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PETROLOGIC STUDIES AND DIAGENETIC HISTORY OF COALY MATTER IN THE PODHALE FLYSCH SEDIMENTS, SOUTHERN POLAND

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Abstract: Common occurrences of terrigenic organic matter (both disseminated and accumulated in layers) in sedimentary rocks were observed. The flysch sediments in the Podhale Trough and in other parts of the Carpathians are inadequately recognised from coal petrologic point of view.

Studies were carried out in the eastern (2008) and western part (2009) of the Podhale Trough. Samples were collected from the exposures. Petrographic studies included microscopic observations of polished sections as well as mean random reflectance measurements of vitrinite (colotellinite) were done.

In the Podhale Flysch, coalified organic matter is represented mostly by vitrinite and, in microscopic scale, mainly by collotellinite. The common occurrence of coaly matter is revealed. It is well–visible in sandstones and mudstones, usually as the bedding planes. The amounts of coaly matter in clay minerals and carbonates are small.

Organic matter hosted in the Podhale Flysch strata represents diversified coalification ranks measured as random reflectance of vitrinite (colotellinite), which falls into the range from 0.49 to 1.00%. Such values are typical for low- to medium ranks of bituminous coal. Measurements of reflectance provided new data suitable for evaluation of thermal history of rocks in the Podhale Trough. The changes of vitrinite (colotellinite) mean reflectance of organic matter from the Podhale Flysch are relevant to the contents of crystalline illite – the recently applied geothermometer of diagenetic (katagenetic) transformations of clay minerals. If the thermal palaeogradient is known, random changes of reflectance of vitrinite can be used for estimations of both the maximum thickness of the Podhale Flysch during deposition and its later amount of erosion. It appears that estimation of maximum thickness of the Podhale Flysch (*i.e.*, depositional thickness after compaction) and the amount of erosion are almost identical with the estimations based upon the illitization of clay minerals.

Key words: terrigenic organic matter, random reflectance of vitrininite, the Podhale Flysch, Poland.

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INTRODUCTION

Common occurrence of terrigenic organic matter (both disseminated and accumulated in layers) in sedimentary rocks together with the development of modern, fast petrographic methods of coalification rank measurements result in wide application of such petrographic observations and measurements in various research projects, *e.g.* of geotectonic history of particular regions.

In the Podhale Flysch sediments, coalified organic matter is represented mostly by vitrinite. Measurements of vitrinite mean reflectance (R_o) enable the scientists to solve many tectonic problems in both the orogenic belts and the platforms as this parameter carries information on coalification as a function of sediment burial within the Earth crust, coeval with deposition and with later orogenic activity.

The flysch sediments in the Podhale Trough and in other parts of the Carpathians, although sufficiently recognised from the geological point of view, reveal many controversies and uncertaintities concerning their geotectonic position. Studies of vitrinite coalification provide new interpretative opportunities, hence, rocks from the Eastern and Western Carpathians, from the Tatra Mts., from the Pieniny Klippen Belt and from the Podhale Trough are recently intensively investigated. The latter deposits are particularly useful due to suggested low degree of their tectonic transformation (despite their significant thickness – several thousands of metres) and the position between the two young- Alpine orogens: the Pieniny Klippen Belt and the Tatra Mts.

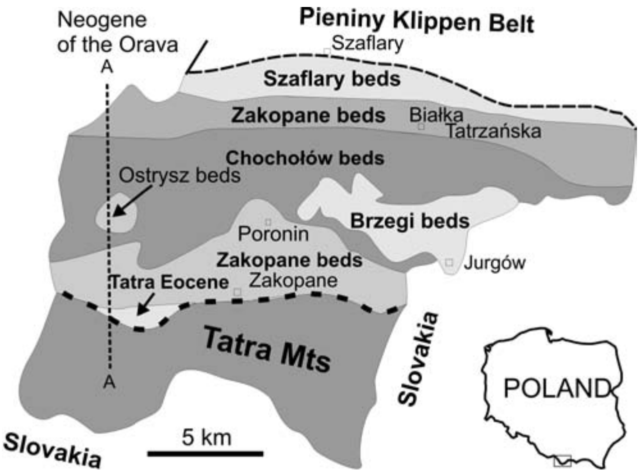

Fig. 1. Geological sketch map of the Podhale Trough with lithostratigraphy of the Podhale Palaeogene Flysch and general cross-section (A – A) through the Podhale Trough (after Chowaniec, 1989; Chowaniec & Kępińska, 2003. In: Krobicki & Golonka, 2008; slightly modified)

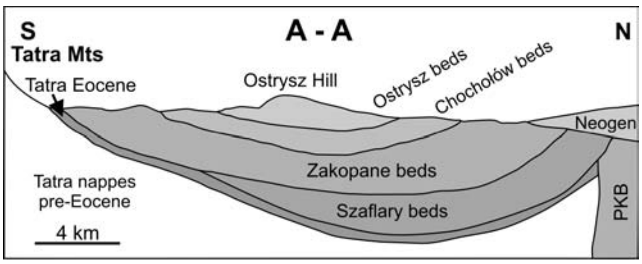

Fig. 2. Lithostratigraphic cross section (A – A, Fig. 1) of the western part of the Podhale Trough (after Gedl, 2000. In: Krobicki & Golonka, 2008). PKB – Pieniny Klippen Belt

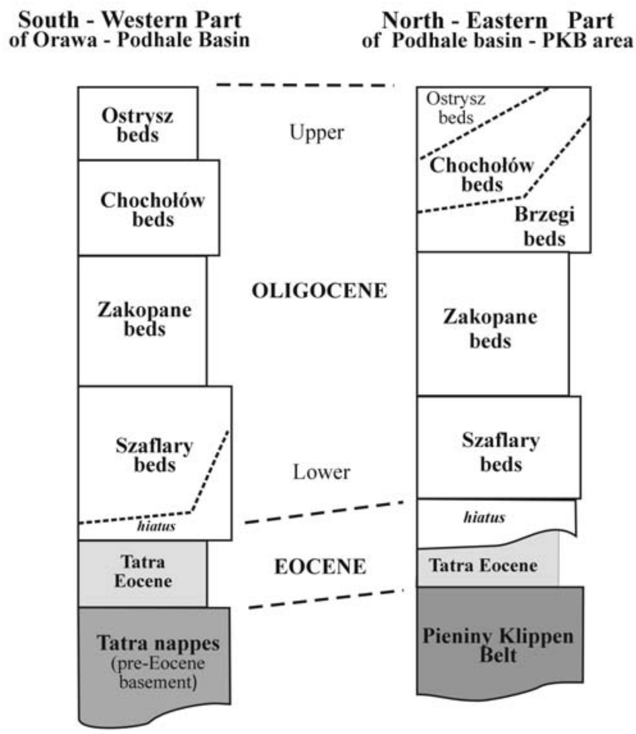

Fig. 3. Lithostratigraphic column of the Podhale Flysch in the important parts of the Podhale Trough (after Geld, 2000, also Krobicki & Golonka, 2008, modified)

Even the preliminary results reveal complicated diagenetic history of the Podhale Flysch reflected in significant differences in coalification of contained organic matter.

GEOLOGICAL SETTING OF THE PODHALE FLYSCH

The Palaeogene sediments of the Podhale Trough are divided into two lithostratigraphic units. The older unit comprises shallow-marine carbonates traditionally named ”the Nummulitic Eocene”. It is followed by the younger, flysch unit named ”the Podhale Flysch” (see, *e.g.*, Watycha, 1959; Mastella, 1975).

The immediate basement of the Podhale Flysch consists of Eocene carbonates which are in tectonic contact with the High–Tatric and Sub-Tatric series, and which form the northern margin of the Tatra Mts. (Fig. 1, 2).

The Eocene carbonates of total thickness about 150 m are exposed only along the northern margin of the Tatra Mts. whereas the younger, Oligocene flysch strata, which fill the Podhale Trough crop out at numerous sites between the Tatra Mts. and the Pieniny Klippen Belt.

In the northwestern part of the Podhale region. *i.e.*, in the Orawa portion of the Nowy Targ–Orawa Trough a part of the Podhale Flysch succession is unconformably covered by the Neogene (Miocene-Pliocene) intramontane molasses. This suite comprises huge alluvial fans, several hundreds of metres thick (maximum thickness – 1,300 m), which have been deposited since the Early Miocene, after the uplift of the Tatra Massif and the folding of the Podhale Flysch. Their characteristic feature is the presence of coaly matter (Kołcon & Wagner, 1991).

The Podhale Flysch includes four lithostratigraphic units (Gedl, 2000; Ryłko, 2004): the Szaflary beds, the Zakopane beds, the Chochołów beds and the Ostrysz beds.

The oldest unit – the Szaflary beds (Fig. 3) – occurs in the northern part of the Podhale Trough but it is absent from the southern part, at the contact with the Eocene limestones. These are mostly sandstones in the lower part (about 300 m thick), sandstones and shales (about 200 m thick) or sandstones and conglomerates in the upper part with the dominance of mudstones and claystones over sandstones (Fig. 4). The sandstones are fine-grained and thin-bedded (0.1–3.0 m). In the upper part of the succession, among claystones, the silicified shales of menilite type occur.

Both the conglomerates and the sandstones of the Szaflary beds contain limestone grains derived from the Pieniny Klippen Belt whereas the flysch strata include full turbidity sequences identified as proximal flysch. Common component of the Szaflary beds is plant detritus and even a few-centimetres-thick coal layers.

Scarce foraminifers identified in the Szaflary beds point out to Late Eocene age, but dinocysts observed in the youn-

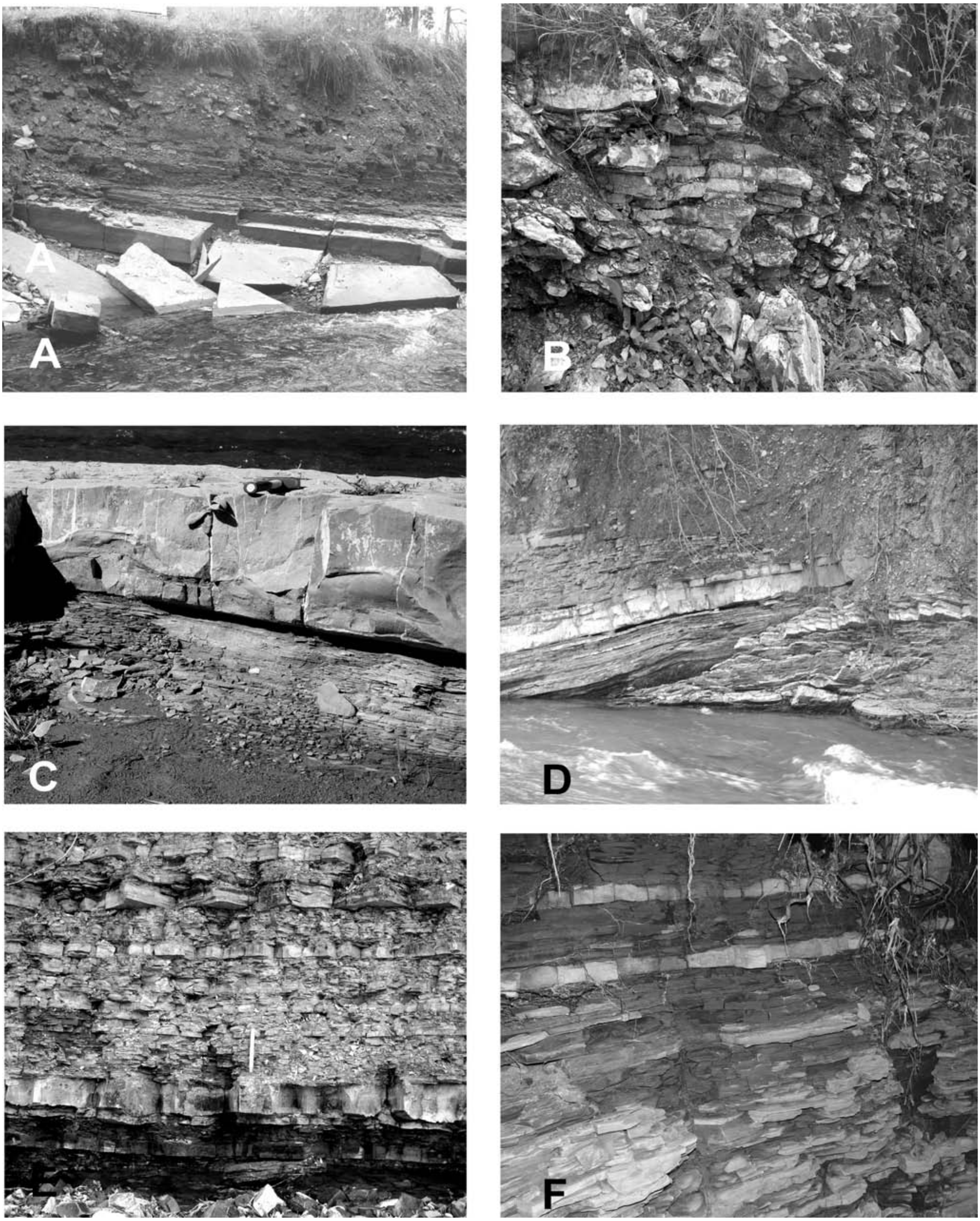

Fig. 4. Sedimentological features of the Podhale Flysch. **A** – Thin-bedded Szaflary beds (Nowe Bystre village); **B** – Folded Szaflary beds in the contact zone with the Pieniny Klippen Belt (Szaflary village); **C** – Lower Chochołów beds in the Biały Dunajec River (near Biały Dunajec village); **D** – Break-thrust of Brzegi beds (Jurgów village); **E** – Thin-bedded Upper Chochołów beds (Kojsówka village); **F** – black shales of Zakopane beds (Zakopane-Olcza village)

ger part indicate the Early Oligocene (Watycha, 1976; Gedl, 2000).

The Zakopane beds, known from the southern and northern parts of the Podhale Trough (Figs 1–3), are dominated by clayey shales. Basing on the frequency of shale occurrence, the lower, shale-dominated and the upper, sandstone-shale-dominated parts were distinguished, of total thickness up to 300 m. The lower part includes dark (Fig. 4), clayey and calcareous shales with rare intercalations of fine-grained sandstones (up to 10 centimetres thick), locally grading into dolomites. The upper part comprises rhythmically interbedded, fine-grained sandstones and dark-grey, clayey shales with rare dolomite lenses.

In the Zakopane beds, typical turbidites are scarce and occur in strata representing the upper Bouma sequences. Coaly detritus is less abundant in comparison to the Szaflary beds. The thickness of the Zakopane beds is estimated as 300– 500 m (*loc. cit*). The foraminiferal assemblage indicates a Late Eocene-Early Oligocene age and it is similar to fauna of the Krosno beds in the Outer Carpathians, whereas the dinocysts point out to the Early Oligocene.

The Chochołów beds conformably rest upon the Zakopane beds. Two members were distinguished: the lower one (800–1,000 m thick) composed of sandstones and conglomerates, and the upper one (650 m thick) composed of shales and sandstones, and named "the Brzegi beds" (Fig. 4). The boundary between the Chochołów and Zakopane beds is conventionally placed where thick sandstone layers appear in the top portion of the Zakopane beds. The Chochołów beds fill the central part of the Podhale Trough (Figs 1, 2). Their lithology is dominated by fine- and medium-grained sandstones with rare conglomerates, the latter containing detrital material eroded from the Tatric sedimentary series. The upper part (*i.e.*, the Brzegi beds) comprises shales and sandstones with thin layers of greenish mudstones and claystones, sometimes highly calcareous. Sandstones of the Chochołów beds are thin – or medium-bedded, with graded bedding. The Chochołów beds are categorized as so-called normal flysch originating from density currents (Roniewicz, 1979). The age of the Chochołów beds is palaeontologically dated as the Early Oligocene (Dudziak, 1986).

The youngest member of the Podhale Flysch is named the Ostrysz beds. Lithology is dominated by sandstones. Poor exposures cause the general lack of palaeontological documentation known only from the vicinity of the Ostrysz Hill (Fig. 1). From the lithological point of view the Ostrysz beds can be regarded as local, sandstone-dominated variety of the Chochołów beds. The thickness of this member reaches 300 m but its topmost part was presumably removed by erosion (Watycha, 1976). The age of the Ostrysz beds was determined as the Early/Late Oligocene (Fig. 3). In Slovakia, where this topmost part was preserved, the age corresponds to the Late Oligocene break (Gross *et al.*, 1980).

The tectonics of the Podhale Flysch distinctly differs from the other parts of the Carpathian orogen. These sediments occupy a vast synclinorium on both sides of the Tatra Massif. In the Polish part (*i.e.* in the Podhale area) their tectonic pattern is simple. The sediments rest on site and form an asymmetric synclinorium of steeply dipping northern limb. General dip angle is low (up to 15°, in central part from 0 to 10°). Only in narrow zones of the Pieniny Klippen Belt and, locally, close to the edge of the Tatra Massif, the Podhale Flysch strata do dip at high angle (even vertically), with some overthrusting from the south (close to the Tatra Mts.) and from the north (border zone of the Pieniny Klippen Belt).

The tectonic pattern of the Podhale Synclinorium includes parallel zones of somewhat different structures. From the north these are:

– the contact zone with the Pieniny Klippen Belt – this is a tectonic contact, the Nummulitic Eocene strata are absent, dips of flysch beds are steep with common overthrusts and overturns caused by numerous faults. The width of this zone is variable, usually a few kilometres,

– the border flexure of the Pieniny Klippen Belt, 450–600 m wide, with steep dips of flysch beds and numerous faults downthrowing the rocks towards the south,

– the zone of low dip angles which, in the eastern part, is a wide brachyanticline cut by numerous, small faults,

– the axial zone with low dip angles and numerous, local folds,

Moreover, the border zone with the Tatra Massif can be distinguished, of tectonic features similar to those bordering the Pieniny Klippen Belt, *i.e.* variable dip angles, northward dipping, micro-overthrusts and numerous, small faults downthrowing the rocks to the north.

According to Mastella (1975), the principal tectonic pattern of the Podhale Synclinorium originates from the Savian phase of the Alpine orogeny. It was controlled by vertical movements of basement blocks and the resulting two-stage uplift of the Tatra Massif and the Pieniny Klippen Belt. At the first stage, the vertical movements of basement blocks took place together with the formation of parallel dislocations whereas at the second stage the meridional faults were formed. The uplift of the Tatra Massif was most intensive in the southern part of the massif in Slovakia, along the eastern segment of the Tatra Fault, whereas along the northern border of the Tatras the vertical movements were less pronounced. In the northern part of the Podhale Trough, the uplift of the Pieniny Klippen Belt was very intensive, as revealed by the contact zone and the border flexure.

METHODS AND MATERIALS TEST

Detailed field studies were carried out in the eastern (2008) and western part (2009) of the Podhale Trough, from the Czarny Dunajec River towards the eastern state border, and from the main Pieniny Fault close to Szaflary village (Figs 1, 7) to the tectonic edge of the Tatra Mts. (the Chochołowska and the Biały Valleys). Samples were collected from the exposures. Additionally, the archival samples were analysed, taken from exposures of the Zakopane beds in Gubałówka and Butorowy Hill near Zakopane town.

Petrographic studies included microscopic observations of polished sections under the reflected light (standard, white and fluorescent, blue) as well as mean random reflectance measurements of vitrinite (colotellinite) in accordance with the ICCP (*International Committee for Coal and Organic Petrology*) requirements.

RESULTS

Forms of occurrence and petrography of coaly matter

Even very general observations of the Podhale Flysch sediments reveal the common occurrence of coaly matter. It is well visible in sandstones and mudstones, usually at the bedding planes. In claystones and carbonates the amounts of coaly matter are lower.

Taking into account the forms of occurrence and the size of particles, the following types were distinguished (Fig. 5):

– coal laminae of variable thicknesses (from a fraction of a millimetre to about 5 cm, but 0.1–1.0 mm, in average);

– disseminated coal detritus of variable size (fine and medium-grained), encountered as dark lenses or streaks, mainly at the bedding planes of fine-grained sediments (plant debris). It is accompanied by fine muscovite flakes. In claystones and carbonates the coal detritus is disseminated in the layers as an accessory component.

Accumulations of coaly matter are mostly thin, elongated lenses of coal. Such forms were observed mostly in thin-bedded sandstones and mudstones with distinct, flat or cross-lamination. Sometimes, accumulation of laminae (15–45 vol.%) permits to include such sediments to coaly rocks. In the exposures such rocks are easily identifiable due to dark-grey color.

Both the layers and lenses of coaly matter are composed of vitrinite. This maceral is black, with black streak and glassy luster. Its typical features are dense contraction cracks, which result in cube cleavage. Under the microscope, the principal component of vitrinite lenses is colotellinite (collinite), which forms two varieties: colotellinite of typical optical properties (vitrinite A, for example Fig. 6B–D) and darker colotellinite (vitrinite B – Fig. 6F) of somewhat lower mean reflectance, which forms extended, thin lenses. Both varieties show distinctly different reflectance. In darker laminae irregular, microscopic-size network of lighter variety was observed.

Rare component of such vitrinite aggregates is tellinite, almost always impregnated with resinite or bituminite (Fig. 6A), fusinite (Fig. 6E) and clay minerals.

A typical accompanying mineral in coal laminae is pyrite, usually observed as framboids and distributed as more or less distinct streaks in colotellinite (Fig. 6A–D, F). Locally, pyrite occupies the internal parts of tellinite cells and/or scarce microfossils. Apart from pyrite, fine crystals of covellite and bornite were observed.

The disseminated coaly matter encountered in claystones and sandy mudstones is a coaly detritus of dominating <0.1 mm fraction with rare larger grains, up to 0.3 mm across. Larger accumulations of coal detritus were typically observed in dark-grey, coaly sandstones and mudstones as well as in some claystones where they form coal laminae intercalated with clayey laminae. Such mudstones and claystones reveal flat lamination originating from sedimentation of density flows in the distal part of abyssal plane.

The disseminated coaly matter is composed mostly of vitrinite (colotellinite) and inertinite (inertodetrinite). Rare components are larger fragments of fusinite, funginite and resinite.

Among of dispersed coaly matter in these rocks, vitrinite forms two varieties: dark (vitrinite A) and light (vitrinite B). Average size of isometric vitrinite grains in disseminated coaly matter falls into the range from 5 to 30 μm; although, as mentioned above, large (up to 0.3 mm), elongated, poorly rounded or angular grains of colotellinite were noticed in sandstones.

Vitrinite reflectograms

Vitrinite reflectograms of rocks from the Podhale Flysch show two different peaks (marked as R^o I and R^o II) within the range of values typical for vitrinite. Both are shifted towards the higher values with the increasing coalification of organic matter. These are:

– R^o I peak: for lowest coalification reflectance values are from 0.38 to 0.44%, with the increasing coalification peak values shifted to 0.49% for medium rank and to 0.88% for the highest rank,

– R^o II peak: for lowest coalification reflectance values are from 0.43 to 0.53%, for medium rank of coal these shift to 0.57% and to 0.98% for the highest rank.

The main peak of colotellinite reflectogram marked as R^oII dominates the recorded plots. Measured total values fall into the range from 0.49 to 1.00% (Table 1).

Microscopic studies revealed that these peak values result exclusively from the presence of different colotellinite phases.

The first peak of random reflectance (R^o I) undoubtedly belongs to the so– called "dark vitrinite". This phase forms thin laminae and fine lenses. In the reflectograms recorded at the scale comparable with the standard deviation (ΔR^o = 0.03%), the R^o I peak forms an isolated maximum shifted towards lower reflectance whereas at the standard record (ΔR^o = 0.05 %, *i.e.* half stage R^o) the maximum does not appear but causes negative skewness.

This peak is always lower by 0.06-0.10%, in average, from the main maximum recorded in the absolute scale. The presence of both peaks reflects petrographic diversity of vitrinite and results from the occurrence of liptinites within the dark vitrinite, presumably with resinite or bituminite, which form submicroscopic mixture impregnate colotellinite. Such origin of dark vitrinite was proposed by Newman and Newman (1982). Additionally, the presence of bituminite seems to be indicated by large amounts of framboidal pyrite within the colotellinite, which points out to reducing depositional environment. The origin of the Podhale Flysch strongly facilitated the formation of dark telocollinite as these sediments were deposited in the shelf zone, within the range of so – called normal shales of the euxinic environment (Morris, 1979).

Main peak of colotellinite reflectogram marked as R^oII dominates in the recorded plots. Some samples show positive skewness of this peak, which results from the presence of limited areas of colotellinite of somewhat higher reflectance (up to 0.05%) surrounding framboidal pyrite aggregates. Such variability can be neglected in final interpretation.

Analysis of differences between the recorded peaks of moderate reflectance leads to the conclusion that dark

Table 1

Characteristic features of more important reflectograms from the Podhale Flysch strata – recorded peaks of random vitrinite reflectance. Stage I (2008) and Stage II (2009)

Sample	Location	R^o total (R^oI + R^oII) [%]	Range [%]	stdv [%]	n
T-13	Trybsz	0.51	0.42–0.64	0.0338	104
BT-11	Trybsz-Białka	0.55	0.48–0.63	0.02	128
BT-1	Białka-Budzowie	0.67	0.60–0.81	0.0399	126
BD-3	Biały Dunajec 3	0.55	0.43–0.66	0.0315	95
BN-4/2	Biały Dunajec 2	0.56	0.41–0.66	0.0294	100
BD-102	Biały Dunajec 1	0.52	0.41–0.64	0.0192	95
P-5a	Poronin 1	0.61	0.52–0.68	0.0216	90
P-6/2	Poronin 2	0.64	0.53–0.75	0.0243	115
MS-24	Łapsze Wyżne	0.58	0.52–0.68	0.0136	90
Z-1	Zakopane Olcza	0.55	0.42–0.69	0.0323	115
Z-1-1		0.56	0.46–0.66	0.025	100
Z-1-2		0.56	0.45–0.68	0.0255	90
J-3	Jurgów	0.63	0.52–0.74	0.0347	105
J-3/1		0.81	0.74–0.88	0.0138	70
B-1	Brzegi-Kucówka	0.73	0.62–0.87	0.0425	90
B-3	Brzegi	0.75	0.64–0.87	0.0415	90
M-8a/1	Palenica Pańszcz.	0.77	0.64–0.87	0.0228	90
M-8	Murzasichle	0.79	0.68–0.90	0.0252	70
MG-10a	Małe Ciche	0.93	0.88–1.04	0.0255	80
MG-9		0.95	0.88–1.04	0.0189	75
MG-11a		1	0.92–1.16	0.0208	100
L-13a	Lichejówka	0.77	0.64–0.92	0.2225	150
Ker-1	Butorowy Wierch	0.57	0.46–0.60	0.0305	100
Choch 1	Chochołów	0.51	0.41–0.64	0.0234	100
Choch 2		0.52	0.47–0.61	0.0176	100
W-1	Witów	0.57	0.51–0.68	0.0442	90
W-5		0.55	0.50–0.69	0.07	90
Koj 1/1	Kojsówka	0.66	0.56–0.76	0.0514	80
SW-4	Chochołowska Valley	0.55	0.47–0.68	0.05	80
Bi 1	Biały Valley	0.72	0.63–0.80	0.0045	85
R-4	Ratułów	0.54	0.55–0.62	0.036	80
M-1	Ratułów-Mulice	0.58	0.51–0.67	0.0372	100
NB-1	Stare Bystre	0.49	0.46–0.51	0.0375	85
NB-2	Nowe Bystre	0.54	0.49–0.64	0.0322	100
A-2	Noski	0.6	0.51–0.72	0.0472	100
OW	Opalony Wierch	0.61	0.50–0.66	0.03	100
St-1	Ząb - Stochy	0.6	0.51–0.68	0.0467	100
SG-1	Skrzypne Grn	0.53	0.49–0.60	0.0398	100
D-2	Dzianisz	0.57	0.46–0.68	0.0547	100

R^o total = RI+RII– random vitrinite reflectance including the dark vitrinite; Range – measuring range of random vitrinite reflectance; n – quantity of measurements; stdv – standard deviation

vitrinite peak should be successfully treated globally in R^oII peak from final evaluation of this parameter in the studied samples (Table 1). The difference in results varies from 0.03 to 0.07%, with average value of 0.05%.

The precise determination of vitrinite reflectance in samples from the Podhale Flysch is particularly important due to generally low and medium ranks of organic matter, which, according to recent principles, is categorized as bituminous coal D and C (see ISO 11760:2002) or, alternatively, as para- and orthobituminous coal (see ECE-UN/ENERGY 50:2002). Including the dark vitrinite into the evaluations, the resulting mean vitrinite reflectances of studied coals and disseminated organic matter fall into the range from 0.49-0.50 to 1.00 % (Table 1). Simple identification features indicate that the rank of organic matter in the Podhale Flysch corresponds to bituminous coal. Moreover, mean reflectance values for organic matter from the Sub-Tatric Series (Poprawa *et al.*, 2004) and the Pieniny Klippen Belt (Wagner, 1996), together with those from the Podhale Flysch, seem to reflect a sequence of geotectonic events.

However, it is worthy to note that although natural boundaries are only rarely sharp, the formal approach to all geological boundaries (including the coal rank) is an important and necessary tool in categorization of phenomena, which is useful in generation of coherent schemes in nature.

DISCUSSION AND CONLUSIONS

Regional changes in vitrinite coalification rank

Organic matter hosted in the Podhale Flysch strata reveals diversified coalification ranks measured as mean reflectance of vitrinite (colotellinite), which falls into the range from 0.49 to 1.00%. Such values are typical of low- to medium ranks of bituminous coal.

The coalification pattern recorded in structural map clearly demonstrates the increase of coalification from the northwest (Chochołów area – samples marked as K and Ch – Table 1; Fig. 7) towards the southeast (Małe Ciche area – samples marked as MC). Moreover, coalification does not depend on stratigraphy (Fig. 7). The best-recognised area (considering the sampling density) is located between Biały Dunajec (BD), Białka Tatrzańska (BT), Małe Ciche and Jurgów (J) villages, where regular and significant changes in mean reflectance were observed from 0.51 to 1.00% (the latter found in the Małe Ciche area).

Such a pattern clearly points out to the highest parts of the Tatra Massif, *i.e.* towards the Łomnica (Lomnicky štit) and Kieżmarski peaks (Kežmarsky štit) where, presumably, the highest amplitudes of vertical movements have occurred.

The lowest values of mean reflectance R^o in the organic matter from the Podhale Flysch (about 0.5%) were found close to the boundary with the Pieniny Klippen Belt and in the vicinity of Chochołów.

Values of mean reflectance of vitrinite from the northern part of the Podhale Trough differ decisively from those measured in the Pieniny Klippen Belt: about 0.93-0.95% in the Aalenian and Bajocian sediments from the Szlachtowa and the Czorsztyn formations (the Skrzypne Formation),

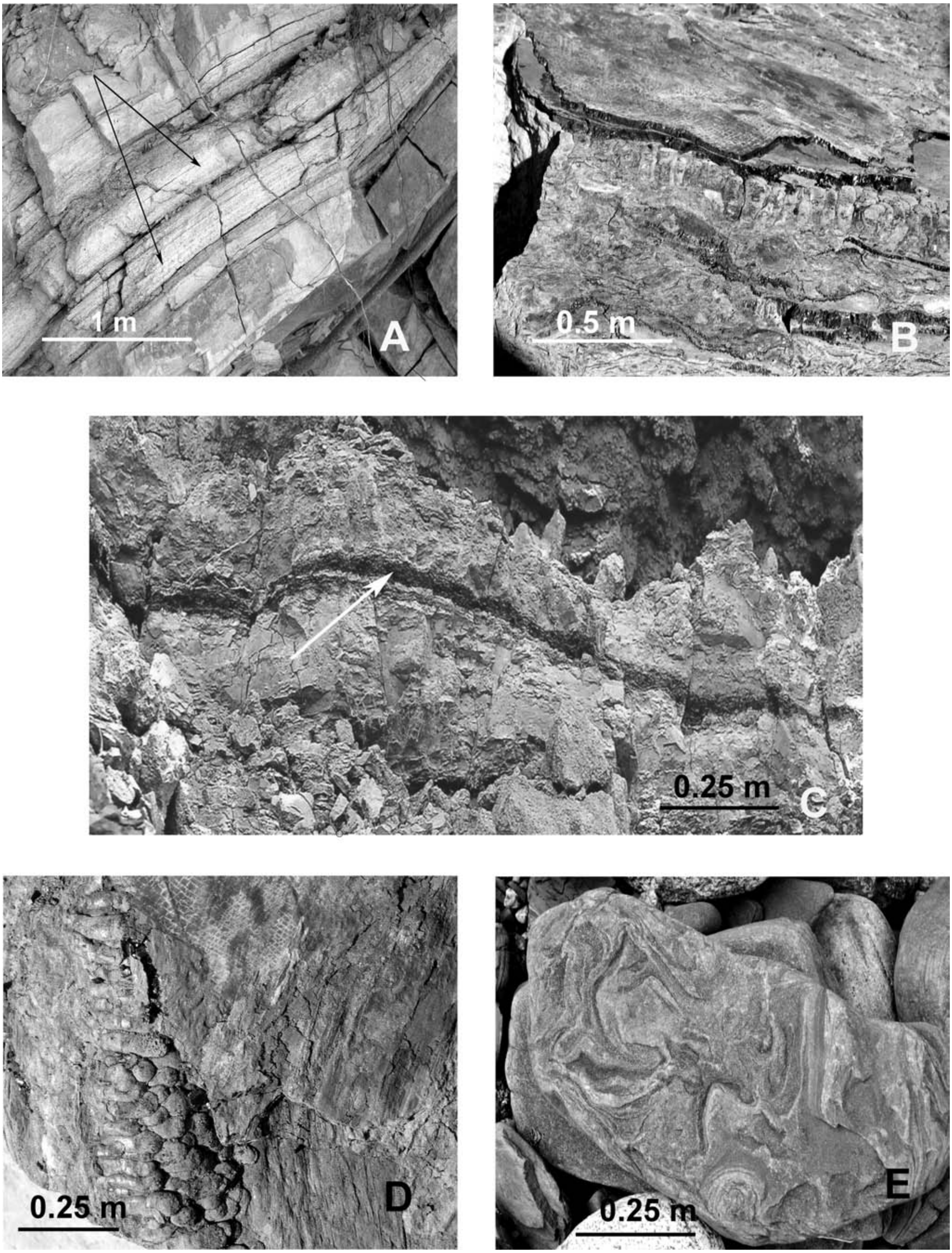

Fig. 5. Types of morphological forms of coaly matter of the Podhale Flysch sediments: **A** – coaly detritus laminae (Lower Chochołów beds from Chochołów village); **B** – coal laminae from coaly tissue of fossil wood (Szaflary beds, Trybsz village); **C** – coalbed from Upper Chochołów beds (Kojsówka village); **D** – coal laminae with external moulds of bark and roots of coaly wood (Szaflary beds, Młyn village); **E** – dispersed organic matter (detritus) near natural moulds of flute and crescent marks (Ratułów village)

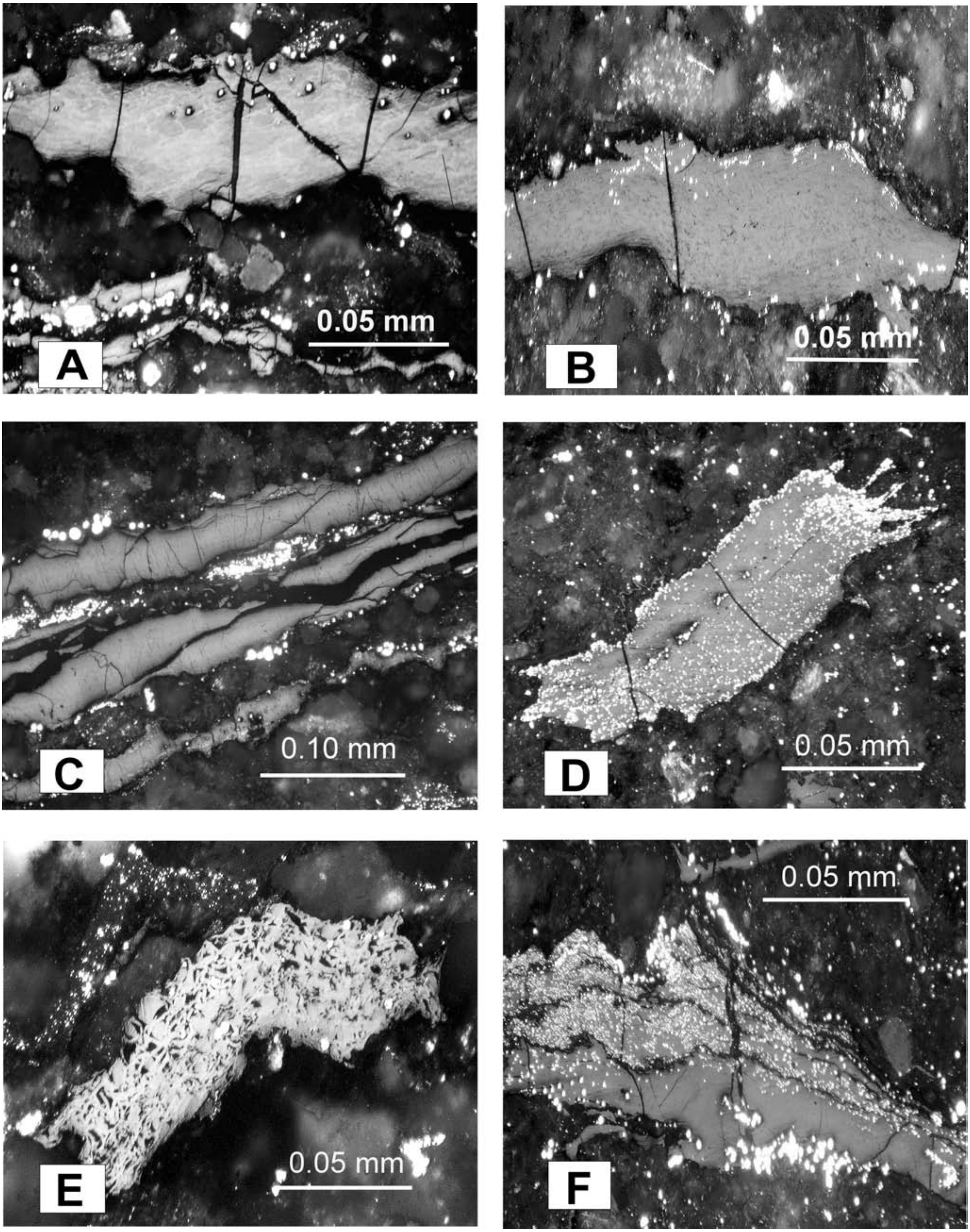

Fig. 6. Microphotographs of coal laminae and coal fragments (pieces) from the Podhale Flysch: **A** – tellinite impregnated of gelinite (sample MG-9; **B** – tellinite (sample R-4); **C** – irregular lenses of telocollinite in sandstones from Brzegi area (samples B-1, B-3); **D** – telocollinite impregnated on pyrite in coal piece (sample BD-3); **E** – fusinite and semifusinite in sandstone from the Chochołowska Valley area (sample SW-3); **F** – Framboidal pyrite in coal piece (sample Z-1). All reflected light, oil immersion

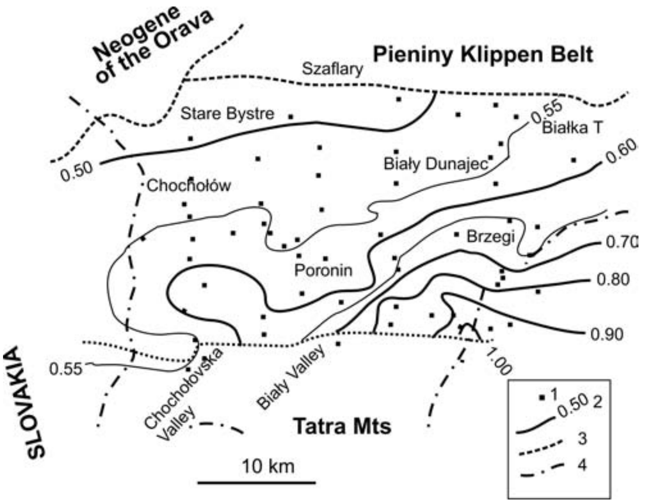

Fig. 7. Sketch-map of changes in mean random reflectance of vitrinite (colotellinite) of coal and coaly matter from the Podhale Flysch. *1* – samples; *2* – isolines of total random reflectivity ($R^oI + R^oII$) – spacing 0.05% ($R^oI + R^oII$); *3* – border of the Tatra Mts and the Pieniny Klippen Belt; *4* – state boundary

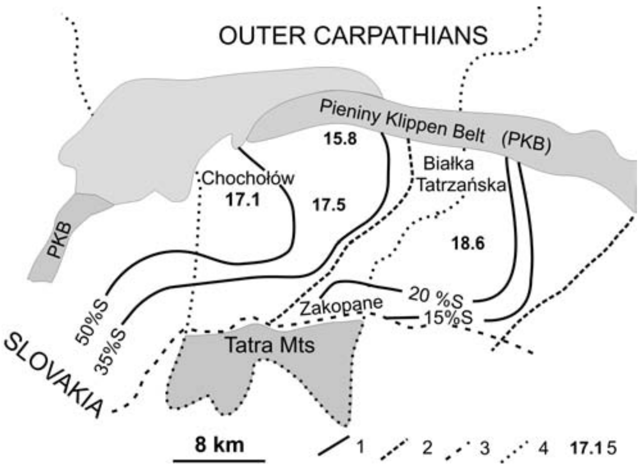

Fig. 8. Map of illite diagenetic changes in clayey shales, K-Ar datings of illite-smectite in bentonites and fission tracks of apatite in the Podhale Trough (after Środoń 2008, modified). *1*– isolines of illitization degree (%S); *2* – lines mark the limit of kaolinite, which disappears due to diagenesis; *3* – border of the Tatra Mts; *4* – state boundary of Poland; *5* – results of K-Ar datings from bentonites (Ma)

and 1.00 to 1.05% in other successions from the Pieniny Mts. (unpublished data). Moreover, these values differ also from those found in sediments from the High- and Sub-Tatric series (from 0.90 to 1.80%; Poprawa *et al.*, 2004).

The changes of vitrinite (colotellinite) mean reflectance of organic matter from the Podhale Flysch are consistent with the contents of crystalline illite – the recently applied geothermometer of diagenetic (katagenetic) transformations of clay minerals (Fig. 8).

This map shows distinct, increasing trend of burial temperatures of sediments towards the southeastern part of the Podhale area. The K-Ar datings of maximum burial (from 15.8 to 18.6 Ma) enables the author to correlate this process with the Savic phase of Alpine orogeny (Środoń, 2006, 2008).

Measurements of mean reflectance provided new data suitable for evaluation of thermal history of rocks in the Podhale Trough. Considering the world literature dealing with the influence of geological factors on coalification of organic matter, the opinion of Sweeney and Burnham (1990) must be taken into account that during coalification period of about 10 Ma the maximum burial temperature can be estimated at about 90°C for vitrinite mean reflectance 0.49–0.51% and about 140°C for vitrinite mean reflectance 1.00%. Similar temperatures can be obtained from diagrams after Bostick (1979): 90°C for $R^o = 0.50\%$ and 155–160°C for $R^o = 1.00\%$. According to the IGCP scheme, also the overall pressure during coalification can be estimated: for lignite-bituminous coal transition ($R^o = 0.50\%$) pressure can be from 10^7 to 10^8 hPa whereas for bituminous D/bituminous C transition ($R^o = 1.00\%$) the pressure might have amounted up to 30 10^{10} hPa.

If the thermal palaeogradient is known, these values can be used for estimations of both the maximum thicknesses of the Podhale Flysch during deposition and its later amount of erosion. Estimations of the thickness of flysch successions in the Podhale Trough are diversified. Basing upon the results of lithologic and tectogenetic studies proposed recent thickness of the southern part of Podhale Flysch to be about 4 km. Watycha (1968) found somewhat over 3 kilometres for the same part of the flysch succession whereas Mastella and Mizerski (1978) estimated the thickness in the southwestern part of the flysch as 2.2 km. Studies of Kępińska (2006) revealed that the thickness of flysch sediments in the central part of the Podhale Trough (Poronin area) might have been 4–5 km at the amount of erosion of 2–3 kilometres, whereas erosion in the vicinity of Zakopane amounted to *ca.* 4 km and in Chochołów to 1.3–1.5 km. According to Środoń (2008), at the thermal palaeogradient close to the recent (?) value (21±2°C/km), depositional thickness of flysch in the western part of the Podhale area reached 5–6 km whereas the amount of erosion was 3.1–3.6 km (Fig. 8).

However, Kępińska (2006) studied Palaeogene sediments and found that thermal palaeogradient during deposition of the Podhale Flysch was higher (mean: 30-40°C/km) than the recent values. As the heat source was placed in the basement rocks of the Tatra successions, it can be assumed that the palaeogradient was relatively constant before the Savic phase of Alpine orogeny (Oligocene/Miocene). If the subsidence was the only important burial mechanism (and, simultaneously, the only factor determining the observed coalification of organic matter), the burial depth in the northwestern part of the Podhale Trough (Chochołów area) should vary from about 3.2 km (at thermal palaeogradient 30°C/km) to 2.7 km (at thermal palaeogradient 40°C/km) and the total thickness of flysch should be about 2.8 km higher (*i.e.*, recent thickness of the Podhale Flysch sequence). In the southwestern part of the trough (Jurgów, Małe Ciche areas), at the mean reflectance about 1.00% (which corresponds to maximum burial temperature of 155–160°C), the burial depth should be about 5 km (thermal palaeogradient 30°C/km) or 4 km (thermal palaeogradient

40°C/km), and maximum thickness of flysch strata might have been 6–7 km (recent thickness of flysch about 2.2 km, after Mastella & Mizerski, 1978).

It appears that estimation of the maximum thickness of the Podhale Flysch strata (*i.e.*, depositional thickness after compaction) and the amount of erosion, both based upon the mean reflectance of colotellinite, are almost identical with the estimations based upon the illitization of clay minerals.

Considering the depositional conditions and, first of all, the later tectonic history of the Podhale Flysch, it seems likely that estimations presented above bear an error, which results from the following reasons:

– during the Savic phase of Alpine orogeny (Late Oligocene-Chattian) flysch and its basement composed of High- and Sub-Tatric series were subjected to strong block tectonics (see, *e.g.*, Mastella, 1975), mostly subsidence, due to continent-continent collision between the Czorsztyn and Andrusov ridges. This process has continued during the later phases of Alpine movements, starting from the Styrian phase (Middle Miocene-Langhian) and caused folding of the Podhale Flysch and uplift of the Tatra massif. Such geotectonic processes resulted in deposition of molasse, which filled the recent Orawa Depression as about 1,300-m- thick alluvial fans (Middle Miocene–Pliocene) (Watycha, 1976) with the seams of soft brown coal (Kołcon & Wagner 1991);

– this molasse might have covered the whole area of the Podhale Trough, similarly to Pleistocene-Holocene alluvial fans which document the continuous uplift of the Tatra massif;

– brown coal (metalignite) recently exposed in the outcrops of the Orava Neogene succession indicates that under the "cool" geothermal gradient (<50°C/km) observed in many coal deposits the overburden thickness had to be over 400 m but less than 1,000 m (Stach *et al.*, 1978), maybe about 700 m,

– consequently, the amount of erosion of the Podhale Flysch should be reduced by this value, at least in the area of Chochołów where these sediments have been partly preserved (vicinity of Czarny Dunajec-Chyżne).

In order to illustrate changes in the diagenetic and katagenetic history of the Podhale Flysch, the studies reported above must be supplemented by detailed investigations in sedimentary series of the Tatric units and the Pieniny Klippen Belt.

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