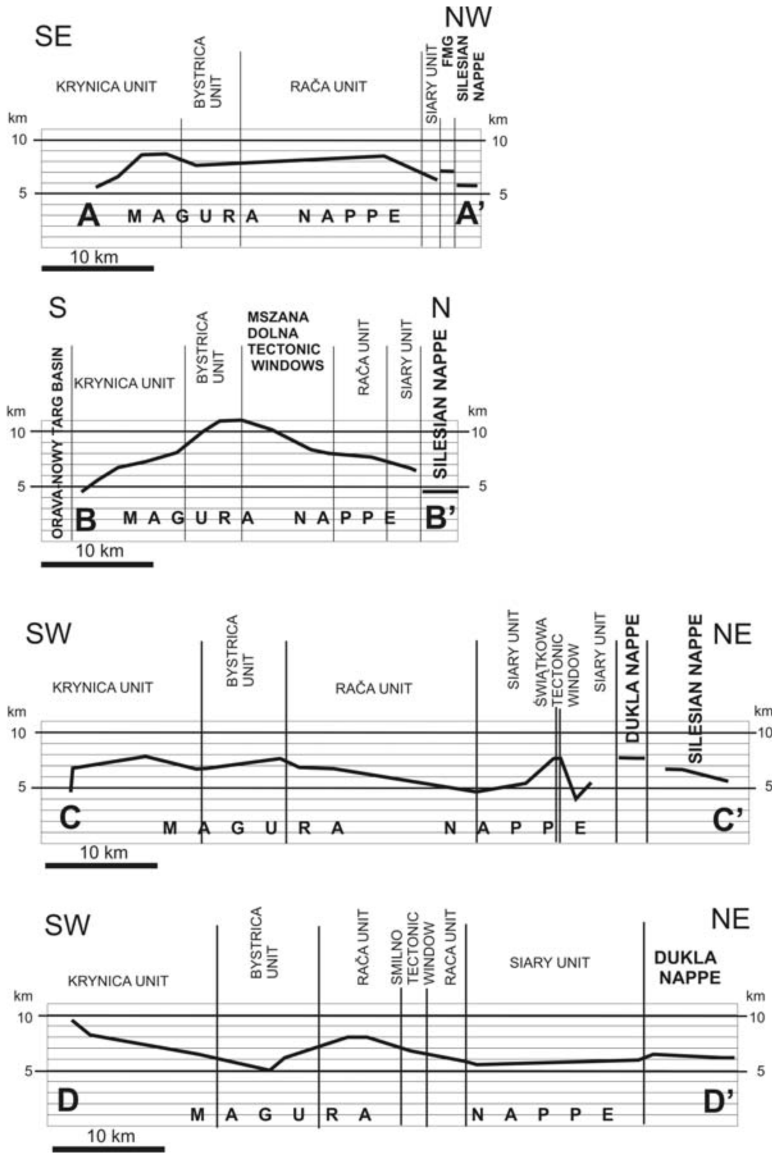

Fig. 13. Profiles illustrating estimated maximum amount of erosion across the Magura Nappe and in adjoining areas. For locations of profiles see Figs 1 B, C and E. See text for further explanation

If the paletemperature gradient were higher, profiles showing amount of erosion across the Magura Nappe would be flatter. However, relative differences in erosion would be preserved.

Thermal overprint and age of altered strata

The results of the studies on correlation between degree of smectite to illite transformation and rock age carried out on small fragments of the Krynica, Bystrica, Rača and Siary units do not agree with corresponding results for the whole Magura Nappe. Observations from the rims of the Orava-Nowy Targ and Nowy Sącz basins show no correlation between the rock age and the degree of smectite to illite transformation in the Magura Nappe nearby (Figs 10, 11). This conclusion agrees with the results of earlier studies on the Magura Nappe (Dudek, Świerczewska 2001; Kotarba 2003; Świerczewska et al. 2003b; Świerczewska 2005). Moreover, the lack of difference in the I/S composition across the internal thrusts separating rocks of different ages indicates that observed degrees of alteration are essentially independent of these thrusts and that the thermal alteration post-dates thrusting. However, summary results for particular units in the Magura Nappe and for the entire nappe show that for each individual unit and for the entire nappe there is a positive correlation between the age and degree of alteration of the sampled rocks (Fig. 5E). This finding is only apparently inconsistent with the results obtained from small discrete portions of the nappe. The contradiction can be explained by reference to the growth mechanism of the accretionary wedge.

Accretion-related deformation of the Magura wedge was initiated during Eocene times (Świerczewska, Tokarski 1998). This means that the diagenetic alteration of the Upper Cretaceous-Paleocene sediments started before accretion. Incorporation of these sequences into the Outer Carpathian accretionary wedge and their deformation occurred prior to the later incorporation of younger sediments. Accretion led to more advanced diagenesis of the sediments in the wedge (Fig. 14). The deformation started in the innermost part of the wedge and migrated towards the foreland (Davis 1996). Thus, sediments incorporated early underwent deeper burial and longer transport inside the wedge than those added later (Willet, Brandon 2002; Brandon 2004). The degree of alteration of the Eocene rocks decreases from the Krynica Unit outwards (Fig. 5E), reflecting the progressive outward-assembly of the wedge during Eocene times.

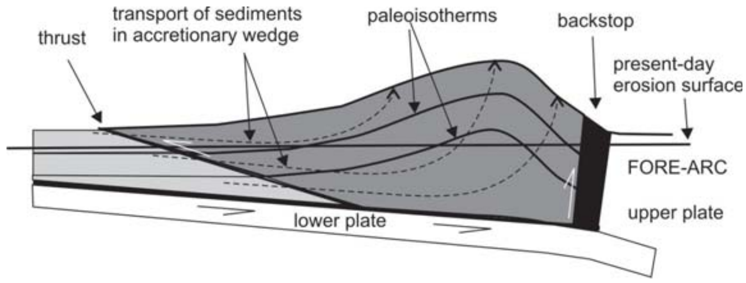

Fig. 14. Cartoon illustrating migration of sedimentary material in accretionary wedge and its thermal alteration due to tectonic burial (based on Willett, Brandon 2002). See text for explanation

It is conceivable that the grade of thermal alteration of the Late Cretaceous-Paleocene rocks reflects a combination of pre-accretion, burial-related diagenesis and accretion-related diagenesis. The consequences of any pre-accretion diagenesis might well have been reset during a later accretion-related diagenesis occurring at higher temperatures. Conversely, if the temperature in the accretionary wedge were lower than that of the Magura basin prior to accretion, the S content would reflect the maximum temperatures that affected the sediments at the earlier time.

The grade of alteration related to the pre-accretion diagenesis appears not to have been reset during the accretion in the Siary Unit. In this unit, the general trend of decreasing thermal alteration from the inner part of the Magura Nappe outwards is obviously disturbed by anomalies related to Upper Cretaceous-Paleocene rocks (Fig. 12). The Siary Unit was the last of the Magura Nappe units to be incorporated into the accretionary wedge. Thus, temperatures affecting the rocks of the unit during its transport through the wedge were not adequate to erase or modify the grade of alteration due to pre-accretion diagenesis. For the Siary Unit, the minimum estimated burial depth of the Upper Cretaceous–Paleocene rocks is either 5.5–6.7 km using a paleogradient of 18°C/km or 3.8–4.6 km using the present-day thermal gradient of 26°C /km (Poprawa et al. 2001) in the Palaeozoic platform below the Outer Carpathians. The latter estimates correlate well with the estimated stratigraphic thickness (~4 km) of the Magura succession. A high thermal overprint makes it impossible to discriminate between pre-accretion diagenesis and accretion-related diagenesis in other units.

Thermal alteration and the morphology of the crystalline basement

Within the Polish segment of the Magura Nappe, the axes of neotectonic elevations do not correlate with the areas of the highest thermal alteration and greatest erosion (Fig. 15). Thus, the observed distribution of paleoisotherms is not a consequence of pre-neotectonic uplift.

Most of the areas of high thermal overprint (>140°C) are located directly above or south of the so-called regional basement slope formed during Ottnangian times (Ryłko, Tomaś 2001). The regional basement slope (RBS) was defined by the latter authors as a longitudinal steeply S-dipping fault zone with up to 5–7 km of relative displacement (Fig. 15). According to Ryłko and Tomaś (2001), the RBS triggered the development of the tectonic windows and hence, significantly influenced the architecture of the Outer Carpathians.

Two large transverse dislocation zones cut and shift the RBS. One of the areas showing high thermal overprint (140–160°) is located in the Babia Góra Mt region above one of the transverse dislocations north of the RBS.

The central segment of the frontal Magura overthrust is located north of the RBS. In this region, this basement slope marks the northern limit of the area where the rocks show highest alteration (>165°C). The Mszana Dolna and Szczawa tectonic windows are located inside the zone of the highest alteration above the RBS, whe-

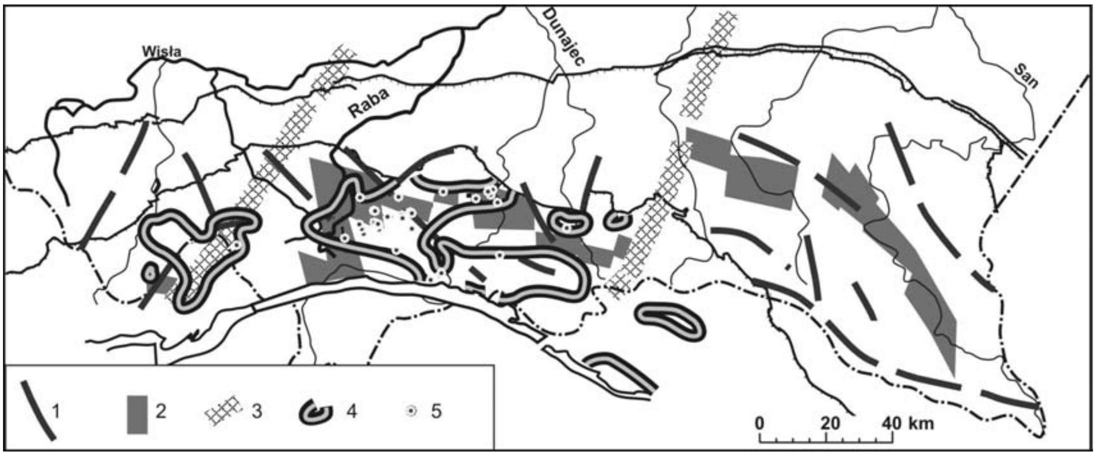

Fig. 15. Sketch-map showing locations of neotectonic elevations (Zuchiewicz et al. 2002), and the location of the regional basement slope (Ryłko, Tomaś 2001) within the Polish segment of the Outer Carpathians. Locations of areas affected by maximum paleotemperatures are also shown.
1 — axes of neotectonic elevation, 2 — regional basement slope, 3 — dislocation zones in the basement, 4 — 140°C paleoisotherm, 5 — location of heating in excess of 165°X

reas the Limanowa-Klęczany tectonic window is located immediately north of the RBS.

Timing of alteration and erosion

The Early Burdigalian age of the folded Zawada Formation rocks (Oszczypko, Oszczypko-Clowes 2002) which show a very low grade of thermal alteration (<75°C) probably identifies the time of the maximum burial in the central segment of the Magura Nappe. Based on data from the Neogene depressions where the erosion took place before Badenian times, it seems that pre-Badenian erosion might well have occurred in other parts of the nappe too.

According to Poprawa et al. (2002), the basement of the Magura basin was tectonically uplifted by up to a few kilometres during Late Eocene-Early Oligocene times. It seems probable that this uplift was at least partially related to the growth of the accretionary wedge. This probability appears to be confirmed by synsedimentary erosion counterbalancing growth of the wedge (Fig. 14 and Brandon 2004).

Evidence for synsedimentary erosion of indurated Magura Nappe rocks is provided by olistolithes derived from the Magura succession (Bromowicz 1999; Kopciowski, Garecka 1996; Jankowski 1997). The Lower Miocene olistostrome (Gorlice beds, Jankowski 1997) exposed in the Magura Nappe front was unaffected by temperatures exceeding 75°C (Figs 1E, 12, Appendix 2). Other erosion-related olistolith-bearing strata show alteration grades reflecting maximum burial to about 6.8 km in the case of the Oligocene-(?)Miocene chaotic complex exposed in the Świątkowa tectonic window (Fig. 3A, Appendix 4 and Kopciowski et al. 1997a) and to about 4 km in the case of the Upper Oligocene Gładyszów beds (Fig. 1E, Appendix 1 and Kopciowski, Garecka

1996). The grade of alteration of the Gładyszów beds indicates that the growth of the accretionary wedge in the Siary Unit and the related burial of sediment were still in progress during Late Oligocene times.

CONCLUDING REMARKS

The present-day thermal structure of the Magura Nappe largely came to being during accretion of the Magura sequence. However, this accretion-related thermal pattern was subsequently disturbed. One disturbance can be observed in the frontal part of the central segment of the nappe where the highly altered rocks of the nappe overlie the less altered Silesian Nappe rocks (Figs 7, 14) and the more altered rocks of the Rača Unit overlie the less altered Siary Unit rocks (Fig. 6). Others can be recognized in the tectonic windows, for instance, where more altered Magura Nappe rocks overlie the less altered Fore-Magura group of nappes in the Mszana Dolna, Świątkowa, Smilno and Limanowa-Kłęczany tectonic windows (Figs 9C, D, F; 12). It is a similar case where more altered Magura Nappe rocks overlie the less altered Silesian Nappe rocks in the Limanowa-Kłęczany and Kotań tectonic windows (Figs 9C, E, 12). However, the thermal alteration of the Magura Nappe rocks in these regions occurred before insertion into their present-day position. Furthermore, completion of the internal thrusting within the Magura Nappe, except for later thrusting of a short segment of the Rača thrust, was followed by thrusting of the entire nappe over its foreland.

The timing of the thrusting of the Magura Nappe over its foreland is recorded in the composition of detrital material in the Upper Badenian-?Lower Sarmatian syn-orogenic strata in the village of Iwkowa north of the Limanowa-Kłęczany tectonic window. The Magura Nappe was thrust over the Grybów and Michalczowa units there during latest Badenian or earliest Sarmatian times (Cieszkowski 1992a). These two units and the Magura Nappe were later, as one tectonic body, thrust over the Silesian Nappe. Thus, the tectonic transport of the Magura Nappe toward the Carpathian Foredeep was still in progress at least during Sarmatian times.

In some places, rocks exposed in tectonic windows show either similar or significantly higher degrees of thermal alteration than do the rocks of the Magura Nappe on their rims (Figs 9A, B, C). A similar degree of the alteration could be easily explained if the Magura Nappe was of such a thickness as to equalise the grade of thermal alteration at the base of the nappe and in subjacent strata. However, any significantly higher alteration of the basement could not be explained if that alteration happened in the present-day structural position. A good example of such is the thermal structure of the Kłęczany Slice in the Limanowa-Kłęczany tectonic window (Figs 3A, 9C); the alteration in the window series cannot be related to burial below the Magura Nappe in the present-day tectonic setting.

The tectonic positioning of differently altered rocks under a relatively thin Magura Nappe would, however, provide a good explanation for the origin of the thermal structure. Moreover, it appears that tectonic transport in the basement of the Magura

Nappe involved major uplift of those fragments of the Magura Nappe which now adjoin the tectonic windows.

In the frontal part of the central segment of the Magura Nappe and in the tectonic windows it is possible to estimate the maximum missing thickness of the nappe from the difference in alteration between the nappe and the subjacent units. The thickness of the Magura Nappe covering the Silesian Nappe ahead of the frontal Magura overthrust must have been <5.5 km, possibly <4.0 km. For the windows, the minimum thickness of the overlying nappe was in excess of 6.5 km.

The hypothetical crustal-scale ramp-overthrust model (Fig. 16) proposed by Molnar and Lyon-Caen (1988) may be applicable to the late stage structural evolution of the Western Outer Carpathians and to the origin of the Carpathian Foredeep (compare Oszczypko 1998). During this stage, the Magura and Silesian nappes were thrust over their forelands. This process started at least during the Early Miocene (Nemčok et al. 2000) or during latest Ottangian times (Oszczypko 2001). The origin of the foreland basin (Carpathian Foredeep), related to loading of the down-going plate by the accretionary wedge, was essentially balanced by substantial uplift of the wedge. In the model of Molnar and Lyon-Caen (1988), the zone of the greatest uplift and erosion is located above a ramp in the basement. Such ramps in the Magura Nappe basement could have been formed by antiformal stacks or duplexes in the underlying nappes. According to Nemčok et al. (2000), antiformal stacks occur beneath the Magura Nappe northeast of the Szczawa tectonic window and in the Smilno tectonic window. Duplexes have been documented in the Świątkowa and Mszana Dolna tectonic windows, (Mastella, Rubinkiewicz 1998; Oszczypko-Clowes, Oszczypko 2004).

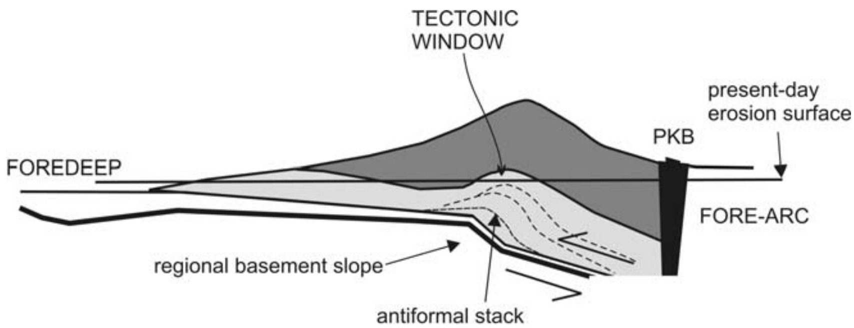

Fig. 16. Cartoon illustrating extents of uplift and erosion in the Outer Carpathian belt based on the model of Molnar, Lyon-Caen (1988). The Magura Nappe is dark gray

Antiformal stacks or/and duplexes may conceivably have formed above the RBS in the Outer Carpathians (Nemčok et al. 2000). The largest stack-related uplift is located inward of the stack, i.e., toward the internal part of the Magura Nappe. This would explain the erosion pattern in the environs of the tectonic windows where zones of maximum erosion are located outside the windows towards the internal part of the nappe (Fig. 13, sections BB′, CC′, DD′). A model involving antiformal stacks and/or duplexes below could thus explain the location of the zones of maximum erosion in the central and eastern parts of the Magura Nappe. The greatest uplift and erosion took place after the RBS was disturbed by movement on oblique-slip fault zones in the earliest Badenian (Ryłko, Tomaś 2001).

The pattern of erosion in the Grajcarek Unit (PKB) fits the model. In the inner part of the Magura Nappe, the amount of erosion is in agreement with a general, hinterland-directed decrease in uplift and erosion (Fig. 13). The uplift of the PKB was initiated during the Early Miocene whereas brittle deformation lasted until Badenian times (Birkenmajer 1986). During the Badenian, thrusting of the Magura nappe was still in progress whereas the PKB was the backstop for the deformed wedge. The cessation of deformation in the innermost part of the wedge occurred before or during Sarmatian times (compare Cieszkowski, 1992b; Birkenmajer, Pécskay 2000).

SUMMARY AND CONCLUSIONS

The X-ray diffraction measurements of the degree of smectite to illite transformation in the rocks of the large geological body carried out by the author, have demonstrated that this method is very useful and successful in regional geological studies.

The Magura Nappe shows evidence of paleotemperatures ranging from <75°C to >165°C (possibly up to 200°C). The burial of already folded and sliced strata was the main reason for the heating. The maximum amount of erosion in the Magura Nappe is estimated to have ranged from <4 km to as much as 11 km. The higher values pertain to areas with maximum thermal overprints.

Within the Magura Nappe, there is a clear general trend of decreasing thermal alteration from the inner part outwards. In addition, in the inner part of the nappe, there is a less distinct and local trend of decreasing alteration towards the Inner Carpathians.

Thermal alteration grades are independent of the ages of sampled rocks in small discrete portions of the Magura Nappe; the rocks in these were incorporated into the Magura wedge, deformed in the wedge and uplifted at the same time. However, for each large tectonic unit, and for the entire nappe, a positive correlation does exist between rock age and thermal grade. This is the result of the progressive outward-directed accretion of the Magura wedge.

The alteration grade of the Late Cretaceous-Paleocene rocks reflects a combination of pre-accretion and accretion-related diagenesis. If temperatures in the accretionary wedge were lower than those in the pre-accretion basin, the observed thermal alteration would be indicative of the pre-accretion maximum temperatures in the basin sediments.

The present-day thermal structure of the Magura Nappe was largely established during accretion. The observed outward-directed decrease in thermal alteration and the positive correlation between rock age and thermal overprint in each of the tectonic units and in the whole nappe are reflections of the progressive growth of the accretionary wedge. The accretion-related thermal structure was greatly modified during the later thrusting of the Magura Nappe over its foreland. This event involved differential uplift and erosion. The uplift was significantly influenced by the morphology of

Carpathian basement. The erosion was greatest above and inwards towards the regional basement slope (RBS). This resulted in the exhumation of the most altered rocks. The thermal alteration of the Magura Nappe rocks occurred before emplacement of these rocks into their present position.

Two main stages of uplift and erosion can be distinguished. The first stage was related to pre-Karpatian uplift of the accretionary wedge when up to 4 km of overburden may have been eroded. A second stage of uplift and erosion was related to thrusting of the Magura Nappe over its foreland and to coeval deformation within it. This stage started in the Early Miocene and was still progressing in Early Sarmatian times (compare Cieszkowski 1992a). This model is supported by 30.8±3.2 Ma apatite fission track ages from of the Rača Unit and by a 20.7±3.0 Ma apatite fission track age from the Obidowa-Słopnice Unit in the Mszana Dolna tectonic window (Struzik et al. 2002). The first age may be reasonably related to the initial uplift of the accretionary wedge, the second to the later stages of the uplift.

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Anna ŚWIERCZEWSKA

ZALEŻNOŚCI POMIĘDZY HISTORIĄ TERMICZNĄ I STRUKTURALNĄ PŁASZCZOWINY MAGURSKIEJ (KARPATY ZEWNĘTRZNE) W POLSCE I NA SŁOWACJI

Streszczenie

Badania minerału mieszanopakietowego illit-smektyt metodami dyfraktometrii rentgenowskiej zostały użyte do rekonstrukcji wielkości pogrzebania, historii termicznej oraz aktywności tektonicznej płaszczowiny magurskiej. Obserwowane przeobrażenia termiczne skał na powierzchni erozyjnej płaszczowiny są wynikiem oddziaływania temperatur z zakresu <75–200 ^{o}C. Temperatury te wynikają z pogrzebaniem tektonicznego do głębokości <4–11 km. Struktura termiczna płaszczowiny magurskiej powstała głównie podczas tworzenia się pryzmy akrecyjnej.

Zidentyfikowano dwa główne etapy wypiętrzenia i erozji. Podczas etapu pierwszego, przed karpatem, w końcowej fazie narastania pryzmy akrecyjnej, nastąpiło usunięcie do 4 km skał pryzmy. Drugi etap związany był z późniejszym nasuwaniem płaszczowiny magurskiej na jej przedpole oraz z deformacjami zachodzącymi w jej obrębie. Utworzona podczas akrecji termiczna struktura płaszczowiny została wówczas istotnie zmodyfikowana. Na wielkość wypiętrzenia wpływała znacząco morfologia podłoża Karpat. Erozja powodująca odsłonięcie najsilniej przeobrażonych skał była największa bezpośrednio nad jak i w najbliższym sąsiedztwie regionalnego skłonu podłoża. Drugi etap wypiętrzenia i erozji rozpoczął się we wczesnym miocenie i trwał przynajmniej do wczesnego sarmatu.

Magura Nappe

KRYNICA UNIT							
Sample	Site	Stream	Topographic maps	L	age	R	%S
105	98/2 Barcice quarry		183.24 Stary Sącz	MF	E2	**R0**	**55**
175	01/4 Klikuszowa	Lepietnica	183.1 Nowy Targ	MF	E2	**R>1**	**24**
203	02/12 Jaszcze Małe	Jaszcze	183.14 Nowy Targ	InB	Cr2-P	**R>1**	**13**
204	02/13 Jaszcze Duże	Jaszcze	183.14 Nowy Targ	MF	E2-E3	**R>1**	**16**
205	02/14 Knurów	Knurowski	183.14 Nowy Targ	MalF	E3-O1	**R0**	**60**
206	02/15 Knurów-Rudniki	Knurowski	183.14 Nowy Targ	MF	E2-E3	**R0**	**40**
207	02/16 Knurów Łuscek	Knurowski	183.14 Nowy Targ	MF	E2-E3	**R>1**	**28**
208	02/17 Waksmund	Dunajec	183.14 Nowy Targ	MalF	E3-O1	**R1**	**38**
209	02/18 Krauszów	Czarny Dunajec	183.3 Zakopane Pn.	MalF	E3-O1	**R0**	**40**
218	02/25 Lipnica Wielka - Małkuchowa	Lipnica	102 Oravske Beskydy	MF	E2	**R0**	**40**
219	02/26 Lipnica Wielka - Lipnica Mała	Lipnica	102 Oravske Beskydy	MF	E2	**R0**	**40**
250	2/51 Łopuszna-Zarębek	Łopuszański	183.14 Nowy Targ	MF	E2-E3	**R1**	**30**
251	2/52 Łopuszna	Łopuszański	183.14 Nowy Targ	MalF	E3-O1	**R0**	**40**
358	03/1 Wojkowa	Wojkowski	184.34 Powroźnik	ZrF	E1-E2	**R>1**	**25**
359	03/2 Wojkowa	Wojkowski	184.34 Powroźnik	ZrF	E1-E2	**R>1**	**22**
360	03/3	Muszynka	184.34 Powroźnik	MF	E2	**R0**	**28**
363	03/6 Muszynka	Szczawnik	184.34 Powroźnik	ZrF	E1-E2	**R1**	**32**
541	541	Dunajec	183.23 Ochotnica Dolna	ZrF	E1-E2		**18**
174a	01/3 Wierchomla quarry		184.31 Piwniczna	MF	E2	**R0**	**25**
174b	01/3 Wierchomla quarry		184.31 Piwniczna	MF	E2	**R0**	**28**
57D	97/1 Samorody	Dunajec	183.14 Nowy Targ	MalF	E3-O1	**R0**	**40**
57G	97/1 Samorody 97/35	Dunajec	183.14 Nowy Targ	MalF	E3-O1	**R0**	**40**
90D	97/38 Jaszcze	Jaszcze	183.14 Nowy Targ	MF	E2	**R>1**	**12**
90G	97/38 Jaszcze	Jaszcze	183.14 Nowy Targ	MF	E2	**R>1**	**8**
98/16	98/16 Ponice	Poniczanka	183.1 Nowy Targ	MF	E1-E2	**R>1**	**12**
98/17	Czarna Woda	Czarna Woda	183.42 Szczawnica	ZrF	E1-E2	**R>1**	**19**
BA	433 Tylmanowa Basznia	Dunajec	183.23 Ochotnica Dolna	MF	E2	**R>1**	**17**
BA1	433 Tylmanowa Basznia	Dunajec	183.23 Ochotnica Dolna	MF	E2	**R1**	**15**
BA2	433 Tylmanowa Basznia	Dunajec	183.23 Ochotnica Dolna	MF	E2	**R>1**	**22**
BA5	433 Tylmanowa Basznia	Dunajec	183.23 Ochotnica Dolna	MF	E2	**R>1**	**18**
Kn1	98/36 Krynica-Czarny Most	Szczawnicze	184.34 Powroźnik	ZrF	E1-E2	**R>1**	**25**
Kn13	99/37 Krynica		184.32 Krynica	ZaF	E1-E2	**R>1**	**16**
Kr1	Krościenko		183.11 Krościenko	SzF	P	**R>1**	**8**
Kr9	Krościenko	Dunajec	183.11 Krościenko	SzF	P	**R>1**	**12**
KU1	97/39 Krauszów - Pod Krauszów		183.3 Zakopane Pn.	MalF	E3-O1	**R0**	**50**
KU2	97/39 Krauszów - Pod Krauszów		183.3 Zakopane Pn.	MalF	E3-O1	**R0**	**40**
LL3	98/38 Leluchów		194.12/L Leluchów	MalF	E3-O1		**28**

LL7	98/38 Leluchów		194.12/L Leluchów	MalF	E3-O1		**58**
PW2	97/45 Piwniczna	Poprad	184.31 Piwniczna	MF	E2	**R>1**	**18**
PW8	97/45 Piwniczna	Poprad	184.31 Piwniczna	MF	E2	**R>1**	**16**
S1	Drienica		104 Cergov	MB	E	**R>1**	**18**
S4	Majdan		104 Cergov	MB	E	**R>1**	**13**
S40	Rabca	Polhoranka	102 Oravske Beskydy	BeB	P-E2	**R>1**	**24**
S41	Rabca – Zubrohlawna		102 Oravske Beskydy	MB	P-E	**R0**	**40**
S43	Namestovo quarry	Biela Orava	102 Oravske Beskydy	MB	P-E	**R0**	**40**
S45	Oravska Jasenica Zapad	Veselianka	102 Oravske Beskydy	BeB	P-E2	**R1**	**30**
S46	Oravska Jasenica Podskalou	Veselianka	102 Oravske Beskydy	BeB	P-E2	**R>1**	**15**
S49	Oravske Vesele	Veselianka	102 Oravske Beskydy	MB	P-E	**R>1**	**15**
S57	Oravsky Podzamok – Lokce		111 Chocske Vrchy	MaRaF	E3-O	**R0**	**40**
S60	Lokce		111 Chocske Vrchy	MaRaF	E3-O	**R1**	**28**
S68	Zazriva		110 Mała Fatra	MB	E1-E2	**R1**	**33**
S7	Richvald		104 Cergov	MalF	E3-O	**R0**	**36**
TY1	Tylmanowa Kolatówka	Dunajec	183.23 Ochotnica Dolna	ZrF	E1-E2	**R1**	**25**
TY2	Tylmanowa Kolatówka	Dunajec	183.23 Ochotnica Dolna	ZrF	E1-E2	**R1**	**22**
ZB	440 Zabrzeż		183.23 Ochotnica Dolna	MF	E2	**R>1**	**27**
ZBR1	440 Czerniec	Dunajec	183.23 Ochotnica Dolna	ZrF	E1-E2	**R1**	**34**
ZBR2	440 Czerniec	Dunajec	183.23 Ochotnica Dolna	ZrF	E1-E2	**R1**	**30**
ZE	97/49 Życzanów	Rzeczanowski	183.24 Stary Sącz	SzF	P	**R>1**	**10**
ZR-1	NS528 Zarzecze	Dunajec	183.23 Ochotnica Dolna	ZrF	E1-E2	**R>1**	**27**
ZR-2	NS528 Zarzecze	Dunajec	183.23 Ochotnica Dolna	ZrF	E1-E2	**R>1**	**30**
BYSTRICA UNIT							
Sample	Site	Stream	Topographic maps	L	age	R	%S
30	PL8-19 Zbludza bridge	Zbludza	183.21 Kamienica	InB	Cr2-P	**R>1**	**17**
31	PL20-27 Zbludza	Zbludza	183.21 Kamienica	BeB	E1		**18**
142	99/4 Krzyżówka		184.14 Florynka	ŁM	E2-E3	**R>1**	**15**
143	99/5 Krynica		184.32 Krynica	ŁM	E2-E3	**R>1**	**16**
172	01/1 Złatna	Straceniec	182.14 Złatna	ŁM	E	**R0**	**33**
173	01/2 Złatna	Kościelec	182.14 Złatna	ŁM	E	**R0**	**28**
176	01/5 Ponice	Poniczanka	183.1 Nowy Targ	MF	E2	**R>1**	**18**
188	02/01 Stary Sącz – Potoki	Poprad	183.24 Stary Sącz	HiB	E2	**R1**	**32**
189	02/3 Stary Sącz – Potoki	Żelaźnikowski	183.24 Stary Sącz	BeF	E1-E2	**R0**	**60**
190	02/2 Stary Sącz – Myślec	Żelaźnikowski	183.24 Stary Sącz	ŻeF	E1-E2	**R0**	**65**
192	02/5 Nawojowa-Szczygłówka	un-named stream	184.13 Kamionka Wlk	BeF	E1-E2	**R0**	**60**
220	02/27 Lipnica Wielka – Sołtystwo	Lipnica	102 Oravske Beskydy	ŁM	E	**R1**	**26**
221	02/28 Lipnica Wielka – Skoczykówka	Kiczorka	102 Oravske Beskydy	BeB	E	**R1**	**25**
222	02/29 Lipnica Wielka – Polana pod Kiczorą		102 Oravske Beskydy	RoB	Cr2-P	**R>1**	**8**
295	2/83	Racza	182.31 Tatarki	ŁM	E	**R0**	**33**
296	2/84 Rycerka G.	Ciapków	182.31 Tatarki	BeB	E	**R1**	**33**

297	2/85	Śrubita	182.31 Tatarki	MF	E2	**R1**	**33**
299	2/87 Glinna		182.32/L Glinka	BeB	E1-E2	**R>1**	**28**
300	2/88 Glinka Wyrobniówka		182.32/L Glinka	InB	Cr2-P	**R>1**	**18**
301	2/89 Glinka – Szymonów	Glinka	182.32/L Glinka	ŁaF	P2-E2	**R1**	**28**
361	03/4 Muszynka	Szczawnik	184.34 Powroźnik	ŁM	E	**R1**	**33**
362	03/5	Szczawnik	184.34 Powroźnik	ŁaF	P2-E2	**R1**	**28**
364	03/7 Tylicz	Muszynka	184.32 Krynica	BeB	E1-E2	**R>1**	**22**
369	03/12 Kamionna	Kamionna	184.14 Florynka	ŁaF	P2-E2	**R1**	**35**
370	03/14	Kamionna	184.14 Florynka	BeB	E1-E2	**R1**	**28**
373	03/16 Kamionna		184.14 Florynka	BeB	E1-E2	**R>1**	**27**
376	03/19 Kamionna		184.14 Florynka	BeB	E1-E2	**R1**	**32**
377	03/20 Czyrna	Czyrnianka	184.32 Krynica	ŁaF	P2-E2	**R0**	**33**
573	NS573 Łącko Zawodzie	Dunajec	183.23 Ochotnica Dolna	MF	E2-E3	**R>1**	**12**
69D	PL 176-9 Koninki	Koninki	183.12 Niedźwiedź	MlF	Cr2	**R>1**	**8**
70 G	PL 180-6 Koninki	Koninki	183.12 Niedźwiedź	MF	E2		**15**
88D	97/36 Koszarki	Kamienica	183.21 Kamienica	InB	Cr2-P	**R>1**	**4**
88G	97/36 Koszarki	Kamienica	183.21 Kamienica	InB	Cr2-P	**R>1**	**4**
89D	97/37 Lubomierz		183.12 Niedźwiedź	SS	Cr2-P	**R>1**	**15**
89G	97/37 Lubomierz		183.12 Niedźwiedź	SS	Cr2-P	**R>1**	**7**
96D	97/40 Zasadne	Zasadne	183.21 Kamienica	ŁaF	P2-E2	**R>1**	**9**
96G	97/40 Zasadne	Zasadne	183.21 Kamienica	ŁaF	P2-E2	**R>1**	**12**
97D	97/41 Zasadne	Zasadne	183.21 Kamienica	BeF	E1-E2	**R>1**	**17**
98/10	Konina Palacze	Konina	183.1 Nowy Targ	HiB	E2-E3	**R>1**	**13**
98/11	Konina Zagroda	Konina	183.1 Nowy Targ	KaB	Cr2	**R>1**	**10**
98/12	Konina	Konina	183.1 Nowy Targ	KaB	Cr2	**R>1**	**10**
98/13	Poręba Wielka – Koninki	Koninki	183.1 Nowy Targ	InB	Cr2-P	**R>1**	**1**
98/14	Poręba Wielka – Koninki, Filipy	Koninki	183.1 Nowy Targ	MF	E2	**R>1**	**12**
98/15	Poręba Wielka – Koninki, Huciska	Koninki	183.1 Nowy Targ	MF	E2		**12**
98/3	Podglinka	Jastrzębik	183.24 Stary Sącz	MF	E2	**R0**	**40**
98/4	Pod Rogami	Słomka	183.22 Chełmiec	ŁM	E	**R0**	**70**
98/5	98/5 Kwasowiec	Suchy	183.22 Chełmiec	BeF	E1-E2	**R0**	**60**
98/6	98/6Mogielnica	Mogielnica	183.21Kamienica	SS	Cr-P	**R>1**	**8**
98/7	98/7 Koszarki	Mogielnica	183.21Kamienica	SS	Cr2-P	**R>1**	**11**
98/8	Konina	Konina–Zapalacz	183.1 Nowy Targ	MF	E2	**R>1**	**8**
98/9	Konina Polana	Konina	183.1 Nowy Targ	MF	E2	**R>1**	**10**
M1	Maszkowice quarry		183.24 Stary Sącz	MF	E2	**R>1**	**25**
M6	Maszkowice quarry		183.24 Stary Sącz	MF	E2	**R>1**	**28**
S16	Bardejov		105 Ondavska Verchovina	BeF	E1	**R1**	**32**
S19	Lukavica		105 Ondavska Verchovina	ZlB	E	**R0**	**60**
S31	Domasa		116 Slanske vrchy	BeF	E1-E2	**R0**	**40**
S5	Krive		104 Cergov	BeF	E1	**R1**	**28**
S50	Oravske Vesele Zajovka	Veselanka	102 Oravske Beskydy	BeF	E1-E2	**R>1**	**20**

S54	Dulov	Mutnanka	102 Oravske Beskydy	BeF	E1-E2	**R1**	**30**
S73	Lutise-Melikovce		110 Mala Fatra	ZlB	E2-E3	**R0**	**40**
S74	Radostka		110 Mała Fatra	ZlB	E2-E3	**R0**	**40**
S76	Lutise-Sykorovce	Radostka	110 Mala Fatra	ZlB	E2-E3	**R0**	**50**
SE	91/1 Sidzina quarry	Sidzina	182.22 Sidzina	MF	E2	**R0**	**25**
RAČA UNIT							
Sample	Site	Stream	Topographic map	L	age	R	%S
153	97/7 Sól		182.13 Rajcza	MB	E2-E3	**R>1**	**28**
191	02/4 Łazy Biegonickie		184.13 Kamionka Wlk	ZwF	M1	**R0**	**85**
193	02/6 Grabowa	Naściszówka	184.11 Nowy Sącz	MF	E2	**R0**	**45**
194	02/8 Naściszowa	Naściszówka	184.11 Nowy Sącz	Sb-M	E3	**R0**	**40**
195	02/7 Naściszowa	Naściszówka	184.11 Nowy Sącz	HiB	E2	**R1**	**28**
196	02/9 Naściszowa	Naściszówka	184.11 Nowy Sącz	ŁaF	E1-E2	**R1**	**35**
197	02/10 Świerkla	Gajduszowiec	183.22 Chełmiec	MF	E2	**R0**	**30**
197	02/10 Świerkla	Gajduszowiec	183.22 Chełmiec	MF	E2	**R0**	**30**
198	02/11 Świerkla	Gajduszowiec	183.22 Chełmiec	InB	Cr2-P	**R>1**	**14**
198	02/11 Świerkla	Gajduszowiec	183.22 Chełmiec	InB	Cr2-P	**R>1**	**14**
210	PL47-57 Tenczyn	Tenczynka	173.33 Lubień	MB	E2-E3	**R0**	**26**
211	02/19 Nowy Sącz	Kamienica	184.11 Nowy Sącz	MB	E2-E3	**R0**	**50**
212	02/20 Librantowa		174.33 Korzenna	InB	Cr2-P	**R1**	**37**
244	2/46 Biała Niżna Sudoł	Sudoł	184.12 Grybów	HiB	E2-E3	**R>1**	**15**
245	2/47 Sośne G.		184.12 Grybów	ŁaF	E1-E2	**R>1**	**23**
246	2/48 Sośne G.		184.12 Grybów	RoB	Cr2-P	**R>1**	**18**
247	2/49 Biała Wyżna – Podjaworze		184.12 Grybów	RoB	Cr2-P	**R>1**	**8**
264	02/61 Kojszówka – Barutowa		172.44 Maków Podhalański	HiB	E2-E3	**R0**	**40**
265	2/62 Kojszówka – Mosarowa		172.44 Maków Podhalański	MB	E2-E3	**R0**	**50**
279	02/68 Limanowa – Jabłoniec	Jabłoniec	173.43 Limanowa	InB	Cr2-P	**R>1**	**14**
283	2/71 Litacz	Sobrzeżenie	183.22 Chełmiec	RoB	Cr2-P	**R>1**	**13**
293	2/8 Sól quarry	Soła	182.13 Rajcza	MB	E2-E3	**R0**	**28**
294	2/82 Rycerka	Rycerski	182.13 Rajcza	PsS	E2	**R0**	**23**
298	2/86 Rycerka quarry	Rycerka	182.31 Tatarki	MB	E2-E3	**R>1**	**33**
304	2/92 Milówka – Milówki	Salamonka	182.13 Rajcza	HiB	E2-E3	**R1**	**27**
305	2/93 Żabnica quarry	Żabniczanka	182.12 Radziechowy	MB	E2-E3	**R0**	**23**
306	2/94 Żabnica – Romanka	Romanka	182.12 Radziechowy	SS	P	**R>1**	**17**
307	2/95	Romanka	182.12 Radziechowy	InB	Cr2-P	**R>1**	**18**
344	2/116 thrust zone		173.43 Limanowa	InB	Cr2-P	**R>1**	**18**
352	2/120 Tokarnia – Gwizdowa	Krzczonówka	173.33 Lubień	MB	E2-E3	**R0**	**30**
365	03/8 Wysowa – Blechnarka	Wysowa	184.41 Wysowa	ŁaF	E1-E2	**R1**	**32**
366	03/9 Wysowa Blechnarka		184.41 Wysowa	HiB	E2-E3	**R1**	**32**
367	03/10 Wysowa Blechnarka		184.41 Wysowa	HiB	E2-E3	**R>1**	**25**
368	03/11 Ropki	Ropka	184.41 Wysowa	HiB	E2-E3	**R>1**	**22**
371	03/13 Polany	Kamionna	184.14 Florynka	HiB	E2-E3	**R1**	**33**

372	03/15	Kamionna	184.14 Florynka	MB	E2-E3	**R0**	**>40**
374	03/17 Kamionna		184.14 Florynka	MB	E2-E3	**R0**	**30**
375	03/18 Kamionna		184.14 Florynka	HiB	E2-E3	**R0**	**>40**
378	03/21 Czyrna Niżna	Czyrnianka	184.14 Florynka	MB	E2-E3	**R1**	**28**
384	03/27 Policzne	Jaworzyna	182.21 Koszarawa	HiB	E2-E3	**R>1**	**16**
385	03/28	Jałowiecki	182.21 Koszarawa	HiB	E2-E3	**R>1**	**30**
387	03/30 Gołynia		172.44 Maków Podhalański	HiB	E2-E3	**R0**	**38**
392	03/35	Przybyłka	182.21 Koszarawa	MB	E2-E3	**R>1**	**22**
393	03/36		182.21 Koszarawa	HiB	E2-E3	**R1**	**34**
419	03/64 Mszana Dolna	Morysów	173.34 Mszana Dolna	InB	Cr2-P	**R>1**	**16**
421	03/66 Mszana Dolna – Podleśniaki		173.34 Mszana Dolna	InB	Cr2-P	**R>1**	**22**
422	03/67 Mszana Dolna – Polana Podchodna		173.34 Mszana Dolna	ŁaF	E1-E2	**R>1**	**23**
423	03/68 Jurków – Krawce	Łososina	173.34 Mszana Dolna	InB	Cr2-P	**R>1**	**10**
353 G	2/121 Osielec quarry		172.44 Maków Podhalański	MB	E2-E3	**R1**	**30**
353D	2/121 Osielec quarry		172.44 Maków Podhalański	MB	E2-E3	**R1**	**30**
77D	97/5 Glinka quarry		182.32 Glinka	MB	E2-E3	**R1**	**25**
77G	97/5 Glinka quarry		182.32 Glinka	MB	E2-E3	**R1**	**28**
DO	Dobra		173.32 Mszana Dolna	Sb-M	E3	**R>1**	**15**
LO	98/27 Łosie	Ropa	184.14 Florynka	MB	E2-E3	**R1**	**32**
S10	Sarisske Cerne		105 Ondavska vrchovina	InB	Cr2-P	**R>1**	**17**
S15	Zborov		105 Ondavska Vrchovina	MB	E2-E3	**R>1**	**19**
S22	Okruhle		105 Ondavska Vrchovina	MaF	E3-O1	**R1**	**32**
S24	Okruhle		105 Ondavska Vrchovina	MaF	E3-O1	**R1**	**34**
S28	Vysny Orlik		105 Ondavska Vrchovina	MKS	E	**R0**	**40**
S79	Klubina		101 Kysucke Beskydy	VB	E2-E3	**R0**	**55**
S81	Krasne nad Kysu	Kysa	101 Kysucke Beskydy	ZlF	E2	**R0**	**28**
S95	Velke Rovne-quarry		!09 Javorniky Cadca	PaS	E2-E3	**R>1**	**23**
SK	98/40 Skawica	Skawica	172.44 Maków Podhalański	MF	E3-O1	**R1**	**>40**
SN11	Gruszowiec		173.34 Mszana Dolna	MF	E3-O1	**R1**	**17**
SN20	Gruszowiec		173.34 Mszana Dolna	MF	E3-O1	**R1**	**18**
SN22	Gruszowiec		173.34 Mszana Dolna	MF	E3-O1	**R1**	**23**
SN23	Gruszowiec		173.34 Mszana Dolna	MF	E3-O1	**R1**	**22**
SN24	Gruszowiec		173.34 Mszana Dolna	MF	E3-O1	**R1**	**18**
SN25	Gruszowiec		173.34 Mszana Dolna	MF	E3-O1	**R1**	**22**
SN9	Gruszowiec		173.34 Mszana Dolna	MF	E3-O1	**R1**	**26**
SO	Sopotnia	Sopotnia Mała	182.12 Radziechowy	InB	Cr2-P	**R>1**	**17**
SIARY UNIT							
Sample	Site	Stream	Topographic maps	L	age	R	%S
140	96/24 Świątkowa		184.24 Krempna	MB	E3-O2	**R0**	**80**
165	00/2 Krępna	Krępna	184.24 Krempna	WS	O1	**R0**	**55**
166	00/3 Folusz hospital	Kłopotnica	184.22 Nowy Żmigród	Sp-M	O1-O2	**R0**	**70**

177	01/6 Zembrzce - Bukoszczówka		172.42 Bieńkówka	Sb-M	E3	**R0**	**40**
186	Świątkowa		184.24 Krempna	MB	E3-O2	**R0**	**80**
215	02/23 Łyczanka	Łososina	173.44 Pisarzowa	Sb-M	E3	**R0**	**35**
216	02/24 Łyczanka		173.44 Pisarzowa	ŁaF	E1-E2	**R1**	**34**
227	02/32 Tylawa – Podcychły		185.31 Tylawa	HiB	E1-E3	**R0**	**40**
230	02/35 Zyndranowa – Horbki		185.31 Tylawa	Sb-M	E3	**R1**	**28**
232	02/37 Zyndranowa Horbki	un-named stream, thrust zone	185.31 Tylawa	Sb-M	E3	**R0**	**42**
233	02/38 Zyndranowa Horbki	un-named stream, thrust zone	185.31 Tylawa	ŁaF	E1-E2	**R1**	**28**
235	02/40 Olchowiec	Olchowiec	185.31 Tylawa	WS	O1	**R0**	**45**
236	02/42 Olchowiec – Ropianka	Olchowiec	185.13 Dukla	ŁaF	E1-E2	**R0**	**55**
237	02/41Olchowiec	Olchowiec	185.31 Tylawa	RoB	Cr2-P	**R1**	**32**
241	2/43 Polany	Hucianka	184.42 Grab	ŁaF	E1-E2	**R0**	**34**
242	2/44 Polany	Zimna Woda – Hucianka	184.42 Grab	WS	O1	**R0**	**65**
243	2/45 Polany	Zimna Woda – Hucianka	184.42 Grab	Sb-M	E3	**R0**	**45**
266	02/63 Maków Dolny quarry		172.44 Maków Podhalański	RoB	Cr2-P	**R1**	**23**
267	02/64 Sucha Beskidzka	Błądzonka	172.42 Bieńkówka	HiB	E2-E3	**R0**	**40**
268	02/65 Sucha Beskidzka Siedlisko	Błądzonka	172.41 Rzyki	CiS	E2-E3	**R>1**	**23**
269	02/66 Sucha Beskidzka	Błądzonka	172.41 Rzyki	InB	Cr2-P	**R>1**	**24**
273	Rozstaje, 96/45	Wisłok	184.24 Krempna	MB	E3-O2	**R0**	**50**
280	2/69 Limanowa – Sowliny	Skrudlak	173.43 Limanowa	ŁaF	E1-E2	**R>1**	**28**
284	2/72	Mordarka	173.43 Limanowa	RoB	Cr2-P	**R>1**	**21**
286	2/74 Męcina – Przeciwko		173.44 Pisarzowa	ŁaF	E1-E2	**R>1**	**23**
289	2/78 Jaworzynka	Czadeczka	551.23 Jaworzynka	JwB	Cr2	**R0**	**28**
290	2/77 Jaworzynka	Czadeczka	551.23 Jaworzynka	Sb-M	E3	**R0**	**35**
291	2/79 Zwardoń – Myto		551.23 Jaworzynka	Sb-M	E3	**R0**	**42**
292	2/80 Tarlicze	Tarliczny	182.13 Rajcza	Sb-M	E3	**R0**	**38**
302	2/90 Milówka	Salamonka	182.13 Rajcza	HiB	E2-E3	**R1**	**36**
303	2/91 Milówka	Salamonka	182.13 Rajcza	MB	E3-O2	**R>1**	**28**
309	2/97 Kotań	un-named stream	184.24 Krempna	ŁaF	E1-E2	**R0**	**47**
315	2/99 Świątkowa	Świątkowy	184.24 Krempna	MB	E3-O2	**R0**	**70**
316	2/100 Świątkowa		184.24 Krempna	InB	Cr2-P	**R>1**	**26**
317	96/32 Świątkowa	Świątkowy	184.24 Krempna	InB	Cr2-P	**R>1**	**25**
323	2/103 Świątkowa-Folusz road		184.24 Krempna	ŁaF	E1-E2	**R0**	**40**
324	2/104 Świątkowa	Rzeszówka	184.24 Krempna	InB	Cr2-P	**R>1**	**22**
325	2/105 Świątkowa	Świątkowy	184.24 Krempna	InB	Cr2-P	**R>1**	**28**
332	2/108 Świątkowa		184.24 Krempna	InB	Cr2-P		**25**
341	2/113 pot. Kiczera	Kiczera	184.24 Krempna	WS	O1	**R0**	**43**
350	2/119 Krasne Potockie		173.44 Pisarzowa	InB	Cr2-P	**R>1**	**10**
354	97/17 Tarnawa Dolna		172.41 Rzyki	CiS	E2-E3	**R>1**	**30**

355	97/20 Zachełmna – Żmudówka		172.42 Bieńkówka	Sp-M	O1-2	**R0**	**45**
356	97/21 Palcza – Natolówka	Pałeczka	172.42 Bieńkówka	MB	E3-O2	**R0**	**29**
379	03/22 Ropa	Ropa	184.12 Grybów	InB	Cr2-P	**R1**	**36**
414	03/59 Stróża		173.31 Myślenice	HiB	E2-E3	**R1**	**33**
415	03/60 Stróża	Raba	173.31 Myślenice	ŁaF	E1-E2	**R>1**	**27**
416	03/61 Stróża – Jamrozówka		173.31 Myślenice	InB	Cr2-P	**R>1**	**31**
417	03/62 Pcim – Kolby	Krzywianka	173.31 Myślenice	Sb-M	E3	**R0**	**38**
418	03/63 Węglówka – Obajtki		173.34 Mszana Dolna	Sb-M	E3	**R0**	**42**
166A	00/4 Wołowiec	Zawoja	184.24 Krempna	WS	O1	**R0**	**60**
81D	97/10 Cięcina quarry	Cięcinka	182.12 Radziechowy	MB	E3-O2	**R1**	**30**
81G	97/10 Cięcina	Cięcinka	182.12 Radziechowy	MB	E3-O2	**R0**	**30**
98-8-4	Sól		182.13 Rajcza	RoB	Cr2-P	**R>1**	**25**
FO	Folusz	Kłopotnica	184.22 Nowy Żmigród	ŁaF	E1-E2	**R0**	**32**
GL1	98/32 Gładyszów		184.23 Uście Gorlickie	Sp-M	O1-O2	**R0**	**60**
GL3	Gładyszów-bridge		184.23 Uście Gorlickie	GB	O2	**R0**	**40**
OW1	Owczary	Siary	184.21 Gorlice	ŁaF	E1-E2	**R1**	**25**
OW2	Owczary	Siary	184.21 Gorlice	InB	Cr2-P	**R1**	**34**
OW3	Owczary	Siary	184.21 Gorlice	InB	Cr2-P	**R1**	**29**
PL	98/29 Polany	Wilsznia	184.24 Krempna	Sp-M	O1-O2	**R0**	**67**
RO	98/33 Ropica Górna	Sękówka	184.21 Gorlice	InB	Cr2-P	**R1**	**33**
ROPG	99/3 Ropica Górna	Sękówka	184.24 Krempna	MB	E3-O2	**R0**	**50**
ROZ	98/35 Rozdziele	Rozdzielanka	184.21 Gorlice	InB	Cr2-P	**R0**	**30**
S26	Dobroslava		106 Laborcka verchovina	MB	E3-O2	**R0**	**75**
S30	Keckovce		105 Ondavska vrchovina	MB	E3-O2	**R0**	**50**
S33	Stakcin		118 Buykovske Vrchy	Sb-M	E3	**R0**	**36**
S38	Ubla		126 Vihorlatske Vrchy	MB	E3-O2	**R0**	**55**
S83	Kasarne		108 Javorniky Puchov	VB	E2-E3	**R0**	**40**
S86	Kasarne		108 Javorniky Puchov	BeF	P2-E1	**R0**	**34**
S87	Kopanice/Makov		109 Javorniky Cadca	VB	E2-E3	**R>1**	**19**
S88	Kelcov		109 Javorniky Cadca	BeF	P-E2	**R>1**	**28**
S89	Wysoka n. Kysucom	Kysa	109 Javorniky Cadca	VB	E2-E3	**R0**	**40**
S91	Korona		109 Javorniky Cadca	SoF	Cr2-P	**R1**	**34**
S92	Olesno – Klokocov	Olesnianka	109 Javorniky Cadca	SoF	Cr2-P	**R>1**	**21**
SE	98/28 Sechna		173.42 Iwkowa	MB	E3-O2	**R0**	**40**
SI3	98/31Siary Górne	Siary	184.21 Gorlice	InB	Cr2-P	**R>1**	**26**
SZY	98/34 Bielanka		184.12 Grybów	InB	Cr2-P	**R1**	**34**

List of samples with locations of the sites sampled, S contents and I/S ordering.

Lithostratigraphic units (L): Beloveža beds (BeBe), Beloveža Formation (BeF), Ciężkowice Sandstones (CiS), Gładyszów beds (GB), Hieroglyphic beds (HiB), Inoceramian beds (InB), Kanina Beds (KaB), Łabowa Formation (ŁaF), Łącko marls (ŁM), Magura Formation (MF), Makovica Sandstone (MKS), Malcov Formation (MalF), Malcov and Racibor Formations (MaRaF), Malinowa Formation (MlF), Pasierbiec Sandstones (PsS), Ropianka beds (RoB), Solan Formation (SoF), sub-Magura Beds (Sb-M), supra-Magura Beds (Sp-M), Szczawina Sandstones (SS), Vsetín Beds (VB), Wątkowa Sandstone (WS), Zarzecze Formation (ZrF), Zawada Formation (ZwF), Zlín beds (ZlB) and Żelaźnikowa Formation (ŻeF)

Other tectonic units

OTHER OUTER CARPATHIANS TECTONIC UNITS							
Sample	Site	Stream	Topographic map	L	Age	**R**	%S
DUKLA NAPPE							
MYS	98/30 Myscowa	Wisłoka	184.24 Krempna	MeB	O	**R1**	**20**
223	2/30 Zawadka Rymanowska	Ambrowski	185.13 Dukla	KrB	O	**R0**	**35**
228	02/33 Tylawa	Smereczanka	185.31 Tylawa	MeB	O	**R1**	**30**
229	02/34 Tylawa	Dynowiec/Panna	185.31 Tylawa	MeB	O	**R1**	**34**
231	02/36 Zyndranowa Horbki	Panna	185.31 Tylawa	MeB	O	**R1**	**33**
430	04/2 Majdan	Solinka	195.22 Cisna	MjB	P-E1	**R>1**	**9**
431	04/3	Solinka	195.24 Kalnica	Łub	Cr2	**R>1**	**23**
434	04/6	Solinka	195.24 Kalnica	CiB	Cr2-P	**R>1**	**7**
436	04/8 train pass	Osławica	185.43 Komańcza		E	**R0**	**40**
437	04/9 Komańcza/Dołzyca	Dołzyczka	185.43 Komańcza	CeB	O	**R1**	**28**
439	04/11 bridge	Dołżyczka	185.43 Komańcza	Łub	Cr2	**R1**	**31**
441	04/13 Jawornik	Jawornik/Osława	185.43 Komańcza		E	**R0**	**60**
445	04/17 Wola Michowa	Osława	195.21 Nowy Łupków	CeB	O	**R1**	**24**
446	04/18 Radoszyce		195.21 Nowy Łupków	Łub	Cr2	**R1**	**21**
FORE-MAGURA GROUP OF NAPPES							
288	2/76 Istebna Byrty	Czadeczka	551.21 Istebna	JB	Cr2	**R>1**	**18**
80G	97/9 Kamesznica	Kamieszniczanka	551.22/L Milówka	KrB	O		**25–30**
SILESIAN NAPPE							
238	96/19 Desznica	Ryj	184.24 Krempna	KrB	O	**R1**	**33**
274	Kąty 97/2	Wisłoka	184.22 Nowy Żmigród	LKrB	O	**R0**	**35**
287	2/75 Istebna bridge	Olza	551.21 Istebna	HiB	E	**R>1**	**23**
308	2/96 Kuków	Targoszówka	172.41 Rzyki	KrB	O	**R1**	**32**
357	2/122 Harbutowice		172.42 Bieńkówka	KrB	O	**R1**	**25**
381A	03/23 Mszanka	Mszanka	174.34 Moszczenica	GoB	O-M	**R0**	**80**
382A	03/23 Mszanka	Mszanka	174.34 Moszczenica	GoB	O-M	**R0**	**85**
383A	03/23 Mszanka	Mszanka	174.34 Moszczenica	GoB	O-M	**R0**	**80**
384A	03/23 Mszanka	Mszanka	74.34 Moszczenica	GoB	O-M	**R0**	**70**
49G	96/16 Nowy Żmigród-Okopisko	Wisłoka	184.22 Nowy Żmigród	LKB	O	**R0**	**50**
50 D	96/20 Desznica		184.24 Krempna	LKB	O		**28**
50G	96/20 Desznica		184.24 Krempna	LKB	O	**R>1**	**32**
71D	96/23 Kolonia Kąty		184.24 Krempna	LKB	O	**R1**	**34**

71G	96/23 Kolonia Kąty		184.24 Krempna	LKB	O	**R1**	**31**
LE	Łęki k/Czchowa		173.42 Iwkowa	IsB	Cr2-P	**R0**	**50**
SIN2	Sienna		174.33 Korzenna	GrSh	E3	**R0**	**45**
Szcz1	Szczyrzyc		173.32 Wiśniowa	KrB	O	**R0**	**65**
Szcz4	Szczyrzyc		173.32 Wiśniowa	VrSh	P-E	**R0**	**50**
ZN3	Znamirowice		173.44 Pisarzowa	MeB	O	**R0**	**66**
SUBSILESIAN NAPPE							
82D	97/11 Lipowa – Twardorzeczka	Leśnianka	172.33 Szczyrk	VrSh	P-E	**R0**	**40**
82G	97/11 Lipowa	Leśnianka	172.33 Szczyrk	VrSh	P-E	**R0**	**40**
NEOGENE DEPRESSIONS							
Sample	Site	Stream	Topographic map	L	Age	**R**	%S
NOWY SĄCZ BASIN							
169	PL482 91 Nowy Sącz Bielowice		184.11 Nowy Sącz	BgF	Badenian	**R0**	**75**
73D	Biegonice – pit		184.11 Nowy Sącz	BgF	Badenian	**R0**	**80**
73G	Biegonice – pit		184.11 Nowy Sącz	BgF	Badenian	**R0**	**85**
ORAVA-NOWY TARG BASIN							
217A	95/6 Lipnica Wielka – Piekarzówka	Lipnica	102 Oravske Beskydy	OrB	M	**R0**	**90**
217B	95/6 Lipnica Wielka – Piekarzówka	Lipnica	102 Oravske Beskydy	OrB	M	**R0**	**70**

List of samples with locations of the sites sampled, S contents and the I/S ordering. Lithostratigraphic units (L). Dukla and equivalents units: Cergov beds (CeB), Cisna beds (CiB), Hieroglyphic beds (HiB), Jaworzynka beds (JB), Krosno Beds (KrB), Lower Krosno beds (LKB), Łupków beds (Łub), Majdan beds (MjB), Menilite beds (MeB). Silesian and Sub-Silesian nappes: Gorlice beds (GoB), Green shales (GrSh), Hieroglyphic beds (HiB), Istebna beds (IsB), Krosno beds (KrB), Lower Krosno beds (LKrB), Verovice beds (VeB), Variegated shales (VrSh). Neogene basins: Biegonice Formation (BgF), Orava beds (OrB).

Pieniny Klippen Belt

PIENINY KLIPPEN BELT						
Sample	Site/stream	Topographic map	L	Age	**R**	%S
GRAJCAREK UNIT						
1/00	Sztolnia	183.42 Szczawnica	Hałuszowa Fm.	Campanian	**R>1**	**10**
Szt15	Sztolnia	183.42 Szczawnica	Hulina Fm.	Albian-Cenomanian	**R>1**	**22**
Szt16	Sztolnia	183.42 Szczawnica	Hulina Fm.	Albian-Cenomanian	**R>1**	**22**
Szt43	Sztolnia	183.42 Szczawnica	Hulina Fm.	Albian-Cenomanian	**R>1**	**21**
Rz6	Szczawnica – Rzeźnia	183.42 Szczawnica	Wronine	Aptian-Albian	**R1**	**25**
Rz2	Szczawnica – Rzeźnia	183.42 Szczawnica	Kapuśnica Fm	Barremian-Aptian	**R0**	**30**
Krz6	Szczawnica – Krzonowe	183.42 Szczawnica	Krzonowe Fm	Aalenian	**R0**	**30**
Szt30	Sztolnia	183.42 Szczawnica	Opaleniec Fm.	Bajocian	**R1**	**30**
Szt1	Sztolnia	183.42 Szczawnica	Szlachtowa Fm.	Toarcian-Aalenian	**R1**	**37**
Szt12	Sztolnia	183.42 Szczawnica	Szlachtowa Fm.	Toarcian-Aalenian	**R1**	**27**
Szt6	Sztolnia	183.42 Szczawnica	Szlachtowa Fm.	Toarcian-Aalenian	**R1**	**32**
JA1	Jaworki	183.42 Szczawnica	Jarmuta Fm.	Cr2-P	**R>1**	**23**
KLIPPEN SUCCESSION						
S70	Zazriva	110 Mała Fatra	Skrzypny Fm.	Aalenian	**R1**	**36**

List of samples with locations of the sites sampled, S contents and the I/S ordering. Lithostratigraphic units (L).

Tectonic windows

TECTONIC WINDOWS							
Sample	Site	Stream	Topographic map	L	Age	**R**	%S
KOTAŃ TECTONIC WINDOW							
310	96/46 Kotań		184.24 Krempna	KrB	O	**R1**	**28**
311	96/47 Kotań		184.24 Krempna	KrB	O	**R1**	**34**
312	2/98 Kotań		184.24 Krempna	KrB	O	**R1**	**33**
LIBRANTOWA-GRYBÓW-ROPA TECTONIC WINDOWS							
213	02/21 Librantowa-Ubiad		174.33 Korzenna	GrB	O	**R1**	**28**
LIMANOWA-KLĘCZANY TECTONIC WINDOW							
278	02/67 Limanowa	Jabłoniec	173.43 Limanowa	GrB	O	**R1**	**30**
282	2/70 Łazy		183.22 Chełmiec	CeB	O	**R>1**	**13**
285	2/73 Męcina	Smolnik	173.44 Pisarzowa	CeB	O	**R>1**	**12**
342	2/114 Białawoda-Tęgoborze		173.44 Pisarzowa	CeB	O	**R>1**	**13**
343	2/115 Zawadka		173.44 Pisarzowa	CeB	O	**R>1**	**13**
345	2/117 Rdziostów		173.43 Limanowa	CeB	O	**R>1**	**14**
347	96/25 Klęczany quarry		173.44 Pisarzowa	CeB	O	**R>1**	**14**
349	2/118 Krasne Potockie – Nowa Wieś		173.44 Pisarzowa	GrB	O	**R>1**	**27**
214	02/22 Ubiad		174.33 Korzenna	CeB	O	**R1**	**26**
348	96/25 Klęczany quarry		173.44 Pisarzowa	VeB	O	**R1**	**32**
MSZANA DOLNA TECTONIC WINDOW							
420	03/65 Mszana Dolna – Sądówka		173.34 Mszana Dolna	GrB	O	**R>1**	**14**
98D	97/42 Mszana Górna – Talarki	Mszanka	183.12 Niedźwiedź	KrB	O		**12**
98G	97/42 Mszana Górna – Talarki	Mszanka	183.12 Niedźwiedź	KrB	O	**R>1**	**8**
99D	97/43 Niedźwiedź		183.12 Niedźwiedź	KrB	O	**R>1**	**16**
PR	Poręba – thrust zone		183.12 Niedźwiedź	?	Cr-O	**R>1**	**<5**
SMILNO TECTONIC WINDOW							
S12	Cigla		105 Ondavska verchovina	KrB	O	**R1**	**28**
S9	Smilno		105 Ondavska verchovina	MnB	O	**R>1**	**23**
SZCZAWA TECTONIC WINDOW							
87D	97/35 Szczawa	Kamienica	183.21 Kamienica	KrB	O	**R>1**	**12**
87G	97/35 Szczawa	Kamienica	183.21 Kamienica	KrB	O	**R>1**	**10**
ŚWIĄTKOWA TECTONIC WINDOW							
318	02/101	Świątkowy	184.24 Krempna	MnB	O	**R>1**	**28**
319	96/33-2	Świątkowy	184.24 Krempna	MnB	O	**R1**	**33**

320	96/33-3	Świątkowy	184.24 Krempna	MnB	O	**R1**	**28**
321	96/33-3	Świątkowy	184.24 Krempna	MnB	O	**R1**	**34**
322	2/102	Świątkowy	184.24 Krempna	MnB	O	**R1**	**28**
326	2/106	Świątkowy	184.24 Krempna	MnB	O	**R1**	**28**
327	96/33-7	Świątkowy	184.24 Krempna	MnB	O		**31**
328	96/33-6	Świątkowy	184.24 Krempna	MnB	O		**23**
329	2/107	Rzeszówka	184.24 Krempna	LKB	O	**R1**	**28**
330	96/34	right tributary of Krokowica	184.24 Krempna	LKB	O	**R1**	**28**
331	96/36	right tributary of Krokowica	184.24 Krempna	LKB	O	**R1**	**33**
333	96/36	right tributary of Krokowica	184.24 Krempna	LKB	O	**R1**	**34**
334	96/35	Krokowica	184.24 Krempna	MnB	O	**R1**	**36**
335	2/109	Krokowica	184.24 Krempna	GoB	M-O	**R1**	**36**
336	96/40	Krokowica	184.24 Krempna	GoB	M-O	**R1**	**28**
337	2/110	Krokowica	184.24 Krempna	GoB	M-O	**R1**	**36**
338	2/111	Krokowica	184.24 Krempna	MnB	O	**R1**	**33**
339	96-41/1 thrust zone	left tributary of Krokowica	184.24 Krempna	GoB	M-O	**R1**	**36**
340	2/112	left tributary of Krokowica	184.24 Krempna	GoB	M-O	**R1**	**29**

List of samples with locations of the sites sampled, S contents and the I/S ordering.

Lithostratigraphic units (L). Dukla Nappe and equivalents units: Cergov beds (CeB), Grybów beds (GrB), Krosno Beds (KrB), Lower Krosno beds (LKB), Menilite beds (MeB).

Silesian Nappe: Gorlice beds (GoB), Menilite beds (MeB), Verovice beds (VeB).