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The journal is focused on problems of the Alpine-Carpathian region.

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International conference

ESSE WECA 2004

Environmental, Structural and Stratigraphical Evolution of the Western Carpathians

The already 4th bi-annual ESSE WECA conference was held at the Faculty of Natural Sciences, Comenius University of Bratislava, in December 3–4, 2005. Besides the main organizer, Department of Geology and Paleontology of the Comenius University, also the Dionýz Štúr State Institute of Geology, Slovak Geological Society, Geological Institute of the Slovak Academy of Sciences and EQUIS Ltd., Bratislava, participated in organization of the meeting. The organizing committee wishes to thank all these institutions for the provided help.

The conference went on in a friendly and creative pre-Christmas atmosphere. Altogether 48 contributions, 25 oral and 23 poster, were presented by 56 participants from Poland, Czech Republic, Austria, Hungary and Slovakia. 35 presentations covered the field of paleontology, stratigraphy, sedimentology, environmental geology and paleogeography, 13 presentations dealt with structural and regional geology, tectonics and geodynamics of various Western Carpathian units and adjacent parts of the North European Platform. These fields of research have become a tradition since the first ESSE WECA meeting in 1998. A considerable part of presented talks and posters was prepared by young scientists and students. We hold this to be the main and welcome goal of this periodic conference and we intend to offer the introductory scientific forum for our young colleagues also in next ESSE WECA meetings. Hence see you again in Bratislava at ESSE WECA 2006!

This ESSE WECA 2004 proceedings issue includes seven full papers presented at the conference. Please note that the papers underwent only a limited review process and, consequently, the authors are fully responsible for the scientific content and language correctness of their contributions.

Dušan Plašienka and Rastislav Vojtko
guest editors

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Geodynamics of ridges and development of carbonate platforms within the Outer Carpathian realm in Poland

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Abstract. The Mesozoic and Cenozoic paleogeography of the Outer Carpathians reflects the series of continental break-ups, rifts and collisions (Golonka et al., 2000, 2003, Golonka, 2004). The Magura Basin originated as part of the Penninic-Pieniny Klippen created during Mesozoic time between Tethyan terranes and Eurasia. The other Outer Carpathian basins had developed in the process of rifting and fragmentation of the European platform. During the Cretaceous tectonic reorganization the new Outer Carpathian realm was formed. Within this realm in the foreland of the folded Inner Carpathians area, several basins divided by ridges and underwater swells became distinctly separated. In Paleogene the movement of Adria and Alcapa terranes resulted in gradual closing of the flysch basins and development of an accretionary prism. The ridges dividing the flysch basins in the Outer Carpathians became more distinguished providing favorable conditions for development of shallow banks with the carbonate platform sedimentation. These platforms have been destroyed during the orogenic process. The platform deposits formed numerous carbonate fragments that have been found in the Outer Carpathians flysch and olistostromes. These fragments were transported with the turbidity currents to the flysch, forming the organodetritic limestones and sandstones. Their distribution provides significant help in an attempt to find the original location of carbonate platforms and finally, to make proper palinspastic reconstruction of the Northern Outer Carpathian realm.

Keywords: Outer Carpathians, plate tectonics, paleogeography, carbonate platform, Mesozoic, Cenozoic.

Introduction

The Northern Carpathians are subdivided into an older range known as the Inner Carpathians and the younger ones, known as the Outer or Flysch Carpathians. At the boundary of these two ranges the Pieniny Klippen Belt (PKB) is situated. The Outer Carpathians are built up of a stack of nappes and thrust-sheets changing along the Carpathians built mainly of flysch. All the Outer Carpathians nappes are overthrusting onto the European platform covered by Miocene deposits of the Carpathian Foredeep. These nappes have mainly allochtonous character, and originated in basins situated outside their present location. On the other hand, traditionally (e.g. Pescatore and Ślączka, 1984) the following sedimentary basins have been distinguished within Northern Outer Carpathians from south to north: the Magura Basin, the Dukla and Fore-Magura set of basins, the Silesian Basin, the Sub-Silesian Ridge and the Skole Basin.

The complex Mesozoic and Cenozoic tectonics of the Outer Carpathians produced series of ridges separating deep water basins. These ridges were providing favorable conditions for development of shallow banks with the carbonate platform sedimentation. The orogenic processes in the Northern Outer Carpathians produced an enormous amount of the clastic material that started to fill the basins. The material was derived from the northern and southern margins as well as from the inner ridges and swells. Each basin had the specific type of clastic deposits, and sedimentation commenced in different time.

The Mesozoic and Cenozoic shallow water carbonate platforms have been destroyed during the orogenic process. The numerous carbonate fragments have been found in flysch and olistostromes within all the Outer Carpathian subbasins. These fragments were transported with the turbidity currents to the flysch, forming the organodetritic limestones and sandstones. Their distribution allows tan attempt to reconstruct the original location of carbonate platforms within the Northern Outer Carpathian realm.

The origin of Czorsztyn Ridge

The Alpine Tethys (Fig. 1) was formed during the Jurassic time. This Alpine Tethys constitutes the extension of the Central Atlantic system (Golonka, 2004) and includes Ligurian, Penninic Oceans and Pieniny/Magura Basin. Bill et al. (2001) date the onset of oceanic spreading of the Alpine Tethys by isotopic methods as Bajocian. According to Winkler & Ślączka (1994) the Pieniny data fits well with the supposed opening of the Ligurian-Penninic Ocean. The orientation of the Pieniny/Magura Ocean was SW-NE (see discussion in Golonka and Krobicki, 2001, 2004, Golonka et al., 2003). This Ocean was divided into the northwestern and southeastern basins by the mid-oceanic Czorsztyn Ridge (Cr, Fig. 2). According

to Birkenmmajer (1986) the Czorsztyn Ridge could be traced from the vicinity of Vienna trough Western Slovakia, Poland, Eastern Slovakia to Transcarpathian Ukraine and perhaps northernmost Romania (Bombiţă et al., 1992). Plašienka (2003) postulated the thermal uplift above the distal, subcrustal part of detachment fault. The origin of the Czorsztyn Ridge is coeval with the spreading phase of the Pieniny/Magura Ocean. However it should be stressed that existence of the oceanic crust beneath the Magura basin could be disputable (Winkler & Ślączka, 1994). The occurrence of the mafic (basalt) intrusions in the eastern termination of the Czorsztyn Ridge in Novoselica Klippen (Lashkevitsch, 1995, Golonka et al, 2004) seems to support the thermal origin of the ridge related to the oceanic spreading.

The triple-junction zone was probably formed somewhere in the present day Eastern Carpathian. The Silesian presumably formed the one arm, the second one was represented by its extension into the Rahiv-Sinaia zone and the third one by the Pieniny Klippen Belt-Magura oceanic realm. The exact location and character of this triple-junction and associated volcanism is one of the subjects of the research undertaken by our team (Krobicki et al., 2004).

The research work on geodynamic evolution and on paleogeography of the Polish part of Carpathian during Neo-Cimmerian time (Golonka et al., 2003) showed, that Mesozoic volcanism of the area could be related to complicated development of rift and subduction environments. A setting associating features of both of them is back-arc basin. Evolution of back-arc basins includes magmatic activity showing rift characteristic (inducted by rising mantle diapir) as well as subduction characteristic. The first possibility is supported by some of the volcanic sequences displaying pattern similar to MORB (Lashkevitsch et al., 1995, Varitchev 1997). On the subduction-related magmatism could point the LILE behavior in some other sequences occurring in the Eastern Carpathians (Lashkevitsch et al., 1995, Varitchev 1997). The LILE behavior could result from melting process induced within mantle wedge above subducted slab, metasomatised by fluids released from the slab. The process could be more intensive acting jointly with hot spot.

The shallowest ridge sequences are represented by the dark Early Jurassic marly (Fleckenkalk/Fleckenmergel-type) facies followed by Bajocian-Tithonian crinoidal and nodular limestones (*Ammonitico rosso* type) and Cretaceous variegated marls (*Scaglia rosa* facies). The transitional slope sequences are known from outcrops south and north of the Czorsztyn Ridge in Poland. Several successions were distinguished within the slope deposits. The exact position of these sequences is uncertain due to the strong tectonic deformations. Ridge sequences as well as transitional slope sequences are also called "the Oravicum" by Slovak geologists (e. g. Maheľ, 1974, Plašienka, 1999). The initial movements during Toarcian-Aalenian had to precede the appearance of the Czorsztyn Ridge which did not exist as the main paleogeographic unit before Bajocian (e.g., Aubrecht et al., 1997).

The rapid change of sedimentation within Pieniny Klippen Basin from dark shales of oxygen-depleted environment (Fleckenkalk/Fleckemergel facies – Aalenian to earliest Bajocian) to overlying light crinoidal grainstones (crinoidal-type facies) corresponded to an important geodynamic event that took place during Early Bajocian – the origin of the mid-oceanic Czorsztyn Ridge (Krobicki & Wierzbowski, 2004).

This ridge emergence was connected with the postrift phase of the basin evolution (Golonka and Ślączka, 2003). The sedimentation of the younger, red, nodular Ammonitico Rosso-type limestones was an effect of Meso-Cimmerian vertical movements, which subsided Czorsztyn Ridge (Fig. 2 – Cr) and produced tectonically differentiated blocks, neptunian dykes and scarp-breccias (e.g. Birkenmajer 1986, Krobicki, 1996, Aubrecht et al. 1997, Wierzbowski et al. 1999, Aubrecht 2001, Aubrecht & Túnyi 2001, Golonka et al., 2003, Krobicki et al, 2003).

During Jurassic – Early Cretaceous time the Czorsztyn ridge was submerged and did not supply clastic material into the Pieniny and Magura basin. This observation provides an argument against the origin of ridge as the rifted away fragment of the European platform.

The origin of Silesian Ridge

The Outer Carpathian rift (proto-Silesian Basin) had developed with the beginning of the Uppermost Jurassic - Lower Cretaceous calcareous flysch sedimentation (Słomka, 1986). The Jurassic – Early Cretaceous Silesian Ridge (Książkiewicz, 1977a, b) originated as a result of the fragmentation of the European platform in this area (Olszewska & Wieczorek, 2001). The proto-Silesian basin was formed during the synrift process wit a strong strike-slip component. The complex system of rotated block was born. The emerged fragment of these blocks supplied material to the basin. The opening of the basin is related to the propagation of the Atlantic rift system (Golonka et al., 2003). The Silesian ridge separated the proto-Silesian basin from the Alpine Tethys. The Eastern Carpathian (Sinaia or „black flysch") as well as to the Southern Carpathian Severin zone (Sandulescu, 1988, Kräutner, 1996) are somehow related to this proto-Silesian basin. The direct connection is obscured however by the remnants of the Transilvanian Ocean in the area of the eastern end of Pieniny Klippen Belt Basin. These remnants are known from the Iňačovce-Krichevo unit in Eastern Slovakia and Ukraine (Soták et al., 2000). In this area existed a junction of the different basinal units – Alpine Tethys, Transilvanian Ocean and Outer Carpathian Basin. The Bucovino-Getic microplate (Golonka et al. 2003) constitutes a fragment of the East European Platform. It includes Precambrian, Early Paleozoic (Caledonian) granites and metamorphic rocks, Late Paleozoic (Variscan) metamorphic rocks as well as the late Paleozoic and Mesozoic sedimentary cover. The connection of this Bucovino-Getic microplate with the Silesian Ridge is uncertain because of existence of transform faults related to the Jurassic opening of Alpine Tethys (Fig. 1).

The Cieszyn Beds (Kimmeridgian-Hauterivian) are the oldest stratigraphic unit of the Silesian Nappe in the Outer Carpathians. It consists mainly of detrital and pelitic limestones, calcareous sandstones, marls and marly

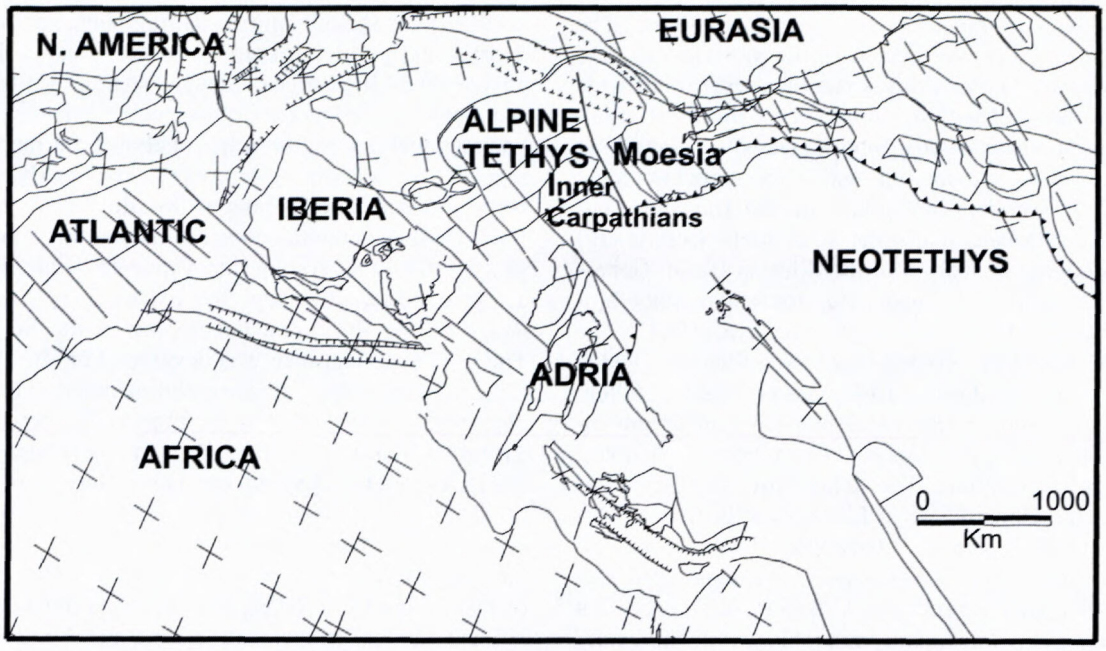

Figure 1. Position of Atlantic, Neotethys and Alpine Tethys. After Golonka, 2002, 2004.

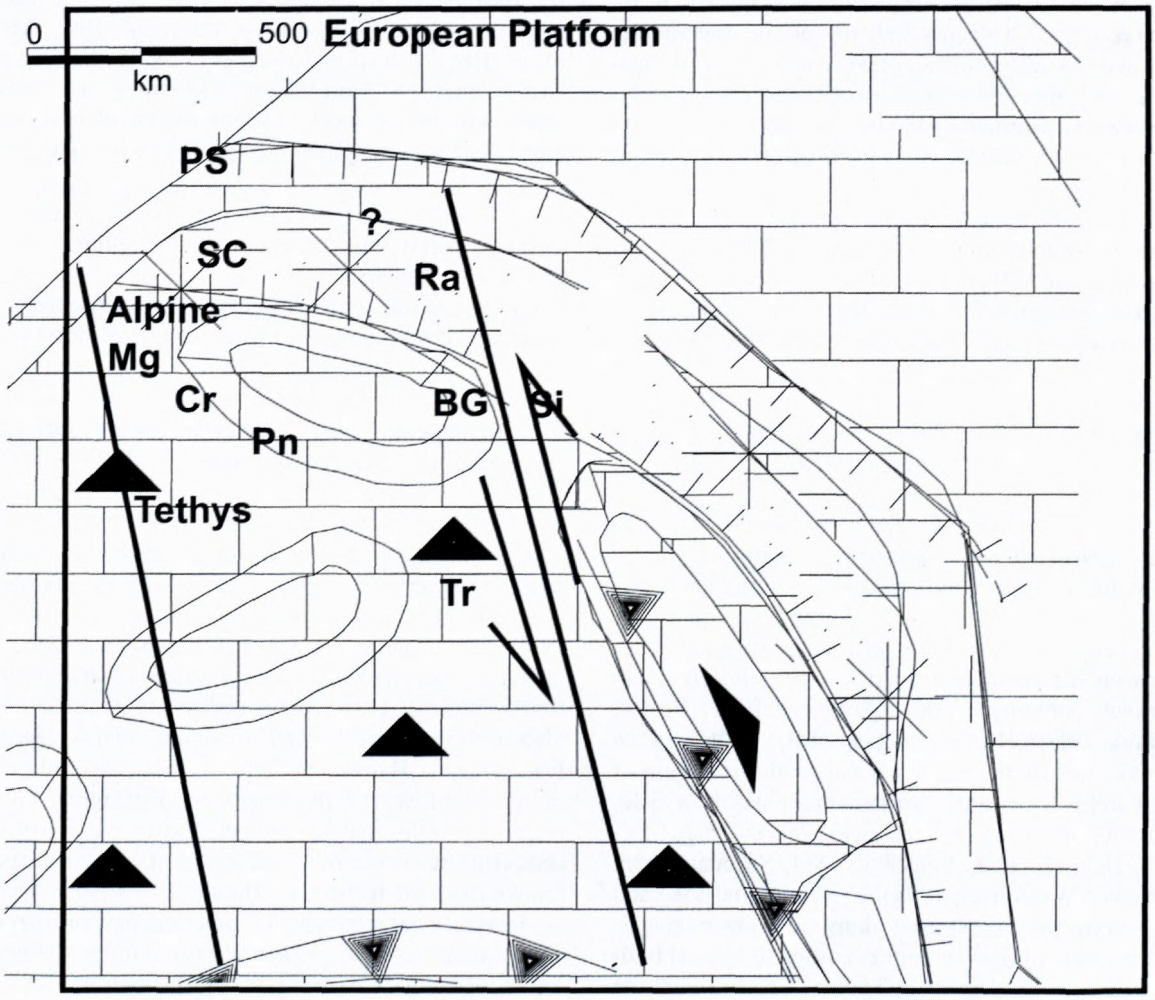

Figure 2. Paleogeography of the Outer Carpathian basins during latest Jurassic – earliest Cretaceous.
BG = Bucovinian-Getic, Mg = Magura basin, Pn = Pieniny Basin, PS = proto-Silesian basin, Ra = Rakhiv, Si = Sinaia, SC= Silesian ridge (cordillera), Tr = Transilvanian Ocean.

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shales. Maximum thickness attains above 800m. The subsidence in the proto-Silesian Basin was accompanied by the extrusion of basic lavas (teschenites) which were probably connected with development of initial rifting in this basin (Narębski, 1990). Simultaneously the shallow-water carbonate sedimentation with coral reefs (so-called Štramberk limestones) took place on the Eurasian platform. The carbonate platforms with reefs (Štramberk) developed along the margin of the Silesian Basin. Generally, reef complexes formed patch-reefs and other biogenic carbonate bodies (Eliáš & Eliášová, 1984). The carbonate platform existed on the Silesian Ridge (Matyszkiewicz & Słomka, 1994) and provided excellent conditions for organic life, represented by calcareous algae, sponges, corals, bryozans, brachiopods, bivalves, ammonites and crinoids. The debris-flow sediments belonging to the Upper Cieszyn Limestone (Berriasian) include clasts of bioclastic limestones (boundstones) of microbial-sponge mud mounds and coral-algal reef with the microencruster assemblage *Lithocodium aggregatum - Bacinella irregularis*. This assemblage unequivocally proves the presence of shallowing-upward reefal sequences on the Silesian Ridge (Matyszkiewicz & Słomka 1994, 2004). According to Matyszkiewicz & Słomka (1994), two belts of carbonate buildups were present on the Silesian Ridge: a deeper belt of microbolite-sponge buildups and a shallower one, represented by coral-algal reefs. The last new findings of exotics provide foundations for a new, alternative model of carbonate buildup distribution on the Silesian Elevation (Matyszkiewicz & Słomka, 2004). The age of the exotics is difficult to establish because of the lack of index fossils. However, the presence of the microbial megafacies suggests that the clasts are not older than Late Jurassic and represent a higher, Kimmeridgian-Tithonian part of the Jurassic or earliest Cretaceous (cf. Darga & Schlagintweit 1991, Moshammer & Schlagintweit 1999, Schlagintweit & Ebli 1999, Schlagintweit & Gawlik 2003). This model accepts the presence of only one belt of the buildups, which underwent transformation from microbolite-sponge mud mounds to coral-algal reefs (Matyszkiewicz & Słomka, 2004). The development of the coral-algal reefs was probably a consequence of intense aggradational growth of microbolite-sponge mud mounds, accompanied by intense uplift movements of the Neo-Cimmerian phase.

The clastic material for Cieszyn Beds were generally derived from the northern margin of the Silesian Basin (e.g. Kruhel, Štramberk) (Książkiewicz, 1960, Peszat, 1967, Malik, 1986). However, a part of the clastic source area was situated on the islands at the southern margin of this basin and related to the northern margins of the Silesian Ridge (Cordillera) (Książkiewicz (ed.), 1962, Ślączka (ed.), 1976, Eliáš & Eliášová, 1984, Słomka, 1986, Matyszkiewicz & Słomka, 1994). Cieszyn Limestone and Upper Cieszyn Shales, exposed along the Soła river valley in the vicinity of Żywiec region comprise several bodies of debris-flow deposits. Their thickness in the particular outcrops oscillates from 2,5 up to 30 meters. The share of the clast framework does not exceed 30%. These sediments correspond to the facies A1.3 after Pickering *et al.* (1986) and facies GyM after Ghibaudo (1992). They include numerous fragments and pebbles of detrital and pelitic limestones of the Cieszyn Beds, organodetrital limestones, marly shales, Carboniferous sedimentary and metamorphic rocks: granitic gneisses, gneisses and crystalline schist. Pebbles are randomly arranged in a mass of structureless, hard marly silt. Both clays and embedded lumps of limestone have bends and folds closing generally towards the north, which would suggest that the sliding mass moved from the south. These deposits document the existence of the Silesian Ridge during the initial developing of the Silesian rift. The carbonate platform was developed on the submarine ridge. Covering the Paleozoic sedimentary and metamorphic rocks. The rift was a subject of latest Jurassic-earliest Cretaceous uplift. Part of the Cieszyn Beds, which originally covered the basin floor was also uplifted. These beds were again eroded and redeposited by debris flows. The existence of coarse-grained facies of the Upper Cieszyn Limestones as well as the appearance of mass-movement debris-flow deposits indicate the significant vertical movements during the Neo-Cimmerian activity. Alternatively, the formation of such allodapic rock beds are also interpreted as an effect of eustatic events (litohorizone Be-7) and correspond very well with the Berriasian part of the Nozdrovice Breccia within Inner Carpathians (Reháková & Michalík, 1992, Michalík *et al.*, 1995, 1996) developed as scarp breccias along active submarine fault slopes (Michalík & Reháková, 1995). On the other side, the eustatic changes are perhaps connected with the global plate reorganization which took place during Tithonian-Berriasian time (Golonka, 2000). This global plate reorganization is also related to the Tethyan Neo-Cimmerian tectonic activities. The Early Cretaceous development of the Silesian Basin, perhaps from rifting into spreading phase, as suggested by the presence of teschenitic magmatism (Narębski, 1990, Lucińska-Anczkiewicz et al., 2000) was probably another effect of this Neo-Cimmerian activity.

The black marls pass gradually upwards into calcareous turbidites (Cieszyn limestones – Sinaia beds) which created several submarine fans (Słomka, 1986). Occurrence of deep-water microfauna (Geroch & Olszewska, 1990) indicates that subsidence of the basins must have been quite rapid (Poprawa *et al.*, 2002). During the early part of the Cretaceous the calcareous turbidites gave way to black calcareous shales and thin sandstones passing upwards into black, commonly siliceous shales (the Věřovice Shales). This type of sediments is already known also from the other Outer Carpathians basins. During the Hauterivian, Barremian and Aptian several coarse-grained submarine fans developed. The supply of clastic material was probably connected with the Early Cretaceous uplift of internal and external source areas, that known from the Bohemian Massif.

Insignificant changes in assemblages of the corresponding deep sea agglutinated foraminifera (generally to *Recurvoides* zone of Haig, 1979) through the Early Cretaceous suggest lack of pronounced changes of depth of basins. It implies generally continuos tectonic subsidence of the basins during that period. This subsidence was equal to the rate of sedimentation. Periodical occurrence

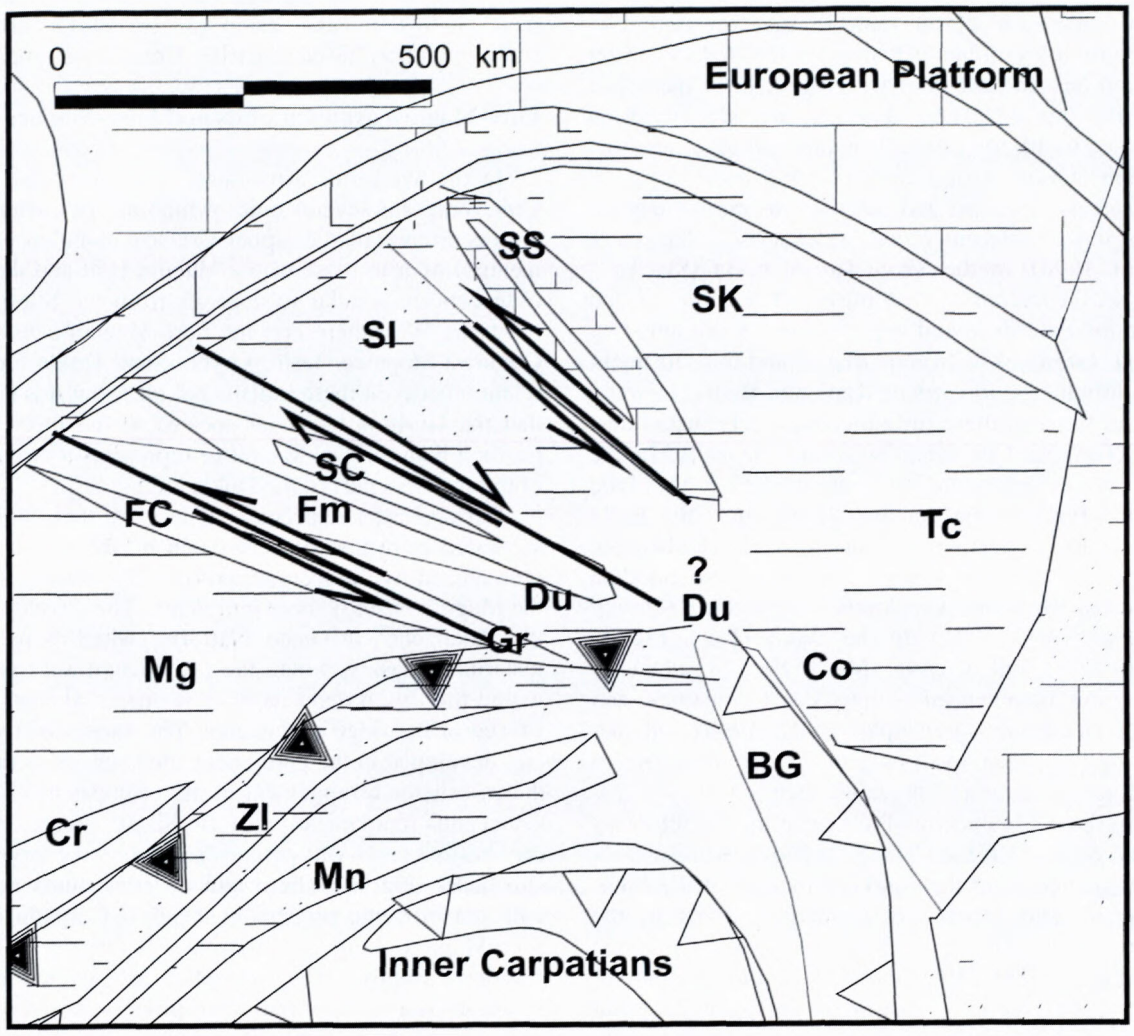

Figure 3. Paleogeography of the Outer Carpathian basins during Late Cretaceous. BG = Bucovinian-Getic, Co = Cornohora, Porkulec, Audia, Teleajen, Cr = Czorsztyn ridge, Du = Dukla, FC = Fore-Magura ridge (cordillera), Fm – Fore-Magura basin, Gr = Grybów, Mg = Magura, Mn = Manin, Si = Silesian basin, SK = Skole, SC = Silesian ridge (cordillera), SS = Sub-Silesian ridge, Tc – Taracau, Zl = Zlatna.

of planktonic microfossils corresponds to global changes of the sea level (Olszewska & Szydło, 2004).

The Cretaceous reorganization

In the early Albian within the black shales, widespread turbiditic sedimentation started, that can be connected with a compressional period very pronounced in the Eastern Carpathians. In that part of the Carpathian domain the compressional movement started during the Aptian and Albian and the inner part of the Carpathians was folded, nappes formed and in front of moving nappes coarse-grained sediments (Bucegi - Soymul Conglomerates) and olistostromes developed (Kruglov, 1989, 2001, Săndulescu, 1988).

In the beginning of the second stage, during the Cenomanian and Turonian, compression embraced the Inner Carpathians (IC) and several nappes with northward polarity developed. Subduction consumed the major part of the Pieniny Klippen Belt Ocean (Fig. 3). Cherty limestones gave way to marls and flysch deposits. With the development of the Inner Carpathian nappes the fore-arc basin was formed between the uplifted part of the IC terrane (so-called Andrusov Ridge) and the subduction zone (Fig. 3). The flysch of the Klape and Złatna (Zl - Fig.3) succession was formed in this area. Behind the ridge the Manín succession (Mn – Fig. 3) was deposited within the back-arc basin. As an effect of these movements the Inner Carpathians and Alps jointed with the Adria plate and the Alcapa terrane was created. In the Cenomanian period, subsidence was faster than the sedimentation rate (Poprawa *et al.*, 2002) and uniform, deep-water pelagic sedimentation of radiolarites, green and red shales embraced a greater part of the Outer Carpathians basins.

In the Outer Carpathians during this stage several ridges have been uplifted as an effect of the orogenic process. These ridges distinctly separated several subbasins, namely Magura, Dukla-Fore-Magura, Silesian, Charnahora-Audia, Skole-Tarcau subbasins (Figs. 3). More outer subbasins (Skole, Silesian, Dukla-Fore Magura) reached diagonally the northern margin of the Outer Carpathians and successively terminated towards the west (Fig. 3). From uplifted areas, situated within the Outer Carpathian realm as well as along its northern margin,

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enormous amount of clastic material was transported by various turbidity currents. This material filled the Outer Carpathian basins (Książkiewicz, 1968). Each basin had the specific type of clastic deposits, and sedimentation commenced in different time. It is interesting to note that this sedimentation started earlier in the outer subbasin (Skole-Tarcau subbasin) and migrated diachronously toward the inner subbasins (Bieda *et al.*,1963, Ślączka & Kaminski, 1998). In the Skole-Tarcau basin (Sk, Tc – Fig. 3) sedimentation started during the Turonian and ended in the Paleocene and deposits were represented by calcareous turbidites (Siliceous Marls) and thin- to thick-bedded turbidites (*Inoceramus*-Ropianka Beds). In western part of the area these turbidites were terminated during late Turonian/Coniacian by slump deposits. In the Silesian basin sedimentation started during the Late Turonian - Early Coniacian and lasted up to the Early Eocene being mainly represented by thick bedded, coarse-grained turbidites and fluxoturbidites (Godula Beds, Istebna Beds and Ciężkowice Sandstone) (Unrug, 1963, Leszczyński, 1981). In the Dukla (Du – Fig. 3) (Ślączka, 1971) and Magura (Mg – Fig. 3) subbasins sedimentation commenced during the Campanian and lasted till Paleocene (Oszczypko, 1992, 1998) and medium and thin-bedded, medium grained turbidites (*Inoceramus*-Ropianka Beds s.l.) prevailed there.

During Late Creataceous-Paleocene the accretionary prism had overridden the Czorsztyn Ridge. The subduction zone moved from the southern margin of the Pieniny Klippen Belt Ocean (Birkenmajer, 1986) to the northern margin of the Czorsztyn Ridge (Fig. 3) (Golonka et al, 2000). The submarine slumps and olistolites along the southern margin of the Magura Basin were related to the destruction of Czorsztyn ridge and movement of the accretionary prism. The huge olistolites containing fragments of destroyed Czorsztyn ridge have been found among the others in the vicinity of Jaworki village (Golonka & Rączkowski, 1984, a,b, Osczypko et al., 2004. The Homole block with the large part of the sedimentary Czorsztyn succession and Biała Woda ridge basalts constitutes the largest olistrostrome (Cieszkowski et al., 2003). The radiolarites and carbonates of the Niedzica succession, which originally were deposited on the southern slope of the Czorsztyn ridge form the submarine slump emplaced on the Czorsztyn succession originally deposited in the central part of the ridge The development of the new accretionary prism in the Magura Basin was related to the origin of the trench connected with new subduction zone (Oszczypko, 1998, Oszczypko et al., 2003). The slope (Zawiasy) and basinal deep water carbonate rock (Grajcarek) originally deposited north of the Czorsztyn succession were included into this accretionary prism. The sedimentation and subsidence rate accelerated more distinctly in the Silesian Basin than in the Magura Basin (Oszczypko et al., 2003), and were accompanied by a continuos uplifting of the Silesian and Subsilesian ridges as well as of southern margin of the European platform. This uplift produced a tremendous amount of clastic material. Especially distinct ridge developed in the SE prolongation of Silesian ridge, that gave clastic material to the Dukla basin and was built partly from rocks metamorphosed in earlier Cretaceous time.

Fore-Magura group of units and Fore-Magura ridge

In the Western Carpathians, north from the Magura Unit, there are several units, which are characterized by the occurrence of the Upper Cretaceous-Paleocene sediments similar to those of the Magura Unit and the Oligocene deposits similar to deposits from the Silesian unit. From the West there are: the Fore-Magura *sensu stricte*, Obidowa-Słopnice, Jasło, Grybów and Dukla units. The relation between these units is not clear but it is supposed that the Grybów Unit was located in the more internal position than the Dukla Unit or represents a prolongation of the southern part of the Dukla Unit.

During Late Cretaceous - Paleogene these units were separated from the Silesian Basin by the Silesian ridge, reorganized by the tectonic process. The separation from the Magura basin is more enigmatic. The development of the Paleogene carbonate platform, which supplied the material to basins, where the Lithothamnium sandstones within the flysch deposits were formed, indicates the existence of the ridge in this area. The variety of flysch facies developed in the partly separated subbasins indicated the en-echelon arrangement of these subbasins. The Late Cretaceous reorganization of the Silesian ridge and adjacent basinal areas was perhaps caused by the large strike-slip faults (Fig. 3). The origin of these faults is related with the orogenic process in the East Carpathians. The Fore-Magura group of subbasins was formed in the transtensional regime. The en-echelon arrangement of these subbasins is a result of pull-apart process caused by major strike-slip faults of NW-SE orientation. The Fore-Magura ridge (cordillera, (FC – Figs. 3, 4) originated during the Late Cretaceous reorganization.

Andrychów Ridge

This unit is represented by several huge blocks on the boundary between the Silesian and Subsilesian units, near Andrychów town. Probably they are remnants of calcareous platform which was situated between Silesian and Subsilesian sedimentary areas or represented a part of Subsilesian substratum. The composition of the klippes differs from the adjacent units, although the Upper Cretaceous sediments show similarity to the sequences of the Subsilesian unit. The non-flysch, calcareous facies are very characteristic for the Andrychów Ridge sequences (Książkiewicz, 1951, Gasiński, 1998, Olszewska & Wieczorek, 2001). The basement of the ridge was built up of granite-gneiss or mylonitised rocks. The sedimentary sequences in elevated parts are represented by crinoidal and shallow water limestones (Štramberk type) of late Jurassic age. The more basinal or slope facies are represented by Maiolica type Late Jurassic-Early Cretaceous cherty limestones (Olszewska & Wieczorek, 2001). These basinal sequences were tectonically deformed and uplifted in Late Cretaceous. Both, originally shallow water and deformed basinal units are covered by transgressive Early Campanian conglomerates and marls, lime-

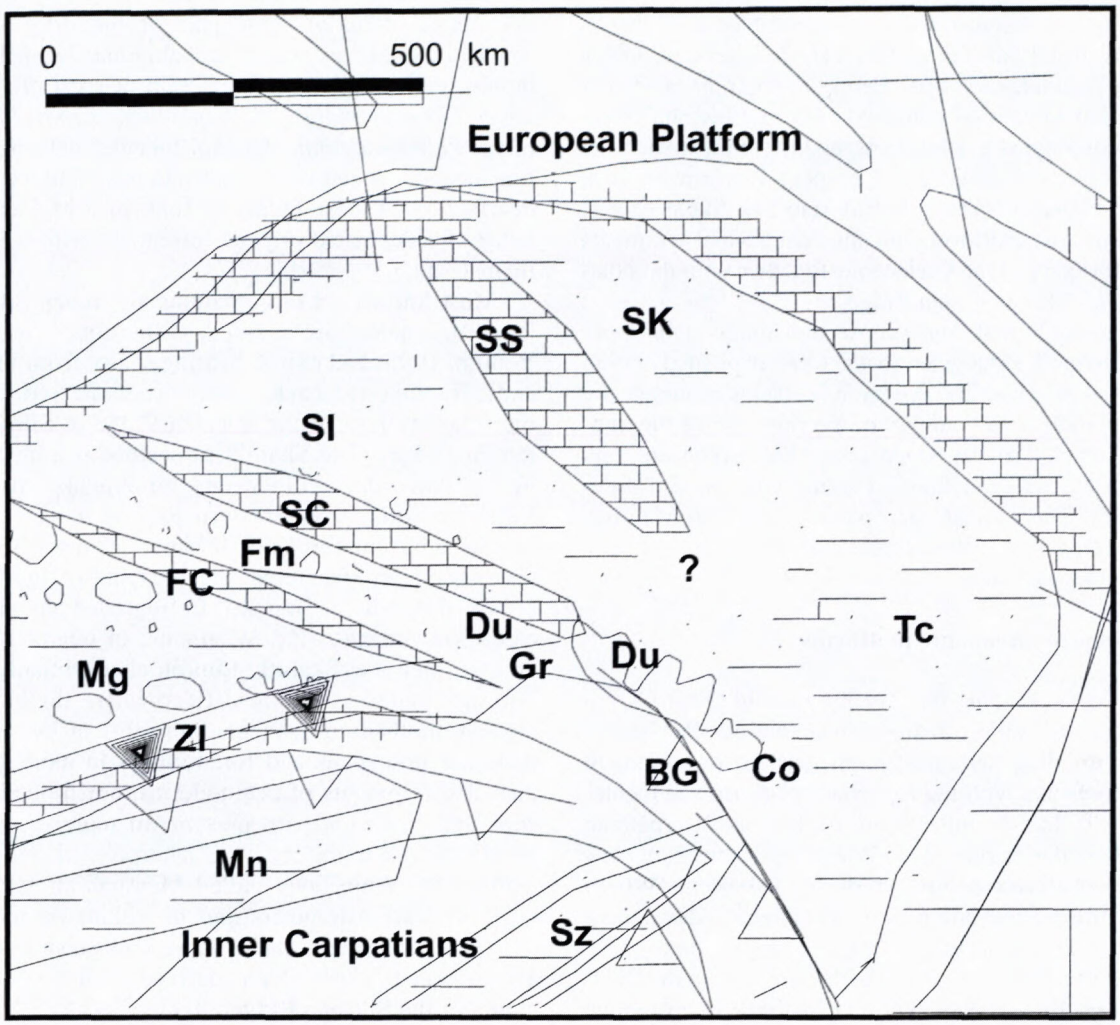

Figure 4. Paleogeography of the Outer Carpathian basins during Paleocene and distribution of carbonate platforms.
BG = Bucovinian-Getic, Co = Cornohora, Porkulec, Audia, Teleajen, Cr = Czorsztyn ridge, Du = Dukla, FC = Fore-Magura ridge (cordillera), Fm – Fore-Magura basin, Gr = Grybów, Mg = Magura, Mn = Manin, , Si = Silesian basin, SK = Skole, SC = Silesian Cordillera, SS = Sub-Silesian ridge, Sz = Szolniok, Tc – Taracau, Zl = Zlatna.

stones and shaly marls of Campanian and Maastrichtian age. Paleocene and Early Eocene are represented by organogenic limestones and shales.

Subsilesian Ridge

The Lower Cretaceous and lower part of the Upper Cretaceous sediments within Subsilesian unit display a basinal character, similar to the Silesian basin but differing in higher calcium carbonate content. These basinal units were deformed during the Late Cretaceous tectonic process and formed the ridge (Inwałd Ridge) (Matyszkiewicz & Słomka, 1994), which displayed the relatively shallow water type of sedimentation represented by marly lithofacies.

A thick complex (about 700 meters) of the deep sea red and green marls (Węglówka Marls) represents Senonian to Mid Eocene. In the western part of the Subsilesian Unit there are intercalations of sandy and conglomeratic complexes of the Upper Senonian and/or Paleocene. Small turbiditic fans developed locally, compatible with a tendency for successive uplift of small fragments of the Subsilesian Ridge – Baška and Inwałd Cordilleras (Słomka, 1995). During the Late Senonian the upper slope grey marls (Frydek Marls) often with exotic rocks, developed in this area. The marly complex pass upwards into variegated shales and/or series of shales and thin bedded sandstones terminated by green shales and *Globigerina* Marls representing the Eocene/Oligocene transition. To the west the Subsilesian sediments and especially red marls continue to the Helvetic zone of the Alpine foreland. In the Moravian Carpathians the Subsilesian lithofacies are partly replaced by sediments of the Ždánice Unit (Stráník et al, 1993).

On the underwater ridge that divided the Skole and Silesian subbasins (Subsilesian sedimentary area, PS – Figs. 3, 4) sequence of the deep-sea red and green marls (Węglówka Marls) of Senonian to Eocene and the upper slope gray marls (Senonian Frydek Marls) were deposited. However north from town of Sanok in marginal part of the Silesian unit there are Barremian Aptian conglomerates and pebbly sandstones (Grodziszcze Sandstones)

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containing coal fragments, limestone pebbles and remains of shallow water fauna of molluscs (*Leda scapha* (d' Orb.), *Exogyra boussinggaulti* (d' Orb.), *Cardita brouzetensis* Cossm. and undefined ostreans), sea urchins and bryozoans (Kokoszyñska, 1949, Koszarski, 1968). It suggests existence of a promontory of European Platform or local platform between Silesian/Subsilesian and Skole basins. These carbonate platform with adjacent basinal sediments were deformed in Late Cretaceous together with the other components of Subsilesian Ridge.

It is possible that Andrychów and Subsilesian Upper Cretaceous and Paleogene rocks were deposited within the same ridge area. The Andrychów facies represent the central, partially emerged part of the ridge, while the Sub-Silesian much broader slope area. The inversion took place during the geodynamic evolution of the Sub-Silesian realm. The basinal deep water Oxfordian Maiolica deposits (Olszewska, Wieczorek, 2001) were emplaced in the ridge elevated area.

The Paleogene carbonate platforms

The ridges dividing the flysch basins in Outer Carpathians became more distinguished during Paleocene-Eocene providing favorable conditions for development of shallow banks with the carbonate platform sedimentation (Fig. 3). In the southern part of the Outer Carpathian realm, along the margin of the Zlatna forarc basin, narrow carbonate platforms originated during Paleocene. Within these platforms the complex reef systems developed. (Köhler, Salaj & Buček, 1993). Large fragments of these reefs occur in Haligovce – Veľký Lipník area in the Pieniny Klippen Belt in Slovakia and in the Váh river area (Samuel, Borza & Köhler, 1972) forming olistolites within the flysch deposits of Žilina formation (Potfaj, 2000). The organogenic limestones are built of *Scleractinia* corals together with *Corallinaceae* Algae (genera *Lithotahamnium. Lithophyllum, Arhaeolithothamnium, Paleothamnium, Ethelia*) Bryozoa, sponges, brachiopods, Gastropodes and foraminifers. The reefal facies, as well as for-reef and back-reef assemblages could be distinguished here. The smaller fragments of the organogenic Paleocene limestones with numerous red *Corallinaceae* algae have been found in the Paleocene flysch deposits of Jarmuta and Szczawnica Formations in the suthern part of the Magura Unit (Golonka, 1974, Burtan et al, 1984). The huge olistolites build of Mesozoic sequences near Haligovce village (Haligovce klippe) also related to the flysch of Žilina formation deposited in the fore-arc Zlatne unit.

The Fore-Magura, Silesian ridge and Subsilesian ridges also formed the alimentation center of detrital material during Paleogene. The Paleocene organogenic and organodetritical limestones are known from the Andrychów area. (Książkiewicz, 1951, 1968, Olszewska & Wieczorek, 2001, Gasiński, 1998). They are similar to those known from the Zlatne Unit. The carbonate platform and reef limestone were also the source carbonate material redeposited to the Szydłowiec sandstone in the Subsilesian Unit.

The eastern part of the Silesian ridge was built up mainly of sedimentary rocks, a source for the mature, siliciclastic material. This part of the ridge was surrounded by shallow water, probably narrow shelf locally dominated by Paleocene reef build of red *Corallinaceae* algae *Lithotahamnium. Lithophyllum, Arhaeolithothamnium, Paleothamnium, Ethelia,* together with bryozoans, brachiopods, sometimes corals and foraminifers. Patchily distribution of these faunas is confirmed by local occurrence of redeposited organic limestones within siliciclastic material.

Most known rocks containing the redeposited shallow carbonates are Skalnik Limestone (Ślączka & Walton, 1992) and exotic-bearing shales from Bukowiec and Roztoki (Ślączka, 1961) were derived from the most eastern part of the Silesian Ridge or Silesian System of Ridges. The Skalnik Limestone is a megaturbidite within the Oligocene bituminous fish-shales (Menilite beds) from western part of the Dukla basin and its adjacent foreland. It shows changes from NW towards SE in structures and contents of bioclasts. In proximal part it is composed from graded and laminated calcareous, towards the SE amount of quartz grains increases and the Skalnik Limestone eventually passes into calcareous sandstones. Everywhere the calcareous algae Lithothamnium is predominant, in less amounts there are bryozoans and foraminifers In more proximal part also fragments of echinoderms, brachiopods, ostracods and *Balanidae* are present. In more distant parts planktonic foraminifers were incorporated into sparitic matrix. The main layer called Metressa stretch on distance of sixty kilometers and its volume is more than 0,5 cubic kilometers and it represents seismo-turbidite. The carbonate material was derived from the east termination of the Silesian Ridge.

Bircza *Lithothamnium* Limestone Bed is the typical example of the limestones constructed of material originated on the shallow-water margin of the North European Platform and redeposited in the Carpathian flysch. These allodapic limestones, which material was derived from the northern margin of the Skole basin, are located in the early Late Paleocene (P 3 zone) in central part of the Skole Unit. There are also exotic clasts of limestones confined exclusively with lithosomes of Babica Clay – dense cohesive flows (Rajchel & Myszkowska, 1998). Similar clasts exist in Ciężkowice sandstone in the Silesian Unit.

Other sediments containing shallow water fauna are known from exotic- bearing shales from Bukowiec. These shales create a lens within the Oligocene Krosno Beds in SE, inner part of the Silesian unit in front of the Dukla Unit. They contain huge (aproximately 15 meters in length) block of shallow water deposits. The sequences visible in blocks are represented by green marly shales containing foraminifers and sometimes thin shells brown or green mudstones with scattered fragments of mollusks, sporadically graded and shaly limestones containing *Ostrea* sp. These sediments display synsedimentary folds. Besides huge block in the muddy matrix there are rounded or sub-rounded blocks up to tens of centimeters of organic limestones and green marls with *Turritella*. These limestones consist of *Lithothamnium, Bryozoa, Nummulites* and fragments of bivalves. The

age of fauna is considered mainly as the Late Eocene, however in the matrix younger, Oligocene, Nummulites (*Nummulites vascus*) were found. Locally, echinoderms and crabs were found. Within the matrix, there are also angular blocks of green and gray schists, quartzites, white marbles and scarce amphibolites. The exotic-bearing shales represent deposit of submarine slumps, which came from the SE, from the ridge situated north-east from the Dukla basin. The lenses of similar deposits are known along the front the Dukla nappe on the distance of more than one hundred kilometers. In both cases the age of fauna mainly is of the Late Eocene and in less extent of Oligocene. The carbonate material was derided from the system of ridges situated NE from the Dukla basin and forming SE prolongation of the Silesian ridge

The final reactivation and destruction of ridges

In the circum-Carpathian region the Adria-Alcapa (Inner Carpathians) terranes continued their northward or NE movement during Eocene-Early Miocene time (Golonka et al., 2000) Their oblique collision with the North European plate led to the development of the accretionary prism of Outer Carpathians. During the compressional stage interbasinal ridges were reactivated. Flysch still continued to be deposited in the subbasins. Numerous olistostromes were formed during this time (Ślączka and Oszczypko, 1987).

The process of migration of clastic facies from inner to the outer part began, connected with development and migration of accretionary prisms. In the inner part of the Outer Carpathians the migration of clastic facies and development of accretionary prisms started already in Early Eocene and lasted till Oligocene. (Oszczypko, 1998, Golonka et al. 2003). Sedimentation within the Magura basin terminated generally by accretionary wedges represented by medium- and thin-bedded sandstones (Malcov Fm.) during the Oligocene. Within the more outer parts of the Carpathians realm, from Dukla to Skole subbasins evidence of migration of depocenter appeared at the Eocene/Oligocene boundary (Ślączka, 1969) as an effect of compressional movements. As the consequence of these movements, the bottom of the basins started to deform and initial anticlines locally developed, slump, and coarse-grained sediments were locally deposited and volcanic activity increased. Deep-marine connection with Tethys Sea was closed and euxinic conditions developed (Ślączka, 1969).

The Oligocene sequences commenced with dark brown bituminous shales and cherts (Menilite Beds) with locally developed sandstone submarine fans or a system of fans up to several kilometers long. The main ones were Mszanka and Cergowa Sandstones in Dukla subbasin and Kliwa sandstones in Skole- Tarcau subbasin. The upper boundary of the bituminous shales are progressively younger towards the north and they pass gradually upwards into sequence of micaceous, calcareous sandstones and grey marls (Krosno beds), and they thin upward. The Menilite Beds grade upwards into a complex of thick and medium bedded, calcareous sandstones and marly shales (Krosno Beds). Both lithostratigraphic units are cut by horizon of pelagic coccolithic limestones (the Jaslo shales) above which the Oligocene/Miocene boundary has been located (Garecka, 1997, Garecka & Malata, 2001). Locally, near village Żegocina, grey mudstones, similar to the Krosno Beds of the Early Miocene age had been found (Górczyk, 2003 personal com).

Cessation of deposition is diachronous across the Carpathians due to migration of tectonic activity and formation of trailing imbricate folds and/or accretionary prisms generally from the south to the north. During the sedimentation of the Krosno beds several slump deposits with blocks of shallow water, Paleogene limestones up to tens of meters long and smaller blocks of metamorphic and igneous rocks were deposited from intrabasinal ridges (Ślączka, 1969). With the final phase of tectonic movement, in front of advancing nappes and/or accretional wedges (prisms), huge (up to kilometers in size) slumps (olistostromes) with material derived from approaching nappes, developed (Ślączka and Oszczypko, 1987).

During the final orogenic stage Africa converged with Eurasia. The direct collision of the supercontinents never happened, but their convergence lead to the collision of intervening terranes leading to the formation of the Alpine-Carpathian orogenic system. Through the Miocene tectonic movements caused final folding of the basins fill and created several imbricate nappes which generally reflect the basin margin configurations after the Cretaceous reorganization and Paleogene development of. The Sub-Silesian ridge deposits were partially included into the Sub-Silesian nappe, the ridge's basement rocks and part of its depositional form olistostromes and exotic pebbles within Menilitic-Krosno flysch. The largest olistostromes were found in the vicinity of Andrychów and are known as Andrychów Klippes (see remarks above about Andrychów ridge). The Fore-Magura and Silesian ridges were destroyed totally and are known only from olistolites and exotic pebbles in the Outer Carpathian flysch. They destruction is related to the advance of the accretionary prism. This prism obliquely overridden the ridges leading to the origin of the Menilitic-Krosno basin. The Malcov Formation was deposited in the smaller piggy-back subbasin. During overthrusting the outer, marginal part of the advanced nappes was uplifted whereas in the inner part sedimentation persisted in the remnant basin. From that, uplifted part of the nappes big olistolites glided down into the adjacent, more distal basins. The nappes became detached from the basement and were thrust northward in the west and eastward onto the North European platform with its Miocene cover. Overthrusting movements migrated along the Carpathians from the west towards the east. The Outer Carpathian allochtonous rocks, as result of Miocene tectonic movements, have been overthrust onto the platform for a distance of 50 to more than 100 km.

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References

Aubrecht, R. & Túnyi, I. 2001: Original orientation of neptunian dykes in the Pieniny Klippen Belt (Western Carpathians): the first results. *Contributions to Geophysics and Geodesy*, vol. 31, p. 557–578.

Aubrecht, R. 2001: New occurrences of the Krasín Breccia (Pieniny Klippen Belt, West Carpathians): indication of Middle Jurassic synsedimentary tectonics. *Acta Geologica Universitatis Comenianae*, vol. 56, p. 35-56.

Aubrecht, R., Mišík, M & M. Sýkora, 1997: Jurassic synrift sedimentation on the Czorsztyn Swell of the Pieniny Klippen Belt in Western Slovakia. In: Plašienka, D., Hók, J., Vozár, J. and Elečko, M. (Eds.): *Alpine evolution of the Western Carpathians*. Geological Survey of Slovak Republic, Bratislava, p. 53-64.

Bieda, F., Geroch, S., Koszarski, L. Książkiewica, M. & Żytko, K. 1963: Stratigraphie des Karpates externes polonaises. *Biuletyn Instytutu Geologicznego*, vol. 182, p. 5–174.

Bill, M., O'Dogherty, L., Guex, J., Baumgartner, P. O. & Masson, H. 2000: Radiolarite ages in AlpineMediterranean ophiolites: Constraints on the oceanic spreading and the Tethys-Atlantic connection. *Geological Society of America Bulletin*, vol. 113, p. 129–143.

Birkenmajer, K., 1986: Stages of structural evolution of the Pieniny Klippen Belt, Carpathians. *Studia Geologica Polonica*, vol. 88, p. 7-32.

Bombiţă, G., Antonescu, E. Malata, E. Müller, C. & Neagu, T. 1992: Pieniny-type Mesozoic formation from Maramures, Romania (second part). *Acta Geologica Hungarica*, vol. 35, p. 117–144.

Burtan, J., Chowaniec, J., & Golonka, J. 1984: Wstępne wyniki badań nad egzotycznymi skałami węglanowymi z zachodniej części polskich Karpat fliszowych; Preliminary results of studies on exotic carbonate rocks in the western part of the Polish Flysch Carpathians. *Biuletyn Instytutu Geologicznego*, vol. 346, p. 147-159. Warsaw.(in Polish)

Cieszkowski M., Golonka, J., Polak, A., Rajchel J. & Ślączka, A. 2003: Olistostroms in the deep water flysch deposits in the Polish outer Carpathians. In: Vlahovic, I. (ed.) *22nd IAS Meeting of Sedimentolog*. Opatija 2003 Abstract Book.. IAS Opatija p. 66.

Darga R. & Schlagintweit F. 1991: Mikrofazies, Paläontologie und Stratigraphie der Lerchkogelkalke (Tithon-Berrias) des Dietrichshorns (Salzburger Land, Nördliche Kalkalpen). *Jb. Geol. B.-A.* vol. 134, p. 205-226.

Eliáš, M. & Eliášova H. 1984: Facies and paleogeography of the Jurassic in the western part of the Outer Flysch Carpathians in Czechoslovakia. *Sbornik Geol. Ved., Geol.*, vol. 39, p. 105-170.

Garecka M., 1997: Biostratygrafia najmłodszych osadów strefy brzeżnej jednostki śląskiej w okolicach Brzozowa na podstawie nanoplanktonu wapiennego. *Posiedzenia naukowe PIG*, vol. 53, p.79-81. (in Polish)

Garecka M. & Malata T. 2001: Nanoplankton wapienny serii menilitowo-krośnieńskiej jednostki skolskiej (rejon na północ od Leska). *Posiedzenia Naukowe PIG*, vol. 57, p. 89-91. (in Polish)

Gasiński, M. A. 1998: *Campanian - Maastrichtian Palaeoecology and palaeobiogeography of the Andrychów Klippes, Outer Carpathians, Poland*. Wydaw. Uniwersytetu Jagiellońskiego, Kraków, 90pp.

Geroch S., & Olszewska B. 1990: The oldest assemblage of agglutinated foraminifers of the Polish Flysch Carpathians. In: C. Hemleben et al (eds.) *Paleoecology, Biostratigraphy, Paleoceanography and Taxonomy of Agglutinated Foraminifera*. NATO ASI Series, C, 327, p. 525-531.

Ghibaudo, G. 1992: Subaqueous sediment gravity flow deposits: particular criteria for their field description and classification. *Sedimentology*, vol. 39, p. 423-454.

Golonka, J., 1974: Calcareous Algae of the Paleogene in Kroscienko (Magura unit) and Zlatne (Pieniny Klippen Belt). *Kwart. Geol.* vol. 18, p. 828-929 (in Polish).

Golonka J., 2002: Plate-tectonic maps of the Phanerozoic. In: Kiessling W., Flügel, E. and Golonka J. (eds.): Phanerozoic reef patterns. *SEPM (Society for Sedimentary Geology) Special Publication* vol, 72, p. 21-75. Tulsa.

Golonka, J., 2004: Plate tectonic evolution of the southern margin of Eurasia in the Mesozoic and Cenozoic, *Tectonophysics*, vol. 381, p. 235-273.

Golonka J. & Krobicki M. 2001: Upwelling regime in the Carpathian Tethys: a Jurassic-Cretaceous palaeogeographic and paleoclimatic perspective. *Geological Quarterly*, vol. 45 (1), p. 15-32. Warszawa.

Golonka, J., & Krobicki, M. 2004: Jurassic paleogeography of the Pieniny and Outer Carpathian basins. *Rivista Italiana di Paleontologia e Stratigrafia*, vol. 110, p. 5-14.

Golonka, J. & Rączkowski, W., 1984a: *Arkusz Piwniczna; Objaśnienia do szczegółowej mapy geologicznej Polski; Detailed Geological Map of Poland*. Geological Institute - Publishing House Wydawnictwa Geologiczne. 85 p. Warsaw. (in Polish)

Golonka, J., & Rączkowski, W., 1984b: *Arkusz Piwniczna. Szczegółowa map geologiczna Polski 1:5000. Detailed Geological Map of Poland:* Geological Institute - Publishing House Wydawnictwa Geologiczne. (in Polish)

Golonka, J. & Ślączka, A., 2000: Geodynamic evolution stages of two orogens: the Carpathians and Ouachita Mts. *Slovak Geological Magazine*, vol. 6, p. 139-142.

Golonka, J. & Ślączka, A., 2003: Geodynamic evolution stages and climate changes in the Outer Carpathians. *Mineralia Slovaca*, vol. 35, p. 11-14.

Golonka, J., Oszczypko, N. & Ślączka, A. 2000: Late Carboniferous – Neogene geodynamic evolution and paleogeography of the circum-Carpathian region and adjacent areas. *Annales Societatis Geologorum Poloniae*, vol. 70, p. 107-136.

Golonka, J., Ślączka, A. & Picha F. 2003: Geodynamic evolution of the orogen: the West Carpathians and Ouachitas case studies. *Annales Societatis Geologorum Poloniae*, vol. 73, p. 145-167.

Golonka, J., Krobicki, M.,Oszczypko, N., Ślączka, A. & Słomka, T. 2003. Geodynamic evolution and palaeogeography of the Polish Carpathians and adjacent areas during Neo-Cimmerian and preceding events (latest Triassic - earliest Cretaceous). In: McCann, T. and Saintot, A. (Eds.): *Tracing tectonic deformation using the sedimentary record. Geological Society, London, Special Publications*, vol. 208, p. 138-158.

Golonka, J., Krobicki, M., Oszczypko, N., Słaby, E, Popadyuk, I. & Netchepurenko, A. 2004: Mesozoic volcanism associated with triple –junction zone of the Eastern Carpathians (Ukraine). *Mineralogical Society of Poland – Special Papers*, vol. 24, p. 45-50.

Haig, D.W. 1979: Global distribution patterns for mid-Cretaceous foraminiferids. *Journal of Foraminiferal Research*, vol. 9, p. 29-40.

Köhler, E. Salaj, J. & Buček, S. 1993: Paleogeographical development of the Myjava Sedimantary area (Western Slovakia) during the existence of the Paleocene reef complex. *Geologica Carpathica*, vol. 44, p. 373-380.

Kokoszyńska, B., 1949: Stratigraphy ofthe Lower Cretaceous in the Northern Flysch Carpathians. *Prace Państw. Inst. Geol.*, vol. 6, 99p. (in Polish)

Koszarski, L., 1968: Marginal zone of the Silesian Unit in the Valley of the River San. In. M. Książkiewicz, (ed.): Geology *of the Polish Flzsc Carpathians*, Inter. Geol. Congress XXIII session, Prague 1968, Guide to excur. C44, Poland, Geology of the Polish Flysch Carpathians. Geol. Inst., Warsaw, p. 46-51.

Kräutner, H. G., 1996: Alpine rifting, subduction and collision in the Romanian Carpathians.In: Amman, G., Handler, K.W. & Steyrer, H.P. (Eds.) *Abstr. VI Symposium für Tektonik Struktur- und Kristallingeologie)*. Salzburg Univ. Press., Salzburg. p. 230–234.

Krobicki, M. 1996: Neo-Cimmerian uplift of intraoceanic Czorsztyn pelagic swell (Pieniny Klippen Belt, Polish Carpathians) indicated by the change of brachiopod assemblages, *in* A. C. Riccardi, ed., Advances in Jurassic Research. *GeoResearch Forum*, vol. 1-2, p. 255–264.

Krobicki, M., Golonka, J., Lewandowski, M., Michalik, M., Oszczypko, N., Popadyuk, I. & Słaby, E. 2004:. Volcanism of the Jurassic-Cretaceous triple-junction zone in the Eastern Carpathians. *Geolines*, vol. 17, p. 60-61.

Krobicki, M. & Wierzbowski, A. 2004:. Pozycja stratygraficzna i paleogeograficzne znaczenie bajoskich wapieni krynoidowych w ewolucji pienińskiego basenu skałkowego (Stratigraphic position of the Bajocian crinoidal limestones and their palaeogeographic significance in evolution of the Pieniny Klippen Belt). *Tomy Jurajskie*, vol. 2, p. 69-82.

Krobicki M., Aubrecht, R. & Golonka, J. 2003: Pieniny Klippen Belt. In: Golonka, J. and Lewandowski, M. (Eds.): *Geology, geophysics, geothermics and deep structure of the West Carpathians and their basement. Publications of the Institute of Geophysics Polish Academy of Sciences. Monographic Volume*, vol. M-28 (363), p. 25-33.

Kruglov, S.S. 1989: Geodynamics of the Ukrainian Carpathians. *Geologica Carpathica*, vol. 40, 101-123.

Kruglov, S.S. 2001: *The Problems of tectonics and paleogeodynamics of Western Ukraine (a critical survey of the new publications).* Ukrainian Interdisciplinary Committee for Tectonics. Lvivol., 83 pp. (in Ukrainian).

Książkiewicz, M. 1951: Kreda Karpat Zewnętrznych. In: Książkiewicz, M. (Ed.): (in Polish), Karpaty, Stratygrafia, PTG, no. 1, p. 86 – 112. (in Polish).

Książkiewicz, M., 1960. Zarys paleogeografii polskich Karpat fliszowych. *Prace Instytutu Geologicznego*, vol. 30, p. 209-231. (in Polish).

Książkiewicz, M. 1968: Evolution structurale des Carpathes polonaises. *Mem. Soc. Geol. France*, vol. 42, p. 529-562.

Książkiewicz, M. 1977a: Hypothesis of plate tectonics and the origin of the Carpathians. *Annales Societatis Geologorum Poloniae*, vol. 47, p. 329–353.

Książkiewicz, M. 1977b: The tectonics of the Carpathians. In: Pożaryski, W. (Ed.): *Geology of Poland, vol. 4: tectonics.* Geological Institute. Warszawa. pp. 476-669.

Lashkevitsch Z. M., Medvedev A. P.,& Krupskiy Y. Z., 1995. *Tektonomagmatitcheskaya evolutsya Karpat; Tectonomagmatic evolution of Carpathians*, Naukovaya Dumka, Kiev. (in Russian).

Leszczyński S. 1981: Ciężkowice Sandstones of the Silesian Unit in Polish Carpathians: a study of Coarse-clastic sedimentation in deep-water. *Annales Societatis Geologorum Poloniae,* vol. 51, p. 435-502.

Lewandowski. M., Krobicki, M., Matyja, B. A.,& Wierzbowski, A. 2003: Palaeogeography and dynamics of the Eastern Pieniny Klippen Basin (Carpathians, Southwestern Ukraine) on the basis of palaeomagnetic data. In: Golonka, J. and Lewandowski, M. (Eds.): *Geology, geophysics, geothermics and deep structure of the West Carpathians and their basement. Publications of the Institute of Geophysics Polish Academy of Sciences. Monographic Volume*, vol. M-28 (363),p. 137-142.

Maheľ, 1974. The Inner Carpathians. In: Maheľ, M. (Ed.): *Tectonics of the Carpathian-Balkan regions.* GUDŠ Bratislav, pp. 91-133.

Malik, K., 1986. Turbidite facies and fan-facies associations in the Cieszyn Limestones Upper Tithonian-Berriasian, Northwestern Carpathians, Poland. In: Teisseyre, A.K. (Ed.): *7-th European Regional Meeting Excursion Guidebook.* Kraków-Poland. Ossolineum, Wrocław, p. 53-66.

Matyszkiewicz J. & Słomka T. 2004: Reef-microencrusters association *Lithocodium aggregatum – Bacinella irregularis* from the Cieszyn Limestone (Tithonian - Berriasian) of the Polish Flysch Carpathians. *Geol Carpathica*, vol. 55, p. 211-248

Matyszkiewicz J. & Słomka T., 1994: Organodetrital conglomerates with ooids in the Cieszyn Limestone (Tithonian-Berriasian) of the Polish Flysch Carpathians and their palaeogeographic significances. *Annales Societatis Geologorum Poloniae,* vol. 63, p. 211-248.

Menčík, E. (Ed..) 1983: *Geologie Moravskoslezskych Beskyd a Podbeskydske pahorkatiny.* Ust. geol., Praha, 304 p.

Mišík, M. 1994: The Czorsztyn submarine ridge (Jurassic-Lower Cretaceous, Pieniny Klippen Belt): an example of a pelagic swell. *Mitteilungen Österreichen Geologische Gesselschaft*, vol. 86, p. 133-140.

Michalík, J. & Reháková, D. 1995: Sedimentary records of Early Cretaceous tectonic activity in the Alpine-Carpathian region. *Slovak Geological Magazine*, vol. 2, p. 159-164.

Michalík, J., Reháková, D. & Jablonský, J. 1996: Geodynamic setting of fluxoturbidites in West Carpathian Upper Jurassic and Lower Cretaceous sedimentary basins. *Slovak Geological Magazine*, vol. 3-4, p. 325-329.

Michalík, J., Reháková, D. & Vašícek, Z. 1995: Early Cretaceous sedimentary changes in West-Carpathian area. *Geologica Carpathica*, vol. 46 (5), p. 285-296.

Moshammer, B. & Schlagintweit, F. 1999: The Ernstbrunn Limestone (Lower Austria): New data on Biostratigraphy and Applied Geology. *Abh. Geol. B.-A.* vol. 56, p. 553-565.

Narębski, W. 1990: Early rift stage in the evolution of western part of the Carpathians: geochemical evidence from limburgite and teschenite rock series. *Geologicky Zbornik - Geologica Carpatica*, vol. 41, p. 521-528.

Olszewska B. & Szydło A., 2004: Anoxic episodes in the Polish Outer Carpathians in view of micropaleontological research. CAG PIG OK Krakow. (in Polish): 1-20.

Olszewska, B.,& J. Wieczorek, 2001: Jurassic sediments and microfossils of the Andrychow Klippes (Outer Carpathians). *Geologica Carpathica*, vol. 52, p. 217–228.

Oszczypko N. 1992: Late Cretaceous through Paleogene evolution of Magura Basin. *Geologica Carpathica*, vol. 43, p. 333-338.,

Oszczypko N., Golonka J., Malata T., Poprawa P., Słomka T.& Uchman A. 2003: Tectono-stratigraphic evolution of the Outer Carpathian basins (Western Carpathians, Poland). *Mineralia Slovaca*, vol.35, p. 17-20.

Oszczypko, N. 1998: The Western Carpathian Foredeep – Development of the Foreland Basin in Front of the Accretionary Wedge and its Burial History (Poland). *Geologica Carpathica*, vol. 49, p. 415-431.

Oszczypko, N., Golonka, J. Malata, T., Poprawa, P., Słomka T.& Uchman, A., 2003: Tectono-stratigraphic evolution of the Outer Carpathian basins (Western Carpathians, Poland). *Mineralia Slovaca*, vol. 35, p. 17-20.

Oszczypko, N., Malata, E., Švábenická, L., Golonka, J., & Marko, F. 2004: Jurassic-Cretaceous controversies in the Western Carpathian Flysch: the "black flysch" case study. *Cretaceous Research*, vol. 25, p. 89-113

Peszat, C., 1967: The lithological development and conditions of sedimentation of the Cieszyn Limestones. *Prace Geologiczne, Oddział PAN Kraków*, vol. 44, p. 1-111.

Pickering, K.T., Stow, D., Watson, M. & Hiscott, R. 1986: Deep-water facies, processes and models: a review and classification scheme for modern and ancient sediments. *Earth Science Review*, vol. 23, p. 75-174.

Plašienka, D. 1999: *Tektonochronológia a paleotektonický model jursko-kriedového vývoja centrálnych Západných Karpát. Tectonochrology and Paleotectonic model of the Jurassic – Cretaceous evolution of the Central Western Carpathians.* Veda, Bratislava, 127 pp. (in Slovak)

Plašienka, D., 2003: Dynamics of Mesozoic pre-orogenic rifting in the Western Carpathians. Mitt. Österr. Geol. Ges., 94 (2001), 79-98.

Poprawa P., Malata T. & Oszczypko N. 2002: Ewolucja tektoniczna basenów sedymentacyjnych polskiej części Karpat zewnętrznych w świetle analizy subsydencji. *Przegl. Geol.*, vol. 50, p.1092-1105.

Poprawa, P., Malata, T., Pécskay, Z., Banaś, M., Skulich, J. & Paszkowski, M. 2004: Paleografia oraz ewolucja tektoniczna zachodnich Karpat zewnętrznych – wstępne przesłanki z datowań K/Ar skał podłoża krystalicznego obszarów źródłowych dla fliszu. *VIII Ogólnopolska Sesja Naukowa – Datowanie minerałów i skał*; Kraków, 18-19 listopada 2004 r.: 107-114.

Potfaj M. 2002: *The saddle between Haligovce and Lesnica.* Guide to geological excursions. XII th Congress Carpath.-Balkan Geol. Assoc., Bratislava, Slovak Republic, Bratislava: appendix

Rajchel, J. & Myszkowska, J. 1998: Exotic clasts of organodetritic algal limestones from lithosomes of the Babica Clay, Skole Unit (Outer Flysch Carpathians, Poland). *Annales Societatis Geologorum Poloniae*, vol.68, p.225-235.

Rakús, M., Mišík, M., Michalík, J., Mock, R., Ďurkovič, T., Koráb, T., Marschalko, R., Mello, J., Polák, M. & Jablonský, J. 1988: Paleogeographic development of the West Carpathians: Anisian to Oligocene. *Mémoire Societe Géologique France, Nouvol. Série*, No. 154, vol. III, p. 39-62.

Reháková, D. & Michalík, J. 1992: Correlation of Jurassic/Cretaceous boundary beds in West Carpathian profiles. *Földtani Közlöny*, vol. 122, p. 51-66.

Samuel, O, Borza, K., & Köhler, E. 1972: *Microfana and Stratigraphy of the Paleogene and djacent Cretaceous of the Middle Váh Valley.* GÚDŠ, Bratislava. 246 p.

Săndulescu, M. 1988: Cenozoic Tectonic History of the Carpathians, In: Royden, L. & Horváth, F. (Eds.): *The Pannonian Basin: A study in basin evolution. AAPG Memoir*, vol. 45. p. 17–25.

Schlagintweit, F. & Ebli, O. 1999: New results on microfacies, biostratigraphy and sedimentology of Late Jurassic - Early Cretaceous platform carbonates of the Northern Calcareous Alps. Abh. *Geol. B.-A.* vol. 56, p. 379-418.

Schlagintweit F. & Gawlik H.-J. 2003: Mikrobolithe und Mikroinkrustierer aus der Plassen-Formation (Kimmeridgium-Berriasium) der Nördlichen Kalkalpen. In: Weidinger, J. T., Lobitzer, H. & Spitzbart, I. (Eds.): *Beiträge zur Geologie des Salzkammerguts,* Gmunder Geo-Studien 2, Gmunden, p. 107-114.

Ślączka, A. 1969: Final stages of the geosynclinal development in the SE part of the Polish Carpathians. *Acta Geologica, Acad. Sci. Hungaricae*, vol. 13, p. 331-335.

Ślączka, A. 1961: Exotic-bearing shale from Bukowiec (Polish Eastern Carpathians). *Annales Societe Geologique de Pologne*, vol. 61, p. 129-143.

Ślączka, A. & Walton, E.K. 1992: Flow characteristic of Metressa: an Oligocene seismoturbidite in the Dukla Unit, Polish Carpathians. *Sedimentology*, vol. 39, 383-392.

Ślączka, A. & Kaminski, M.A. 1998: Guidebook to Excursions in the Polish Flysch Carpathians. Grzybowski Foundation Special Publication No 6, Kraków, 171pp.

Ślączka, A. 1971: Geology of the Dukla unit. *Prace Instytutu Geologicznego*, vol. 1, p. 1-63 (in Polish with English summary).

Słomka T. 1986: Statistical approach to study of flysch sedimentation – Kimmeridgian-Hauterivian Cieszyn Beds, Polish Outer Carpathians. *Annales Societatis Geologorum Poloniae*, vol. 56, p. 227-336.

Słomka T. 2001: Early Cretaceous debris flow deposits in the Cieszyn Beds of the Żywiec region (Carpathians, Poland),. *Kwart. AGH – Geol.*, vol. 27, p. 89-110. (In Polish, English summary).

Słomka, T. & Krobicki, M. 2000: Syn-rift debris flow deposits (Tithonian-Valanginian) in the northernmost Western Tethys (Cieszyn Beds of the Polish Flysch Carpathians). *IAS Regional Meeting; Dublin Ireland; 13-15 September 2000*, p. 140-141.

Soták, J. Biroň, A., Prokešová, R. & Spišiak, J. 2000: Detachment control of core complex exhumation and back-arc extension in the East Slovakian Basin. *Slovak Geol. Mag.* vol. 6, p.130-132.

Stránik, Z., Dvořák, J., Krejčí, O. Muller, P., Přichystal, A. Suk, M. & Tomek, C. 1993: The contact of the North European Platform with the West Carpathians, *Journal of the Czech Geol. Societ. (Prague)*, vol. 38, no. 1-2, p. 21-29.

Unrug R. 1963: Istebna beds – a fluxoturbidity formation In the Carpathian Flysch. *Rocz. Pol.Tow.Geol.*, vol. 33, p. 49-92.

Vašícek, Z., Michalík, J. & Reháková, D. 1994: Early Cretaceous stratigraphy, paleogeography and life in Western Carpathians. *Beringeria*, vol. 10, p. 1-170.

Varitchev, A. 1997: Major and trace element geochemistry of Mesozoic igneous formation of the Ukrainian Carpathians as an indicator of paleotectonic settings. *Prz. Geol.*, vol. 45, p. 1109-1110.

Wierzbowski, A. & Remane, J. 1992: The ammonite and calpionellid stratigraphy of the Berriasian and lowermost Valanginian in the Pieniny Klippen Belt (Carpathians, Poland). *Eclogae geologicae Helvetica*, vol. 85, p. 871-891.

Wierzbowski, A., Jaworska, M.& Krobicki, M. 1999: Jurassic (Upper Bajocian-lowest Oxfordian) ammonitico rosso facies in the Pieniny Klippen Belt, Carpathians, Poland: its fauna, age, microfacies and sedimentary environment. *Studia Geologica Polonica*, vol. 115, p. 7-74.

Winkler, W., Ślączka, A. 1994: A Late Cretaceous to Paleogene Geodynamic Model for the Western Carpathians in Poland. *Geologica Carpathica*, vol.45, p. 71-82.

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The Pieninic exotic cordillera (Andrusov Ridge) revisited: new zircon FT ages of granite pebbles from Cretaceous flysch conglomerates of the Pieniny Klippen Belt (Western Carpathians, Slovakia)

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Abstract. We have studied granitoid pebbles from Cretaceous flysch conglomerates of the Pieniny Klippen Belt by means of fission-track (FT) measurements on zircon grains with the aim to reveal their low-temperature thermal history. This study contributes to the elucidation of provenance and source areas of granitoids that have been regarded as "exotic" for many decades. First data from our samples provide zircon FT ages that are close to the depositional ages of host conglomerates. The central age of one granite sample from the Albian – Cenomanian conglomerates of the Klape unit is 92.1±6.0 Ma, ten samples of the Coniacian – Santonian conglomerate pebbles from the Kysuca and/or Klape unit provided ages ranging from 89.5±7.2 to 120.8±8.8 Ma. The very short time lag of the cooling ages relative to the depositional ages of conglomerates, as well as large sizes of granitoid and various other clasts and synorogenic, thickening- and coarsening-upward character of conglomerate-bearing wildflysch formations collectively indicate that this source area was an actively deforming, exhuming and rapidly eroding mountain range with a complex geological structure.

Key words: Western Carpathians, Pieniny Klippen Belt, Cretaceous conglomerates, granite pebbles, zircon, fission-tracks

Introduction

The Pieniny Klippen Belt (PKB) is a prominent Western Carpathian tectonic structure, which separates the External Western Carpathians (EWC – the Flysch Belt), representing the Tertiary accretionary complex, from the Central Western Carpathians (CWC) that originated by Cretaceous crustal shortening and nappe stacking. The PKB is an almost 600 km long and only several kilometres wide zone with intricate tectonic structure (Fig. 1). It comprises sedimentary rock complexes of Jurassic to Tertiary age, which are affiliated to numerous tectonic and stratigraphic units. Some of these units, the Klape unit in particular, involve Cretaceous conglomerate-bearing flysch complexes traditionally treated as "exotic".

The exotic, so-called Upohlav conglomerates occur in two stratigraphic levels: Upper Albian – Lower Cenomanian, referred to as the conglomerate age Group I in the following text, and Coniacian – Lower Campanian (Group II conglomerates). These conglomerate complexes are separated by the Upper Cenomanian – Lower Turonian shallowing-upward sequence of thick-bedded sandstones with tempestites and oyster banks (Orlové sandstones) in the Klape unit. The conglomerates have a very variegated composition with numerous rock types, which were thoroughly studied and described e.g. by Mišík et al. (1977, 1980, 1981, 1991), Mišík & Sýkora (1981), Marschalko (1986), Mišík & Marschalko (1988), Birkenmajer et al. (1990), Faryad & Schreyer (1996), Faryad (1997). Besides many common rock types, the most noticeable exotic material are basinal Triassic limestones, Upper Jurassic platform limestones, Urgonian limestones with serpentinite clasts, Permian A-type granites with Lower Cretaceous FT cooling ages (Uher & Pushkarev, 1994; Kissová et al., 2004 and the present paper), large amount of calc-alkaline volcanics of uncertain age (Permian, Upper Jurassic/Lower Cretaceous?), Upper Jurassic glaucophanites (Dal Piaz et al., 1995), prevailing Cr-spinels in heavy mineral spectra (Mišík et al., 1980; Jablonský et al., 2001) etc. To explain the source of these exotic clasts, which do not occur in primary position in the PKB and neighbouring zones at all, the concept of a temporarily active Cretaceous "exotic ridge", "Klape ridge", or "Pieniny (ultra-Pieninic) cordillera" was developed many decades ago. Birkenmajer (1988) renamed this structure as the Andrusov Ridge in honour of Dimitrij Andrusov, the prominent Carpathian geologist and ever-best expert in geology of the PKB.

After the advent of plate tectonic theory, the exotic ridge has been interpreted as a compressional tectonic structure in an active margin setting – imbrications of obducted oceanic material or subduction mélange transiently outcropped along the outer structural high of an accretionary paleoprism (Mišík, 1978; Mišík & Marschalko, 1988), subduction complex exhumed in the rear part of the South Penninic – Vahic accretionary wedge (Klape unit – Maheľ, 1989), or a magmatic island arc

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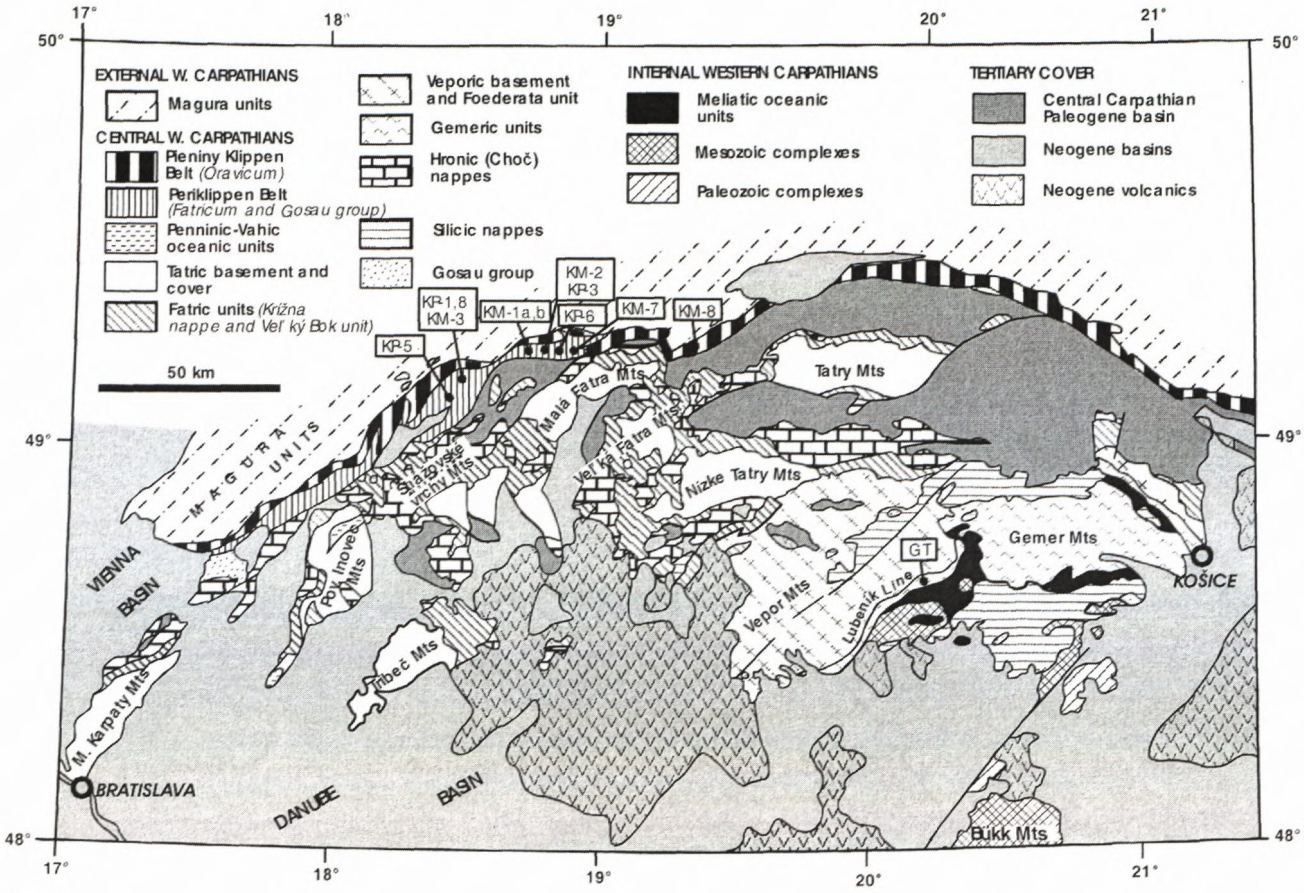

Fig. 1. Tectonic sketch of the Western Carpathians and sample location. GT marks the position of a reference sample from the Gemeric Turčok A-type intrusive granite body mentioned in the text.

(Birkenmajer, 1988). Exotic pebble material would indicate Triassic opening of the corresponding oceanic basin and its Late Jurassic – Early Cretaceous closing (e.g. Birkenmajer, 1988; Dal Piaz et al., 1995). However, this concept is in a severe contradiction with the geological record of all other PKB and neighbouring units, where no such events can be documented. On the other hand, these events surely occurred in the southern Western Carpathian zones, where they were associated with opening and closing of the Meliata ocean.

The granitoid pebbles belong to several types; the exotic character was mainly ascribed to the "Upohlav" granites with A-type petrochemical characteristics (Uher & Marschalko, 1993; Uher et al., 1994), which do not occur in potential source areas of the presently adjacent units at all. U-Pb zircon dating revealed their Permian crystallization age (274±13 Ma – Uher & Pushkarev, 1994). Similar granite pebbles were also found in the "Cenoman Randschuppe" – the most external subunit of the Northern Calcareous Alps (Frasl & Uher, 1996). Based on whole-rock K-Ar data, these granites experienced a Late Jurassic – Early Cretaceous thermal event, originally considered as an intrusion age (Marschalko, 1986; Birkenmajer, 1988 and references therein). Until now, the lower temperature thermochronological data like the fission-track (FT) zircon and apatite ages were nearly missing from the granite pebbles, as well as from the entire PKB. However, they are essential for constraining the late thermal history and cooling path of the source area and for evaluating its possible location.

The aim of our study is to identify the paleotectonic position of the source areas of the granitoid pebbles and to elucidate their exhumation histories using the zircon FT thermochronology. We classify the petrological type of granitoids from the point of view of their petrography, bulk chemistry, REE characteristics and morphology of zircon crystals. Then we employ our geochemical data and obtained zircon FT ages to discuss the provenance and possible tectonic scenarios of uplift and exhumation of the source area.

Sample location

Conglomerates with "exotic" granitoid pebbles occur in two stratigraphic levels in several units of the PKB. As it was recognized in the middle Váh valley of western Slovakia, Albian to Lower Cenomanian conglomerates (Group I – Fig. 6) are exclusively restricted to the Klape unit. On the other hand, Coniacian to Santonian conglomerates (Group II), in addition to the Klape unit, are found also in the Manín and Kysuca units. However, the stratigraphic age of some conglomerate bodies is not quite clear. This applies particularly to the Stupné locality, which according to Marschalko (1986) belongs to the

Tab. 1. Codes and coordinates of localities and sample characteristics. P – single pebble samples, MP – collection of 20 small pebbles of the same phenotype.

Code	Locality	Latitude	Longitude	Conglomerate age group	Character of samples	Petrography
KP-5	Dubový Háj	18° 21' 50"	49° 07' 20"	I	P	granite
KM-8	Oravský Podzámok	19° 21' 26"	49° 15' 24"	II	MP	granite
KP-1	Stupné	18° 25' 32"	49° 11' 37"	II	P	granite
KM-3	Stupné	18° 26' 15"	49° 11' 55"	II	MP	granite
KP-8	Stupné	18° 26' 15"	49° 11' 55"	II	P	granite
KM-1a	Divinka	18° 41' 54"	49° 15' 27"	II	MP	granite
KM1-b	Divinka	18° 41' 54"	49° 15' 27"	II	MP	granite
KM-2	Považský Chlmec	18° 44' 16"	49° 14' 49"	II	MP	granite
KP-3	Kysuca – rieka	18° 44' 21"	49° 14' 36"	II	P	granite
KP-6	Zádubnie	18° 46' 24"	49° 14' 29"	II	P	granite
KM-7	Zástranie	18° 49' 15"	49° 14' 50"	II	MP	granite

Coniacian – Santonian conglomerates of the Kysuca unit, while Salaj (1994) ranged it to the Albian – Cenomanian conglomerates of the Klape unit. We follow the opinion of Marschalko (1986) and assign our Stupné samples to the Group II conglomerates. Our sampling strategy was to study granitoid pebbles from conglomerates of both age groups to be able to reconstruct evolution of the source areas. Therefore, we collected samples from the Group I conglomerates of the Klape unit in the Púchov sector of the PKB (Dubový Háj, Upohlav) and the Group II conglomerates of the Kysuca unit in the Púchov, Varín and Orava sectors of the PKB (Stupné, Divinka, Považský Chlmec, Zádubnie, Zástranie, Oravský Podzámok). We assembled two types of samples from conglomerates: single large pebbles or population of 20 smaller pebbles of the same lithological phenotype to obtain enough material for analytical studies. The sampling localities are shown in Fig. 1 and characterized in Tab. 1.

Analytical procedure

The samples weighed 5 to 7.5 kg. Thin-sections from all samples were studied under optical microscope for the petrographical description and planimetry. The rest of the samples was prepared with the routine procedure including crushing and pulverizing of 30 g of single pebble samples. This powder was used for whole rock analysis by ICP MS carried out in laboratories of ACME Lab. (Vancouver, Canada). The rests of crushed samples were sieved (0.400 μm) and concentrated using Wilfleys' table and dried at room temperature. Further procedures included heavy liquid separation in bromoform and Na-polytungstate (>2.93 g/cm^3), magnetic separation (isodynamic magnetic separator COOK) and hand picking for determination of external zircon morphology. Scanning electron microscope was used for zircon typology. All these procedures were realized in the laboratories of the Geological Institute SAS, Bratislava.

Sample preparation for irradiation included mounting of the zircon crystals into PFA Teflon, polishing and etching. We were using grinding paper (1200 and 2500) and polishing diamond suspensions of different grain size (9 μm, 3 μm, 1 μm). The etchant for the zircon mounts was KOH-NaOH eutectic liquid used at 215 °C for 51 to 89 hours. After etching every mount was covered with flakes of low-U muscovite from India, packed using foam, polyethylene and Parafilm M and irradiated in the nuclear reactor of Oregon State University, USA. Standard of a known age (Fish Canyon Tuff and Tardree Rhyolite) and CN2 glass dosimeters with known uranium concentration were included in the sample package for irradiation and used for the calculation of a personal ζ-value (123±5.7). This part of preparation was realized in the laboratories of the University of Tübingen, Germany.

All fission track age standards and samples were counted using the same microscope setup (Zeiss Axioscope, 1000x magnification using immersion oil). The data were evaluated by the software Trackkey (Dunkl, 2002). This part of work was realized at the University of Göttingen, Germany.

Results

Petrography

Most of our pebble samples represent the Upohlav-type exotic granites as they were described by Uher et al. (1994). Granites are leucocratic, medium- to fine-grained, usually with pink, often porphyric K-feldspar. Based on petrography from thin sections and planimetrical study, the mineral composition includes quartz (Qtz) 26–40%, K-feldspar (Kfs) 34–58%, plagioclase (Pl) 6–34%, biotite (Bt) 2–13%, muscovite (Ms) <2% and subordinate microcline and epidote (Ep) <1%. Quartz is present in various forms, but always is undulating, sometimes with polygonal texture. Feldspars form euhedral and subhedral porphyric grains, typically with perthitic texture. Some feldspars are hyposolvus (Stupné, Oravský Podzámok). This feature is characteristic for the mantle-derived granites (Pupin, 1980). Sometimes poikilitic feldspar blasts (including plagioclase and quartz grains) and myrmekites were observed. Among the accessory minerals, we observed zircon, allanite-Ce and magnetite. Secondary min-

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erals are present in every sample, represented especially by frequent fine-crystalline white mica ("sericite", mainly in cores of feldspar grains) and chlorite (after biotite). Secondary carbonates and quartz veins were observed very rarely.

For the majority of pebbles the QAP diagram (Fig. 2) reveals the trend of alkaline granites, two samples match the common granite suite. The area (3a) represents syenogranite (mineral composition: Qtz 26 %, Pl 19 %, Kfs 41 %, Bt 12 %, Ms 2 % – sample from Oravský Podzámok). Another field (3b) defines the monzogranite area (one sample from the Zástranie locality, its mineral composition is: Qtz 30 %, Pl 34 %, Kfs 34 %, Bt 2 %, Ms 0.2 %).

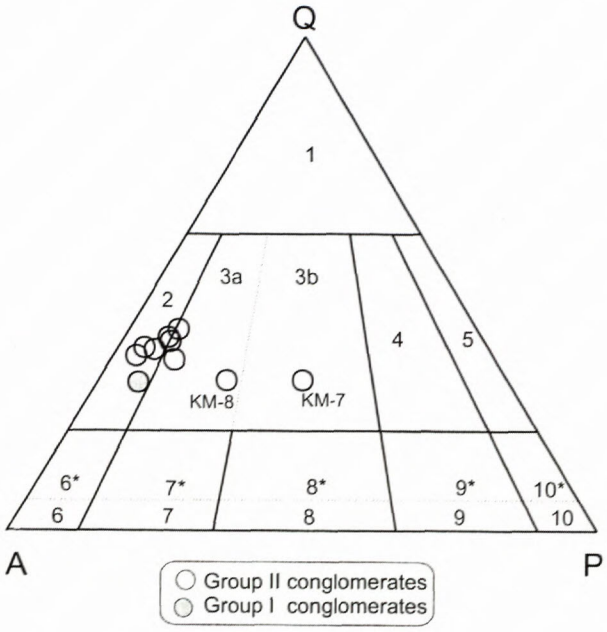

Fig. 2. Classification of granitoid pebbles according to the QAP diagram (Streckeisen & Le Maitre, 1979), the plots of investigated samples are indicated by small circles.
1 – quartzrich granitoides, 2 – alkali-granite, 3a,b – granite, 4 – granodiorite, 5 – tonalite, 6 – alkalifsp.-syenite, 7 – syenite, 8 – monzonite, 9 – monzodiorite, 10 – diorite.

Geochemistry

Detailed geochemical characterisation of the granitoid pebbles from Cretaceous flysch conglomerates of the PKB was first presented by Uher et al. (1994). We supplement their results by four analyses from three localities: Stupné (KP-1, KP-8), Kysuca – rieka (KP-3) and Zádubnie (KP-6). The whole-rock analyses of single-pebble samples are presented in Tab. 2.

The samples from all localities have a higher content of SiO_2 (70.7–75.2 wt %). Three samples have average of Na_2O 3.5 wt %, Zádubnie has a very low Na_2O content 0.09 wt %. Similar situation is with K_2O, average contents are 5.0 wt %, Zádubnie has 6.5 wt %. Content of CaO is less than 1.1 wt %, only Zádubnie includes slightly more CaO (1.5 wt %). Ba content varies considerably: the Stupné localities have 420–550 ppm, Zádub-

Tab. 2. Chemical compositions of the PKB granitoid pebbles.

		Stupné KP-1	**Stupné** KP-8	**Kysuca - river** KP-3	**Zádubnie** KP-6
SiO_2	%	74,15	73,92	70,73	75,26
Al_2O_3	%	13,16	13,12	14,15	11,69
Fe_2O_3	%	1,58	1,87	3,22	1,2
MgO	%	0,19	0,12	0,47	0,67
CaO	%	0,61	1	1,14	1,46
Na_2O	%	3,61	3,57	3,64	0,09
K_2O	%	4,96	5,08	4,57	6,46
TiO_2	%	0,13	0,14	0,31	0,11
P_2O_5	%	< .01	0,01	0,07	0,01
MnO	%	0,01	0,03	0,04	0,01
Cr_2O_3	%	< .001	< .001	< .001	< .001
Ba	ppm	415	548	977	153
Ni	ppm	< 20	< 20	< 20	< 20
Sc	ppm	10	8	14	4
LOI	%	1,4	0,9	1,4	3
TOT/C	%	0,12	0,18	0,11	0,37
TOT/S	%	0,01	< .01	0,02	0,02
SUM	%	99,85	99,82	99,85	99,97
Co	ppm	1,5	1,2	2,8	0,9
Cs	ppm	2,8	9,9	3,1	4,8
Ga	ppm	22,3	22,4	21,7	19,2
Hf	ppm	7,2	8	9,2	7,2
Nb	ppm	15,3	17,4	16,8	19,4
Rb	ppm	182,3	205,1	176,6	231,4
Sn	ppm	4	5	5	3
Sr	ppm	19,6	31,7	83,3	34,4
Ta	ppm	1,1	1,3	1,3	1,4
Th	ppm	20,4	18,8	17,1	20,1
U	ppm	2,7	2,6	3	3,1
V	ppm	< 5	< 5	16	< 5
W	ppm	9,9	9,1	7,8	6,8
Zr	ppm	225,6	266,5	316,4	214,3
Y	ppm	45,3	46	38,3	58,6
La	ppm	42,5	55,2	44,9	33,1
Ce	ppm	107,4	135,1	113,8	94,9
Pr	ppm	12,73	15,74	13,39	10,95
Nd	ppm	48,2	59,6	51,5	43,2
Sm	ppm	9,2	10,9	9,4	8,2
Eu	ppm	0,78	0,85	1,43	0,22
Gd	ppm	7,87	8,7	8,19	8,07
Tb	ppm	1,25	1,41	1,25	1,51
Dy	ppm	7,44	7,9	7,46	9,54
Ho	ppm	1,3	1,35	1,24	1,68
Er	ppm	3,91	3,95	3,89	5,53
Tm	ppm	0,62	0,6	0,57	0,78
Yb	ppm	4,28	4,5	4,35	5,54
Lu	ppm	0,61	0,61	0,56	0,75
Mo	ppm	0,1	0,2	0,1	< .1
Cu	ppm	10,2	1,5	4,8	0,5
Pb	ppm	4,7	14,5	11,1	1,8
Zn	ppm	22	63	52	6
Ni	ppm	1,8	0,5	2,4	0,5
As	ppm	1,7	2,4	1,5	2,4
Cd	ppm	< .1	< .1	< .1	< .1

		Stupné KP-1	Stupné KP-8	Kysuca - river KP-3	Zádubnie KP-6
Sb	ppm	0,2	0,2	0,2	0,1
Bi	ppm	< .1	0,1	< .1	< .1
Ag	ppm	< .1	< .1	< .1	< .1
Au	ppb	0,8	< .5	< .5	< .5
Hg	ppm	0,01	0,01	0,02	0,01
Tl	ppm	0,2	0,3	0,4	< .1
Se	ppm	< .5	< .5	< .5	< .5

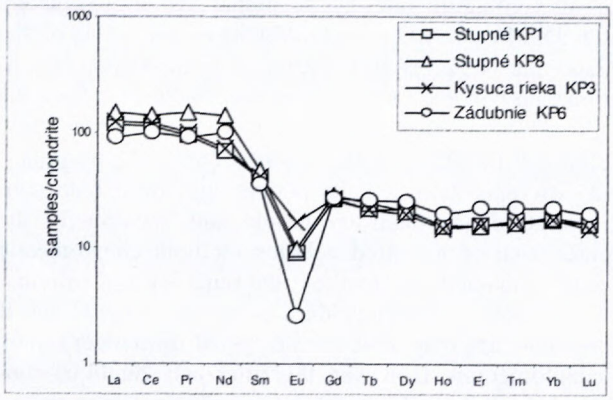

Fig. 3. Chondrite-normalized REE patterns of analysed granite samples.

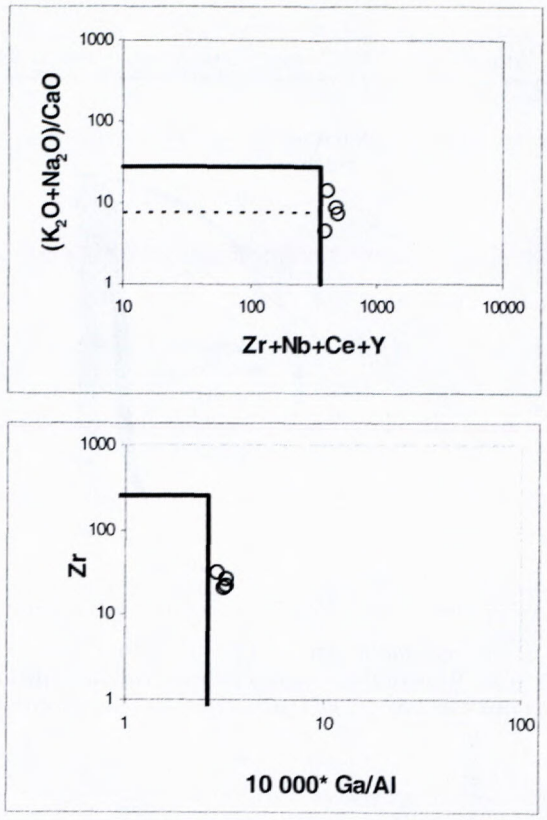

*Fig. 4. a – Zr+Nb+Ce+Yb versus (K_2O+Na_2O)/CaO diagram of A-type granites and unfractionated M-, I-, and S-type granites. Co-ordinates of these fields are X=350, Y=28 (Whalen, 1987). b – 10 000 * Ga/Al versus Zr diagram of A-type granites in comparison with common ISM granites. Coordinates: X=2.6, Y=250 (Whalen et al., 1987). Our analysed granitic pebbles are shown by circles that plot in the A-type granite field.*

nie 153 ppm, but Kysuca – rieka has an elevated content 977 ppm Ba. The reason may be secondary barite, it will be checked by the microprobe. Stupné and Zádubnie have low Sr concentration of 20–35 ppm. However, the Sr value is twice higher in the Kysuca – rieka locality – 83.3 ppm.

The rate of Eu anomaly can be quantified. The values less than 1.0 indicate negative anomaly (Rollinson, 1993), which is a typical feature for less fractionalised A-type granites and this is also our case. Our data are less than 0.35, only the Kysuca – rieka sample has a little bit higher value 0.5. Studied granite pebbles have characteristic chondrite-normalized REE patterns with significant negative Eu anomalies (0.28 to 0.5), which is a typical feature for less fractionalised A-type granites and this is also our case (Collins et al., 1982; Whallen et al., 1987 – Fig. 3). The samples are enriched in LREE (light rare earth elements). A steepness of LREE curve is determined by the La/Sm relationship. This value is usually more that 1.0, for A-type granites it is around 3.0. Our La/Sm ratios range between 2.5 and 3.18 in all samples. A-type granites are HREE (heavy rare earth elements) depleted, compared to LREE. This relationship is also characterised by steepness of the curve. It is determined by the Gd/Yb ratio, the optimal value is around 1.0–1.2. Our samples provided values 1.2–1.6 (Rollinson, 1993).

Zr+Nb+Ce+Yb vs. (Na_2O+K_2O)/CaO and Zr vs. Ga/Al diagrams (Whallen et al., 1987; Fig. 4 a, b) were used for determination of the petrochemical type of granites. All our samples clearly fall into the A-type granites field. As a result, these geochemical characteristics confirm that they are post-orogenic A-type granites, according to the recent classification and knowledge (Whalen et al., 1987).

Zircon typology analysis

The typological study of zircon population (Pupin 1980, 1988) from granitic rocks resulted in the proposition of a genetic classification with three main divisions: (1) granites of crustal or mainly crustal origin; (2) granites of crustal-mantle origin, hybrid granites; (3) granites of mantle or mainly mantle origin. This method may indicate geochemical and geotectonic magma type, its relation to the orogen and indirectly characterizes the geotectonic situation in the time of intrusion (Pupin, 1980).

According to studies of Broska & Uher (1991, 2003), the Western Carpathian granitoids belong to several distinctive groups that follow the Pupin's classification (Fig. 5). All of our granite pebbles (10 samples) belong to the field of Variscan post-orogenic A-type granites (Fig. 5). The D zircon subtype (>40 %) and P_5 (20–40 %) dominates, but P_{4-3} and J_{5-4} subtypes are also present (5–10 %). Very rarely S_{25-24} subtype crystals were found (<2 %). The relatively high A- and T-indices point to a hot and dry granitic magma probably of mantle origin (Pupin, 1980),

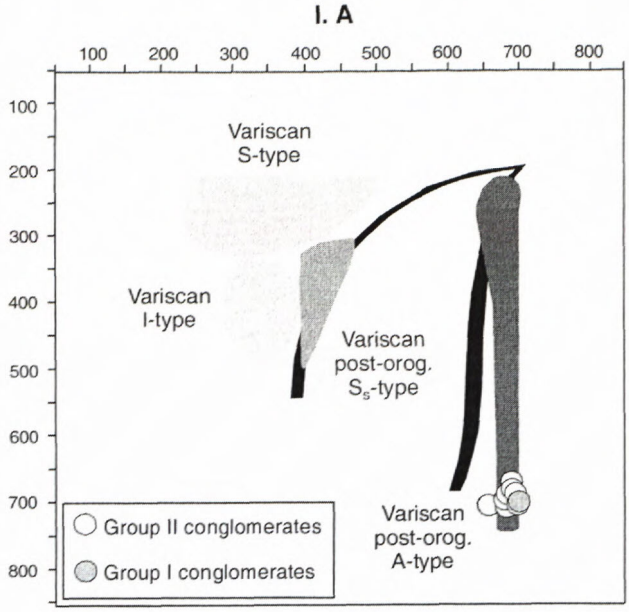

Fig. 5. Zircon typology diagram (Pupin, 1980). Characteristic fields of the Western Carpathian Variscan granitoids are taken from Broska & Uher (2003), our examined samples are indicated by circles that fall in the post-orogenic A-type granite field.

which produced hypersolvus granites with characteristic string perthites in our samples. The P and D types are common in alkaline rock (Pupin, 1980), especially in A-type granites. These alkaline and hyperalkaline granites are usually found in subvolcanic bodies of anorogenic magmatic complexes. Our observations are consistent with the first typological analyses of zircons from Upohlav-type granites, granite porphyries and rhyolites performed by Uher & Marschalko (1993).

The granitic rocks with similar zircon typologies have been described in the Western Carpathians only from a small intrusive body near Turčok (northern boundary of the Gemeric superunit – Uher & Gregor, 1992; Uher & Broska, 1996; our own unpublished data; cf. Fig. 1). As far as the zircon typology is considered, another analogous, late- to post-Variscan leucocratic, higher-alkaline granites and granite porphyries occur in the Velence Mts. (Transdanubian Range) in northern Hungary (Gbelský & Határ 1982, Uher & Broska 1996). Very similar zircon typology distribution is generally characteristic for Permian alkaline granites and rhyolites of the Western Mediterranean province, e.g. in Corsica (Pupin 1980, 1988).

Zircon FT measurements

We have analysed altogether 16 zircon concentrates from 15 granitoid pebble samples for fission-tracks. However, some samples provided not enough zircon grains, or the zircons were metamict and not suitable for FT measurements. At least 18 measured grains from single-pebble samples and 50 grains from multi-pebble samples were taken as the lowest limits for FT calculations. The inconvenient samples came mostly from other types of granitoids than A-types, therefore our whole discussion is focused on the measured A-type granitoids that yielded reliable results. The resulting calculated FT ages and measurement conditions of 11 trustworthy samples are presented in Tab. 3. Zircon FT ages of granitoid pebbles compared to the sedimentary age ranges of respective conglomerate groups are then summarized in Fig. 6.

Discussion

FT ages and erosion rates

Our data show zircon FT ages that are not very much different from the depositional ages of respective conglomerates. The cooling age of a granite sample from the Group I conglomerates (depositional age approximately 105–95 Ma according to Gradstein et al., 2004) of the Klape unit is 92.1±6.0, ten samples of the Group II conglomerate pebbles (depositional age 90–80 Ma) from the Kysuca and/or Klape unit provided ages ranging from 120.8±8.8 to 89.5±7.2 Ma. There seems to be no principal difference between the pebble ages from both conglomerate depositional age groups and, accordingly, the source area of granitoid pebbles for both conglomerate groups remained apparently at the same level of exhumation, or more probably pebbles occurring in the Group II conglomerates may have been recycled from older Group I conglomerates. However, this inference should be confirmed by additional data from Group I conglomerates.

The mid-Cretaceous FT zircon ages from the exotic granitoids are younger than and thus consistent with the Valanginian to Aptian (140 to 115 Ma) whole-rock K-Ar ages of granitoid clasts and associated volcanic rocks (Rybár & Kantor, 1978 and references in Mišík & Sýkora, 1981; Marschalko, 1986; Birkenmajer, 1988). These K-Ar ages likely correspond to exhumation and associated cooling from mid-crustal levels, thus this event might indicate crustal shortening and basement nappe stacking. However, it should be noted that the mentioned whole-rock K-Ar ages cannot be considered as fully reliable from the point of view of current standards. Because of great uncertainty in blocking temperature of K-Ar system in polymineralic rocks, the corresponding exhumation rate may be only very roughly estimated as being probably less than a tenth of mm per year (Fig. 7).

In general, we interpret the source area of the PKB Upohlav-type granitoid pebbles as an unspecified exhuming terrain that underwent a low-grade thermal event (cooling below the blocking temperatures of K-Ar system) in the earliest Cretaceous (140–115 Ma) and subsequently cooled lower than approximately 240 °C (FT zircon ages) around the Early/Late Cretaceous boundary (roughly between 110 and 90 Ma). There are several possible models that might elucidate these data. The first and preferable model A (Fig. 7) takes on the recycling concept and presumes only the Late Albian – Early Cenomanian (105–95 Ma) original deposition age of granite pebbles. Hence if we take the 95 Ma as the minimum possible primary deposition age of all pebbles, and assume the positive error bars as the maximum possible FT ages (hence not considering unrealistic negative time lags), the time lag (difference between the cooling and depositional ages) would range between 2–3 and 20 Ma.

Tab. 3. Fission track results from the granitoid pebbles of the PKB. Track densities (□) are as measured and are (x 10^5 tr/cm^2); number of tracks counted (N) is shown in brackets; P (χ^2) is probability of obtaining χ^2 value for n degree of freedom (where n=no.crystals^{-1}); Disp. – dispersion, according to Galbraith & Laslett (1993); central ages calculated using dosimeter glass CN2 with zeta=123±5.7.

Code	Locality	Crystals	Spontaneous		Induced		Dosimeter		$P(c^2)$	Disp.	FT age*		
		numbers	rs	(Ns)	ri	(Ni)	rd	(Nd)	(%)		(Ma ± 1s)		
KP-5	Dubový háj	26	94,90	1446	57,36	874	9,09	6008	67	0,03	92,1	±	6,0
KM-8	Oravský Podzámok	60	98,01	3160	54,87	1769	9,74	6008	12	0,08	106,2	±	6,1
KP-1	Stupné	35	94,96	2763	51,52	1499	8,69	6008	0	0,18	97,2	±	6,5
KM-3	Stupné	55	74,31	2089	40,69	1144	9,05	6008	82	0,03	101,2	±	6,1
KP-8	Stupné	18	115,14	1030	72,44	648	9,49	6008	7	0,15	91,5	±	7,1
KM-1a	Divinka	60	76,08	2311	38,55	1171	8,60	6008	99	0,00	103,9	±	6,2
KM-1b	Divinka	60	104,74	3892	50,97	1894	8,65	6008	2	0,12	108,7	±	6,3
KM-2	Považský Chlmec	59	68,79	2360	37,19	1276	8,74	6008	34	0,12	98,9	±	5,9
KP-3	Kysuca – rieka	20	111,35	1412	48,58	616	8,79	6008	19	0,11	120,8	±	8,8
KP-6	Zádubnie	18	95,47	1220	56,58	723	8,84	6008	2	0,28	89,5	±	7,2
KM-7	Zástranie	54	83,53	2176	46,76	1218	9,54	6008	78	0,01	104,3	±	6,2

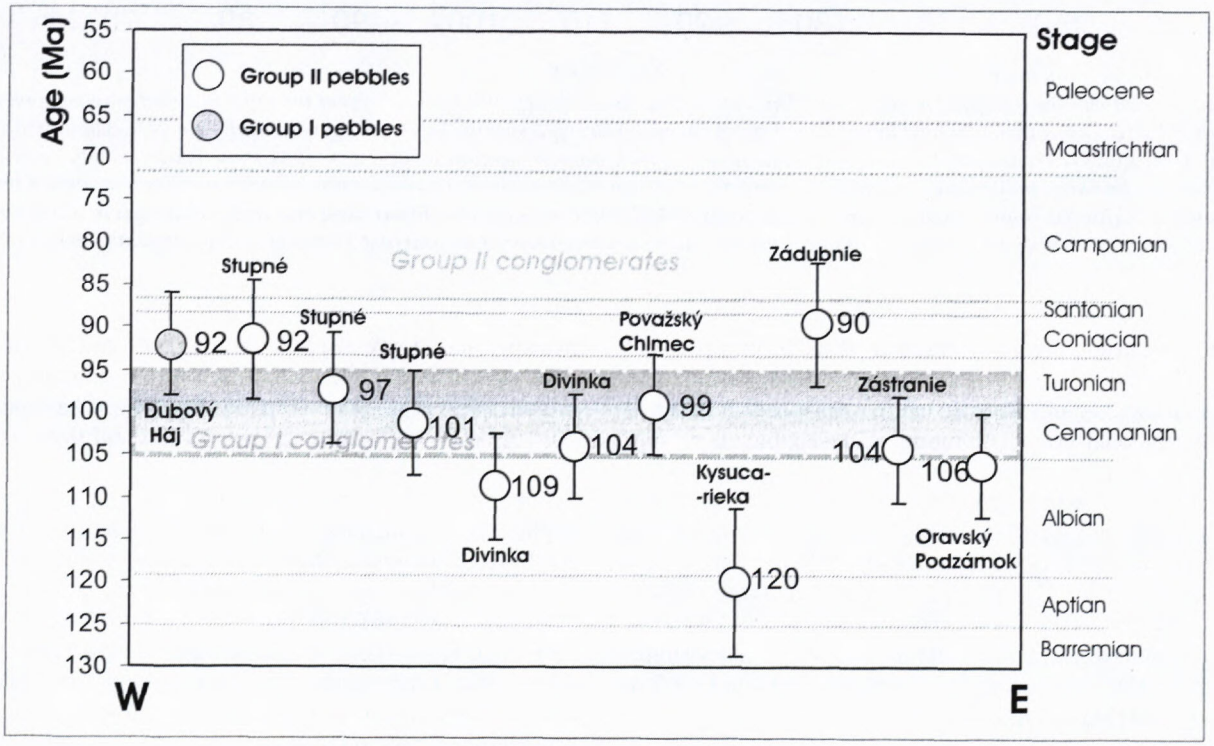

Fig. 6. Zircon FT ages of granitoid pebbles vs. the sedimentary age of conglomerate groups of the Pieniny Klippen Belt. Samples are arranged geographically from west to east.

Adopting a standard continental geotherm with a thermal gradient of about 30 °C/km in the upper crust, we obtain corresponding erosion rates between 4 and 0.4 mm per year, respectively (model A in Fig. 7). These comparatively high rates are reduced to 0.5–0.2 mm.a^{-1} (model B), however, in the case the Coniacian – Early Campanian (90–80 Ma, minimum possible age 80 Ma) depositional ages of conglomerates are considered as primary (calculating the central FT ages). If we calculate the maximum FT ages, as in the previous case, the corresponding figures are as low as 0.3 to 0.15 mm.a^{-1} (model C). On the other hand, the minimum measured FT ages (model D) compared to minimum possible deposition age would indicate erosion rates with values identical to the model A. Altogether we infer that the most realistic erosion rates of the source areas for our samples approximated 0.5 to a few mm.a^{-1}.

These adopted erosion rates are at the upper limit of those commonly referred from collisional orogens. In general, exhumation rates in excess of 1 mm/a are interpreted as being dominated by crustal extension and tectonic unroofing. Nevertheless, as pointed out by Burbank

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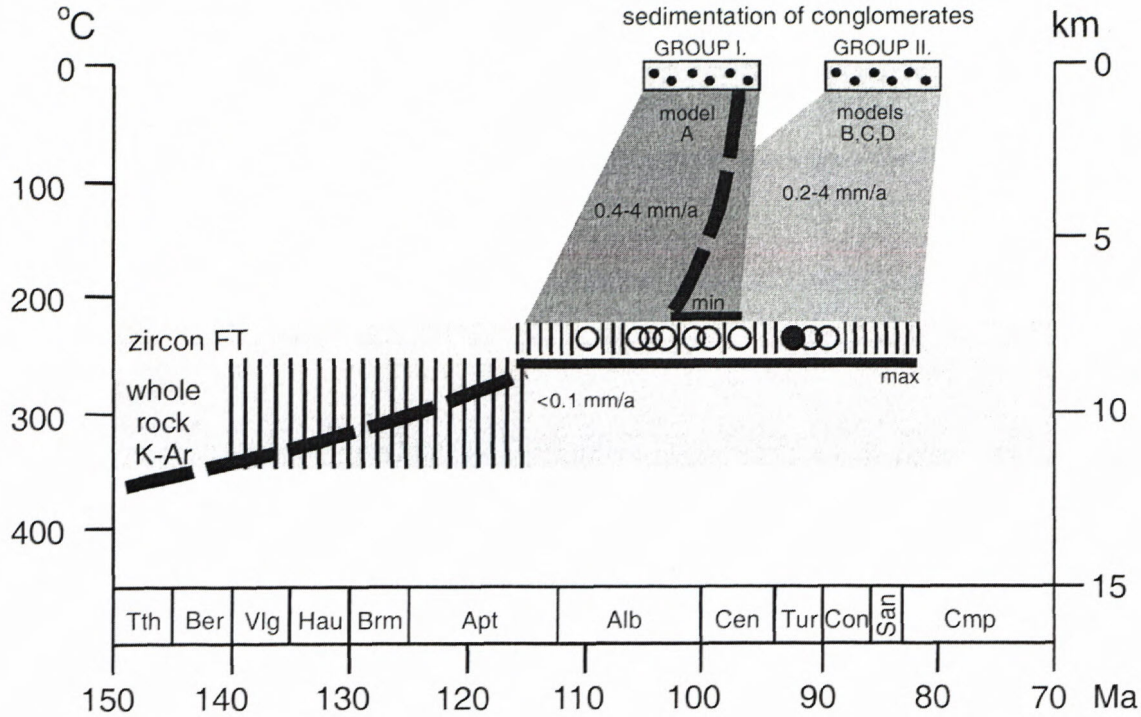

Fig. 7. Tentative exhumation diagram of granite pebbles. Central FT ages are shown by small circles (full for pebbles from the Group I conglomerates, empty for Group II). The "min" and "max" horizontal bars represent the minimum and maximum possible zircon FT ages (assuming standard deviations of track measurements), respectively. Depth estimates refer to 30 °C/km thermal gradient. Grey fields cover the possible range of exhumation/erosion rates for various models described in the text; the thick dashed line outlines the favoured path within the model A. The grey "zircon FT" area refers to the approximate closure temperature range of zircon fission-tracks, similar field labelled "whole-rock K-Ar" outlines estimated closure temperatures for Ar system in polymineralic rocks dominated by feldspars. Vertical ruling indicates the time range of measured FT ages including standard deviations, as well as the span of K-Ar cooling ages taken on from the literature.

(2002), transient erosion rates as high as 10 mm per year are still realistic and may account for high exhumation rates commonly observed in collisional orogens, even if the extensional crustal thinning is negligible. It is supposed here that the absence of mylonitic fabric in studied granitoids and indications of a high mountainous relief in source areas are signs of a compressional tectonic setting with surface erosion dominating the exhumation process in the hinterland. This is confirmed also by large sizes of granitoid and other clasts and synorogenic, thickening- and coarsening-upward character of conglomerate-bearing wildflysch formations, with boulders up to 3.5 m in diameter (Marschalko, 1986).

Possible source terrains

A-type granites with similar mineralogical and geochemical characteristics and Permian crystallization ages as those in the Upohlav-type granite pebbles occur in intrusive bodies exclusively in the southern CWC and in the Internal Western Carpathian (IWC) zones (Uher & Broska, 1996; Broska & Uher, 2000, 2001). A-type granites were interpreted as post-orogenic intrusions related to continental rifting and derived from relatively hot and dry melts. These are especially the Turčok granite in the Gemeric superunit and the Velence granite in the Transdanubian Central Range of NW Hungary. They intrude into low-grade Lower Paleozoic volcano-sedimentary complexes. On the other hand, A-type granites are completely missing in the pre-Alpine basement of the Tatric superunit, which neighbours the PKB exotic conglomerates in their present position (Fig. 1). The Tatric basement is dominated by high-grade metamorphites and synorogenic Variscan I- and S-type granites.

In spite it was known that composition of "exotic" pebbles admits their derivation from the southern Western Carpathian zones, there was seemingly no way how to transport the A-type granite pebbles, along with other exotic clasts, across the Tatric realm into flysch of the PKB area (e.g. Mišík & Marschalko, 1988). These authors stressed that there existed a wide zone with marine sedimentation and with a rugged morphology between the deposition area of conglomerates and the possible "southern" source area at the time of their deposition. These were the main arguments to construct the "Pieniny exotic cordillera" ("Andrusov Ridge" sensu Birkenmajer, 1988) – a compressional positive morphological feature that was inferred to have existed between the Klape basin and the Central Western Carpathians, i.e. in the "northern" position. The ridge should have vanished during the latest Cretaceous and earliest Tertiary when also the exotic clasts disappeared from the sedimentary record, although its younger local reactivation was possible (Neopieninic exotic ridge of Mišík et al., 1991).

Nevertheless, two other hypotheses were published that still consider the southern Western Carpathian zones as the possible source area for exotic conglomerates. According to Plašienka (1995), the Klape unit with

its exotic conglomerates might represent a subunit of the Krížna nappe system that originally neighboured and received clastic material from the "southern" source terrain. In this case the Klape unit would have represented a diverticulation partial nappe of the Krížna system that after closure of the Krížna basin glided far north towards the front of the CWC nappe stack during the Turonian. An alternative view infers that the deposition realm and source areas were also originally close to each other, but they were split by a large-scale left-lateral transform fault zone along the outer CWC boundary that gradually completely separated the flysch basin from the source terrain (Rakús & Marschalko, 1997; Rakús et al., 1998), i.e. an overall conservative plate boundary setting is presumed. However, the existing structural and paleomagnetic data do not support such a scenario.

In both cases, the Group I conglomerates could have been deposited in the neighbourhood of the collisional mountain range in the southern Western Carpathian zones that formed due to the Late Jurassic – Early Cretaceous closure of the Meliata ocean. If this concept is verified, it could explain the "southern" provenance of the majority of the exotic material in the Klape flysch conglomerates, including the A-type granites.

Although the traditional concept of the "Pieniny exotic ridge" cannot be definitely excluded, its existence is highly improbable from the point of view of regional tectonics and structural evolution of the PKB and adjacent CWC zones (Plašienka, 1995). Conversely, the southern CWC and IWC zones exhibit tectonic evolution and thermochronologic data consistent with those observed in the PKB conglomerates. Therefore we still keep the working hypothesis that the source area for exotic granitoids occurred in the southern Western Carpathian zones. This opinion is based mainly on the following arguments:

- the majority of "exotic" pebbles could find their analogues and source areas in these zones without problem and similar pebbles occur also in conglomerates of the Tatric-Fatric Poruba flysch basin (Mišík et al., 1981);
- exceptional diversity of exotic pebbles point to their derivation from a collisional orogenic zone with very complex geological structure – the southern CWC and IWC zones were in a collisional setting after closure of the Meliata ocean during the Late Jurassic;
- Upper Jurassic blueschists in primary occurrences are only known from the Meliatic Bôrka nappe;
- postorogenic A-type granites with Permian to Lower Triassic intrusive ages occur only in these zones, their low-grade country rocks (phyllites, lydites, metapsamites, metacarbonates) have also some rarely occurring analogues in the PKB pebbles;
- Early Cretaceous amphibole $^{39}Ar/^{40}Ar$ cooling ages from the Gemeric basement (140 Ma, Vozárová et al., 2000) and K-Ar ages with a similar time span as in the PKB (140–115 Ma) were documented in the Bükk Mts. (Árkai et al., 1995), pointing to a very similar exhumation history;
- the Bükk, Gemer and south Vepor areas are completely devoid of Lower Cretaceous sediments, thus they were very probably uplifted and prone to erosion at that time (on the other hand, the Upper Cretaceous Gosau-type sediments occur there, though in relics only);
- the Upper Cretaceous south Veporic metamorphic core complex formed after an important Lower Cretaceous collision and thrusting event (Janák et al., 2001), most probably the Veporic superunit was overridden by the Gemeric–Meliatic–Turnaic thrust stack that provided also the pebble material for exotic conglomerates.

To evaluate this hypothesis, we measured also zircon FT ages of granitoids with Permian intrusive ages (Poller et al., 2002) from the Gemeric superunit (Fig. 1). These provided cooling ages ranging from 88.4±6.8 to 62.2±4.2 Ma (including two samples from the A-type Turčok granite that yielded 74.8 and 71.9±4.7 Ma – Kissová et al., 2004), i.e. they are mostly considerably younger than our pebble ages. The difference between zircon FT ages from PKB pebbles and present-day Gemeric outcrops may be explained by the difference in the exhumation level during mid-Cretaceous and Late Cretaceous to Recent times, respectively. An alternative view assumes that the Gemeric superunit experienced a compressional tectonic event during the Early Cretaceous, which is indicated by the lack of sedimentary record, deformation and 140 Ma thermal event (Vozárová et al., 2000); hence the area was likely uplifting and continuously eroded. This would be the first exhumation pulse culminating in mid-Cretaceous times, which was triggered by compression, surface uplift, erosion and deposition of eroded material (including exotic granitoids) in an adjacent flysch basin. After that, the Upper Cretaceous zircon FT ages of Gemeric granites were set by the heating from the hot footwall during contemporaneous extensional unroofing of the Veporic metamorphic core complex. This extensional event was accompanied also by intrusion of the Rochovce granite body into the footwall Veporic basement (75.6±1.1 Ma by U-Pb single-grain dating of zircons; Poller et al., 2001), which might annealed the original FT zircon ages in country rock complexes, including the hanging wall Gemeric granites. Accordingly, the Late Cretaceous zircon FT ages from Gemeric granites could record this second exhumation pulse associated with extension and minor surface uplift and erosion.

Tectonic scenario

The above considerations and further assumptions about the Alpidic geodynamic evolution of the Western Carpathians (Plašienka, 1999, 2002) result in a possible tectonic scenario of the source terrain and its interaction with the depositional area that is partitioned into three main periods:

1. Initial Neo-Kimmerian collision after closure of the Meliata ocean (160–150 Ma) was followed by partial nappe stacking (the Gemeric sheet overriding the Veporic) of the southern margin of the lower CWC plate of the con-

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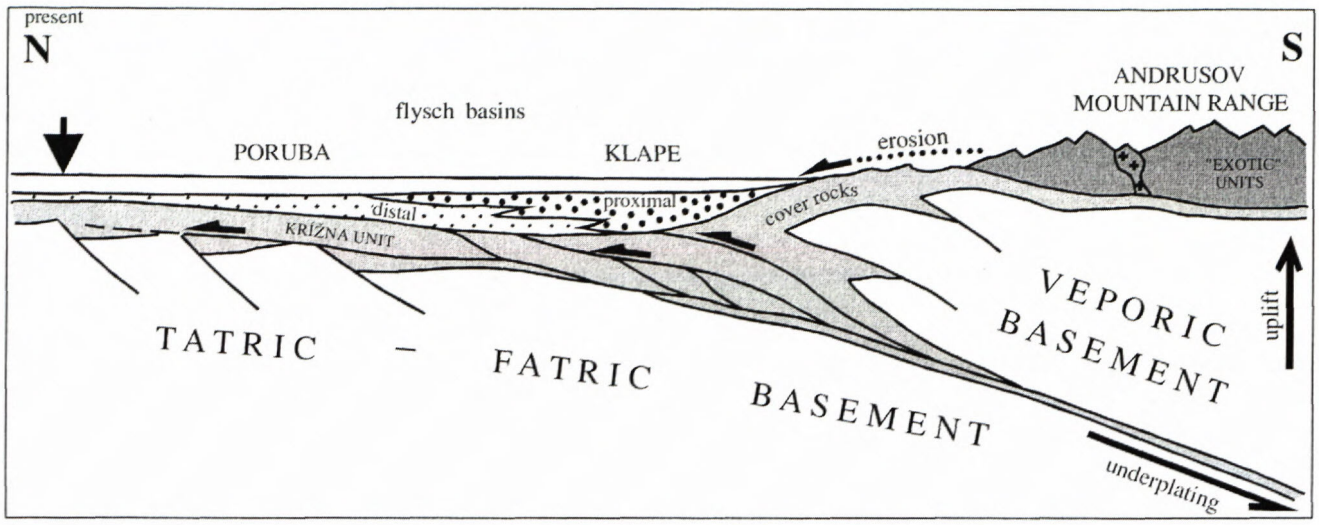

Fig. 8. Geodynamic framework of the inner Central Western Carpathian zones during the "pre-Gosauian" orogeny at around 100 Ma (Albian/Cenomanian boundary). Not to scale.

vergence system. Starting from the earliest Cretaceous (140 Ma), this inferred source terrain – the "eo-Carpathian" collisional belt, experienced gradual exhumation and non-deposition. However, the relief was likely low and smooth, since only fine-grained clastic material (often ophiolite-derived) occurs locally in siliciclastic turbiditic beds within the Neocomian pelagic marlstones in the neighbouring Krížna basin (Michalík et al., 1996). The whole source terrain experienced slow cooling and exhumation at the rate of less than 0.1 mm/a, which was fully compensated by chemical weathering and erosion.

2. By the Early Albian (around 110 Ma), shortening affected the Krížna basin, the continental basement of which started to be underthrust below the Veporic basement wedge and the overlying eo-Carpathian nappe stack. This was the paleo-Alpine (or "pre-Gosauian") orogenic epoch (Fig. 8). As a consequence of crustal thickening, the source area was rapidly uplifting and temporarily (105–95 Ma) building up a mountainous relief that was prone to fast erosion. Exhumation rate increased considerably and the rock uplift was not more compensated by erosion, although the surface erosion intensified to some 0.5–3 mm/a. Coarse-grained erosional products, including exotic pebbles and boulders in Group I conglomerates, were deposited in prograding proximal flysch fans in the gradually shortening Krížna (Klape) basin. The Krížna basement was fully underthrust by 90 Ma and the detached Krížna nappe, including its uppermost Klape diverticulation, glided northward to cover the Tatric substratum and its foreland. After cessation of shortening, the eo-Carpathian collision stack in the source area collapsed gravitationally, mountainous relief was diminished and the Veporic metamorphic core complex was exhumed by extensional tectonic unroofing (90–70 Ma).

3. In a new allochthonous position in front of the Tatric realm, far from the original source areas, the Klape unit probably overlay the oceanic substratum of the Vahic (South Penninic) ocean, which started to be subducted beneath the Tatric basement wedge by the earliest Senonian (90 Ma). In a position of a "false" accretionary wedge the Klape unit suffered further deformation and erosion, therefore the pebble material was resedimented into the Coniacian – Santonian flysch basins developed within the same Klape and/or adjacent Kysuca and Manín units. However, these younger Group II conglomerates and olistostromes are enriched in some material derived from the neighbouring active Tatric margin (e.g. orthogneisses) and blocks of contemporaneous shallow-marine rudist reefs (Marschalko & Rakús, 1997), as well as Orlové sandstones in addition to the recycled exotic clasts. The recycling event repeated once more during the Maastrichtian and Paleocene (Jarmuta and Proč flysch formations), when the Vahic ocean closed, the CWC collided with the Oravic ribbon continent and the principal PKB units were formed.

Conclusions

We have applied a classic method of provenance studies in clastic formations – the low-temperature thermochronology of pebble material, for unravelling the exhumation history and probable location of the source area of Cretaceous conglomerates of the Pieniny Klippen Belt of Western Carpathians. It has been long known that most of this material does not occur in the presently adjacent tectonic zones at all, hence the pebbles and their hypothetic sources were described as "exotic" already in early thirties of the previous century (Zoubek, 1931). It is therefore not surprising that our first zircon FT data from granitoid pebbles show ages, which cannot be considered as recording exhumation and cooling processes that might have been operating within an orogenic zone neighbouring the actual position of the PKB.

Results of our zircon FT age determinations and their consequences for the provenance and tectonic evolution of the source area are summarized in the following points:

- It has been confirmed by bulk petrography, geochemistry, REE content and study of zircon crystal mor-

phology that the studied granitoids belong to the A-type anorogenic granites, which are very similar to the Turčok and Velence granite bodies occurring in the southern Western Carpathian zones, but are completely missing in units currently adjacent to the PKB. All these A-type granites share similar post-Variscan, generally Early Permian crystallization ages.

- One sample from the Group I conglomerates of the Klape unit exhibits an age 92.1±6.0 Ma; the upper limit of 98 Ma is considered as the most realistic to match the depositional age of conglomerates that should not be younger than 95 Ma. In any case, a very fast corresponding erosion rate up to several mm per year has to be taken into account.
- Nine samples from the Group II conglomerates scatter between 89.5 and 120.8 Ma central ages. Since the single age from older conglomerates falls within this age range, we tentatively suppose that all studied pebbles were originally resting in Group I conglomerates and were later partially recycled into younger conglomerates. This assumption would again infer high erosion rates.
- The available K-Ar data (though poorly reliable) and our FT data indicate a slow Early Cretaceous exhumation of the source terrain, which was considerably increased in one order of magnitude during erosion and deposition of the synorogenic conglomerates. We ascribe this increase to a temporary accumulation of compressive stresses that triggered surface uplift and mountain building in the source areas.
- All these data and inferences coincide well with the thermotectonic history of the southern Western Carpathian zones, where a similar succession of tectonic events may be documented. We therefore see no need for construction of a totally hypothetical structure, the Pieniny exotic cordillera or Andrusov Ridge, as the source area for the exotic pebble material. Problems with transport ways of exotic material from their sources to apparently very distant deposition place may be readily avoided by some tectonic process, e.g. by a nappe transport of conglomerate-bearing Klape unit as a constituent of the Krížna nappe system (Plašienka, 1995). The post-nappe Group II conglomerates show some features of resedimentation from Group I conglomerates – our FT data rather support than contradict to the recycling concept.

Nevertheless, it is clear that our first age data show some scatter, which calls for the need of a denser database. Processing of a new set of samples is in progress and will hopefully clarify some still ambiguous points in our existing data, especially concerning the age data from the Group I conglomerates, because only one successfully completed measurement is clearly insufficient for definite conclusions. Consequently, the discussion and conclusions presented here may be considered as preliminary only.

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References

Árkai P., Balogh K. & Dunkl I., 1995: Timing of low-temperature metamorphism and cooling of the Paleozoic and Mesozoic formations of the Bükkium, innermost Western Carpathians, Hungary. *Geol. Rundsch.*, 84, 334–344.

Birkenmajer K., 1988: Exotic Andrusov Ridge: its role in plate-tectonic evolution of the West Carpathian foldbelt. *Studia Geol. Pol.*, 41, 7–37.

Birkenmajer K., Kozur H. & Mock R., 1990: Exotic Triassic pelagic limestone pebbles from the Pieniny Klippen Belt of Poland: a further evidence for Early Mesozoic rifting in West Carpathians. *Annales Soc. Geol. Pol.*, 60, 3–44.

Broska I. & Uher P., 1991: Regional typology of zircon and its relationship to allanite/monazite antagonism (on an example of Hercynian granitoids of Western Carpathians). *Geol. Carpath.*, 42, 271–277.

Broska I. & Uher P., 2000: The role of silicic magmatism in the Western Carpathians: from Variscan collision to Early-Alpine extension. *Slovak Geol. Mag.*, 6, 278–280.

Broska I. & Uher P., 2001: Whole-rock chemistry and genetic typology of the West-Carpathian Variscan granites. *Geol. Carpath.*, 52, 79–90.

Broska I. & Uher P., 2003: Zircon typology of the Western Carpathian granitoids (in Slovak). *Bull. Mineral. Petrol. Odd. Nár. Muz. Praha*, 11, 131–136.

Burbank D.W., 2002: Rates of erosion and their implications for exhumation. *Mineral. Mag.*, 66, 25–52.

Collins W.J., Beams S.D., White A.J.R. & Chappell B.W., 1982: Nature and origin of A-type granites with particular reference to Southeastern Australia. *Contrib. Mineral. Petrol.*, 80, 189–200.

Dal Piaz G.V., Martin S., Villa I.M., Gosso G. & Marschalko R., 1995: Late Jurassic blueschist facies pebbles from the Western Carpathian orogenic wedge and paleostructural implications for Western Tethys evolution. *Tectonics*, 14, 874–885.

Dunkl I., 2002: Trackkey: a windows program for calculation and graphical presentation of fission track data. *Comp. & Geosci.*, 28, 3–12.

Faryad S.W., 1997: Petrological model for blueschist facies metamorphism in the Pieniny Klippen Belt. In Grecula P., Hovorka D. & Putiš M. (eds): *Geological evolution of the Western Carpathians.* Mineralia Slov., Monogr., 155–162.

Faryad S.W. & Schreyer W., 1996: Petrology and geological significance of high-pressure metamorphic rocks occurring as pebbles in the Cretaceous conglomerates of the Klippen Belt (West Carpathians, Slovakia). *Eur. J. Mineral.*, 9, 547–562.

Frasl G. & Uher P., 1996: Zur Kenntnis der exotischen Granitgerölle (Upohlav Typ) im Kreideflysch der Klippenzone der Westkarpaten: ihre metamorphose und ihre Forsetzung in die Ostalpen. *VI. Symp. "Tektonik, Struktur- und Kristallingeologie"*, Salzburg, abstract.

Galbraith R.F. & Laslett G.M., 1993: Statistical models for mixed fission track ages. *Nucl. Tracks Radiat. Meas.*, 21, 459–470.

Gbelský J. & Határ J., 1982: Zircon from granitoid rocks of the Velence and Mecsek Mountains (Hungary). *Geol. Zbor. – Geol. Carpath.*, 33, 343–363.

Gradstein F.M., Ogg J.G., Smith A.G., Bleeker W. & Lourens L.J., 2004: A new Geologic Time Scale, with special reference to Precambrian and Neogene. *Episodes*, 27, 83–100.

Jablonský J., Sýkora M. & Aubrecht R., 2001: Detritic Cr-spinels in Mesozoic sedimentary rocks of the western Carpathians (overview of the latest knowledge); (in Slovak, English summary). *Mineralia Slov.*, 33, 487–498.

Janák M., Plašienka D., Frey M., Cosca M., Schmidt S.Th., Lupták B. & Méres Š., 2001: Cretaceous evolution of a metamorphic core complex, the Veporic unit, Western Carpathians (Slovakia): P-T conditions and in situ $^{40}Ar/^{39}Ar$ UV laser probe dating of metapelites. *J. Metamorphic Geol.*, 19, 197–216.

Kissová D., Dunkl I., Frisch W. & Plašienka D., 2004: Cretaceous cooling history of the Western Carpathians: New zircon FT ages from Gemeric granites and pebbles from conglomerates of the Klippen Belt. *Geolines*, 17, 53–54.

Maheľ M., 1989: The Klippen Belt from the aspect of the geodynamic model (in Slovak, English summary). *Mineralia Slov.*, 21, 99–108.

Marschalko R., 1986: *Evolution and geotectonic significance of the Klippen Belt Cretaceous flysch in the Carpathian megastructure* (in Slovak, English summary). Veda Publ., Bratislava, 139 p.

Marschalko R. & Rakús M., 1997: Development of the Cretaceous flysch in the Klape unit and the recyclicity problem of the clastic material. In Plašienka D., Hók J., Vozár J. & Elečko M. (eds): *Alpine evolution of the Western Carpathians and related areas.* Internat. conf., Introduct. articl. exc., Geol. Surv. Slov. Rep., Bratislava, 71–78.

Michalík J., Reháková D. & Jablonský J., 1996: Geodynamic setting of fluxoturbidites in West Carpathian Upper Jurassic and Lower Cretaceous sedimentary basins. *Slovak Geol. Mag.*, 3-4/96, 325–329.

Mišík M., 1978: Some paleogeographical problems concerning Klippen Belt (in Slovak, English summary). In J. Vozár et al. (eds): *Paleogeographical evolution of the West Carpathians.* Konf., Symp., Sem., GÚDŠ, Bratislava, 147–159.

Mišík M. & Marschalko R., 1988: Exotic conglomerates in flysch sequences: Examples from the West Carpathians. In Rakús M., Dercourt J. & Nairn A.E.M. (eds): *Evolution of the northern margin of Tethys, Vol. I.* Mém. Soc. Géol. France, Nouvelle Série No. 154, 95–113.

Mišík, M. & Sýkora, M. 1981: Der pieninische exotische Rücken, rekonstruiert aus Geröllen karbonatischer Gesteine Kretazischer Konglomerate der Klippenzone und der Manín-Einheit (in Slovak, German summary). *Záp. Karpaty, Geológia*, 7, 7–111.

Mišík M., Mock R. & Sýkora M., 1977: Die Trias der Klippen-Zone der Karpaten. *Geol. Zbor. – Geol. Carpath.*, 28, 27–69.

Mišík M., Jablonský J., Fejdi P. & Sýkora M., 1980: Chromian and ferrian spinels from Cretaceous sediments of the West Carpathians. *Mineralia Slov.*, 12, 209–228.

Mišík M., Jablonský J., Mock R. & Sýkora M., 1981: Konglomerate mit exotischen Material in dem Alb der Zentralen Westkarpaten – paläogeographische und tektonische Interpretation. *Acta Geol. Geogr. Univ. Com., Geologica*, 37, 5–55.

Mišík M., Sýkora M., Mock R. & Jablonský J., 1991: Paleogene Proč conglomerates of the Klippen belt in the west Carpathians, material from Neopieninic exotic ridge. *Acta Geol. Geogr. Univ. Com., Geologica*, 46, 9–101.

Plašienka D., 1995: Mesozoic evolution of Tatric units in the Malé Karpaty and Považský Inovec Mts.: Implications for the position of the Klape and related units in western Slovakia. *Geol. Carpath.*, 46, 101–112.

Plašienka D., 1999: *Tectonochronology and paleotectonic evolution of the Central Western Carpathians during the Jurassic and Cretaceous* (in Slovak, English summary). Veda, Bratislava, 127 p.

Plašienka D., 2002: *Alpidic tectonic progradation and its structural record in the West Carpathian units* (in Slovak). MS, DSc Thesis, Geol. Inst. Slov. Acad. Sci., Bratislava, 149 p.

Poller U., Uher P., Janák M., Plašienka D. & Kohút M., 2001: Late Cretaceous age of the Rochovce granite, Western Carpathians, constrained by U-Pb single-zircon dating in combination with cathodoluminiscence imaging. *Geol. Carpath.*, 52, 41–47.

Poller U., Uher P., Broska I., Plašienka D. & Janák M., 2002: First Permian – Early Triassic zircon ages for tin-bearing granites from the Gemeric unit (Western Carpathians, Slovakia): connection to the post-collisional extension of the Variscan orogen and S-type granite magmatism. *Terra Nova*, 14, 41–48.

Pupin J.P., 1980: Zircon and granite petrology. *Contrib. Mineral. Petrol.*, 73, 207–220.

Pupin J.P., 1988: Granites as indicator in paleodynamics. *Rend. Soc. Ital. Mineral. Petrol.*, 43, 237–262.

Rakús M. & Marschalko R., 1997: Position of the Manín, Drietoma and Klape units at the boundary of the Central and Outer Carpathians. In Plašienka D., Hók J., Vozár J. & Elečko M. (eds): *Alpine evolution of the Western Carpathians and related areas.* Internat. Conf. "Carpathian Geology 2000", Introduct. Art. Excurs., Geol. Surv. Slov. Rep., Bratislava, 79–97.

Rybár M. & Kantor J., 1978: Radiometric dating of selected formations of the Western Carpathians. $^{40}Ar/^{40}K$ ages of eruptive rocks from the Upohlav conglomerates of the Klippen Belt (in Slovak). MS, Open File Report, Geofond, Bratislava, 111 p.

Rakús M., Potfaj M. & Vozárová A., 1998: Basic paleogeographic and paleotectonic units of the western Carpathians. In M. Rakús (ed.): *Geodynamic development of the Western Carpathians.* Geol. Survey Slov. Rep., D. Štúr Publ., Bratislava, 15–26.

Rollinson H.R., 1993: *Using geochemical data: Evaluation, presentation, interpretation.* Longman Scientific & Technical, UK, 352 p.

Salaj J., 1994: Geology of Middle Váh valley. Klippen and Periklippen belt, Súľov Paleogene and Mesozoics of northern part of Strážovské vrchy hills – part 1 (in Slovak, English summary). Zem. Plyn Nafta, 39, 195–291.

Streckeisen A. & Le Maitre R.W., 1979: A chemical approximation to the modal QAPF classificaton of the igenous rocks. *N. Jb. Mineral. Abh.*, 136, 169–206.

Uher P. & Gregor T., 1992: The Turčok granite: product of postorogenic A-type magmatism? (in Slovak, English abstract). *Mineralia Slov.*, 24, 301–304.

Uher P. & Broska I., 1995: The Velence Mts. granitic rocks: geochemistry, mineralogy and comparison to Variscan Western Carpathian granitoids. *Acta Geol. Hung.*, 37, 45–66.

Uher P. & Broska I., 1996: Post-orogenic Permian granitic rocks in the Western Carpathian-Pannonian area: geochemistry, mineralogy and evolution. *Geol. Carpath.*, 45, 375–378.

Uher P. & Marschalko R., 1993: Typology, zoning and chemistry of zircon from main types of granitic and rhyolitic pebbles in conglomerates of the Pieniny Klippen Belt Cretaceous flysch (western Slovak segment, Western Carpathians). *Geol. Carpath.*, 44, 113–121.

Uher P. & Pushkarev Yu., 1994: Granitic pebbles of the Cretaceous flysch of the Pieniny Klippen Belt, Western Carpathians: U/Pb zircon ages. *Geol. Carpath.*, 45, 375–378.

Uher P., Marschalko R., Martíni E., Puškelová Ľ., Streško V., Toman B. & Walzel E., 1994: Geochemical characterization of granitic rock pebbles from Cretaceous – Paleogene flysch of the Pieniny Klippen Belt. *Geol. Carpath.*, 44, 113–122.

Vozárová A., Frank W. & Kráľ J., 2000: $^{40}Ar/^{39}Ar$ data from contact aureole of Súľová granite (Gemericum, the Western Carpathians). *Slovak Geol. Mag.*, 6, 363–366.

Whalen J.B., Currier L.C. & Chappell B.W., 1987: A-type granites: geochemical characteristic, discrimination and petrogenesis. *Contr. Mineral. Petrol.*, 95, 407–419.

Zoubek V., 1931: Caractéristique de quelques roches cristallophilliens et eruptives des galets exotiques des conglomerats sénoniens et paleogenes de Carpates Occidentales. In Matějka A. & Andrusov D. (eds): *Guide des excursions dans les Carpathes occidentales.* Knih. St. geol. ústavu Čs. rep., 13A, 353–358.

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Lower Cretaceous sequences of the Manín Unit (Butkov Quarry, Strážovské vrchy Mts, Western Carpathians) – integrated biostratigraphy and sequence stratigraphy

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Abstract: The pelagic limestone sequence of Mt Butkov exposed by quarry of the Ladce Cement Works in middle Váh Valley is the best documented Lower Cretaceous sequence in Western Carpathians at all. Basal Berriasian gap represents a characteristic feature of the Manín Unit, it is connected with the paleogeographic setting of this unit in the basin. The Ladce Formation comprises Campylotoxus-, Verrucosum- and Peregrinus ammonite zones correlable with calpionellid Calpionellites Zone and with the lowermost part of the Tintinnopsella Zone. The Mráznica Formation is a product of a dysoxic episode spanning the ammonite Furcillata Zone – an equivalent of dinoflagellate Validum Zone. The Kališčo Formation has been deposited during ammonite Radiatus-, Loryi-, Nodosoplicatum-, Sayni-, and Ligatus zones. The lower part of the formation belongs to dinoflagellate Staurota and Stoveri zones, dinocysts are poorly represented higher up in the sequence. The Lúčkovská Formation is a terminal part of the Lower Cretaceous pelagic limestone sequence. Its lowermost part (? Balearis Zone) is poorly dated by ammonites, higher part of the sequence belongs to Hugii-, Nicklesi-, Pulchella-, Compressissima-, and Vanderheckii zones. The last mentioned zone is comparable with dinocyst Operculata Zone. The Podhorie and Manín formations represent products of „Urgonian" carbonate platform, which developed here since Aptian to the end of Early Albian. The Butkov Marl Formation is equivalent to nannoplankton Turriseiffelii Zone, compared with the duration of ammonite Inflatum and Dispar zones. Correlation of ammonites, aptychi, calpionellids, dinocysts and nannoplankton gives clue to precisioning of biostratigraphic division of Lower Cretaceous sequences in the Mediterranean area.

Key words: Lower Cretaceous, pelagic carbonates, sequence stratigraphy, ammonites, dinocysts, nannoplankton, biostratigraphy, Western Carpathians

1. Introduction

More than one half of century, the Manín Unit remains the source of controversies in the Carpathian geology. Extensive outcrops of its Lower Cretaceous sequence is exposed by the Butkov Quarry of the Ladce Cement Works in the middle Váh Valley. It has been studied by scientists of the Geological Institute of Slovak Academy of Science, the Comenius University in Bratislava and the Technical University in Ostrava from point of view of stratigraphy, paleontology, carbonate sedimentology and tectonics (Borza et al. 1987, Michalík & Vašíček 1987, Michalík et al., 1990, Vašíček et al., 1994, etc.). Since 1979 to 2004 more than twelve hundred ammonite specimens were collected. At present, this place represents the richest locality of Lower Cretaceous ammonites in the whole Western Carpathians with purely Mediterranean species from Early Valanginian Campylotoxus Zone to Late Barremian Vandenheckii Zone (Vašíček & Michalík 1986, Skupien et al. 2003). The ammonite associations resemble these from the Vocontian Trough in France. The Butkov section could serve as a key Valanginian – Barremian West Carpathian section correlable with these described from classical French and Spanish Mediterranean regions. However, active quarrying works remove documented sections each year.

The distribution of ammonites fits well with the orthostratigraphic scale proposed by Hoedemaeker et al. (2003). Vertical distribution of ammonites and aptychi in the sections studied was correlated with the distribution of calcareous microplankton (calpionellids, calcareous dinoflagellates and nannoplankton) as well as with the distribution of non-calcareous dinoflagellates.

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2. Biostratigraphy and sequence stratigraphy

2.1. Berriasian gap

The Butkov Lower Cretaceous sequence starts with the „Basal Breccia" with thickness of 1 to 5 meters. In fact, the breccia comprises clasts of Tithonian and Berriasian limestones only. Overlying limestone layers yielded Valanginian ammonite fauna. Thus, the Berriasian part of

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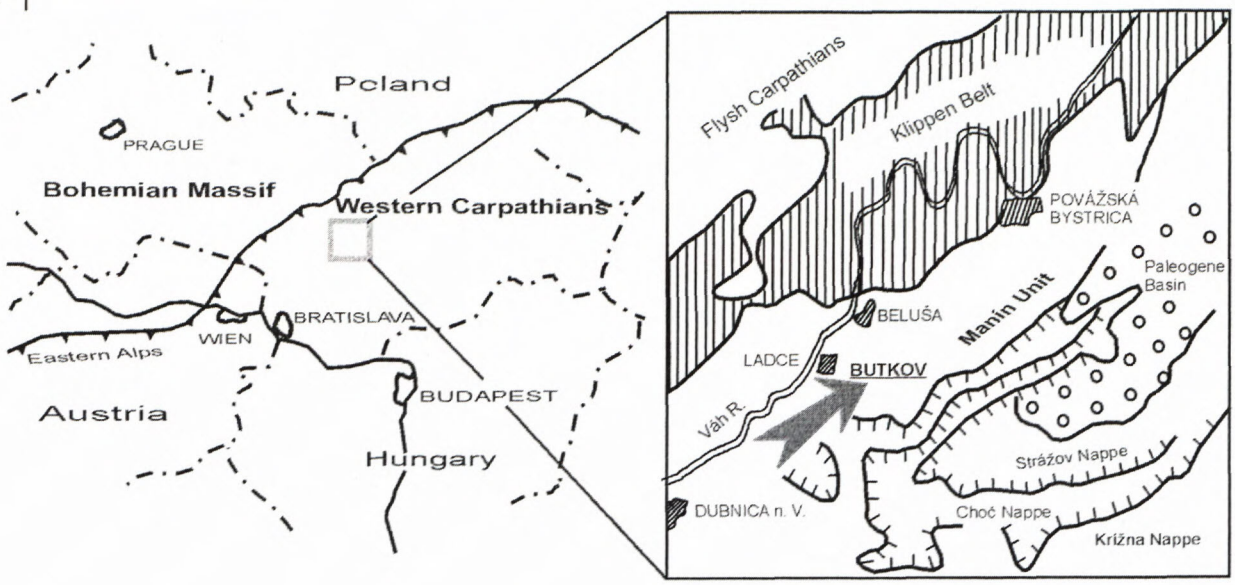

Figure l.: Setting of the Mt Butkov locality in the frame of Slovakia (left) and in the middle Váh Valley (right)

sequence is represented by a „hidden discordance" (Michalík & Vašíček 1987) and by sedimentary gap.

The regression at the Jurassic/Cretaceous boundary (Detraz & Mojon 1989) influenced sedimentation in the Mediterranean Tethys. Purbeck and sebkha facies characterised by calcrete horizons and by erosive gaps sedimented in the Boreal Realm (southern England, Paris Basin, nothern Germany), but also in Sub-Boreal and Sub-Mediterranean provinces (Basse-Provence, Sardegna and Spain, Jura Mountains, Hoedemaeker in Michalík, 2002). Frequent breccia beds are intercalated in the „maiolica" facies in southeastern France („Bréche de Chomerac" Jan du Chene et al. 1993) and in Italy. Despite of temporary middle Berriasian submersion, sea level rise continued at the end of the stage. Frequent gaps accompanied by allodapic layers with clasts of underlying rocks were described from the Berriasian – Valanginian boundary sequence along the border of the European continent and in the Vocontian Trough. Detraz & Mojon (l.c.) defined two „post-rift discordances" (at the beginning of both Late Berriasian and Early Valanginian), which should have been connected with mid Atlantic rifting, and with the Neo-Cimmerian movements. According to authors, mentioned above, this tectonic pulse merged with original eustatic signal (Vail et al., 1984), which represented the decisive element in Early Cretaceous evolution of sedimentary basins in closure of the Mediterranean Tethys.

In central Western Carpathian, Cretaceous basal breccia is typically developed in the Tatric Ridge (Reháková & Michalík, 1992) and its adjacent slope (Borza & Michalík 1987, Michalík et al. 1990b). However, its stratigrafic range is laterally variable. This fact could be explained by elevation of the Tatric Block during Late Cimmerian tectonic movements (Michalík 1990), combined with global sea-level fall during Early and Late Berriasian. At the end of the Berriasian (Be_{-7} sequence) sediments were eroded and the clastic material was deposited in channel fillings and submarine fans (the „Nozdrovice Breccia") on the Fatric Basin bottom, opened by pull-apart type tensional faults (Michalík & Reháková 1995, 1997). It is worth of mention, that in the Manín Unit all this part of sequence is missing, possibly due to erosion and transport into the Fatric Basin during deposition of Be_{-7} to Va_{-2} sequences.

2.2. The Ladce Formation

The basal unconformity on the base of the Ladce Formation comprises amalgamated Be-7 and Va-1 sequence boundaries (the „Late Cimmerian unconformity" of Haq et al., 1988). The Va-2 and Va-3 unconformities occur in the lowermost part of the formation, which is bare in ammonites. The Va-4 boundary is well developed, accompanied by redeposited sediments and by local gap (the „Oravice Event"). Short eccentricity cycles (á 100 ky) determine distribution of both clay component and the abundance of ammonites, which peak in transgressive system tracts. Supply of oxygen was insufficient during deposition, which probably coincided with the presence of warm deep water with increased salinity. The organic matter in planktonic „rain" was oxidized during passage through higher levels of water column.

The ammonite fauna of the Campylotoxus Zone confirms the start of thin bedded pale marly limestone deposition of the Ladce Formation during Early Valanginian. The basal Pertransiens Zone was not confirmed. *Vergoliceras salinarium* (Uhlig), *Kilianella retrocostata* Sayn, *Karakaschiceras inostranzewi* (Karakasch) occur together with the index *Busnardoites campylotoxus* (Uhlig). *Neocomites teschenensis* (Uhlig), *N. platycostatus* (Sayn), *N. beaumugnensis* (Sayn), *Olcostephanus guebhardi* Kilian occur somewhat higher up in the sequence. The sedimentation of the Ladce Formation was finished during Late Valanginian, which is documented by the occurrence of *Olcostephanus nicklesi* Wiedmann et Dieni, O. *tenuituberculatus* Bulot, *Himantoceras trinodosum* Thieuloy, *Rodighieroites belimelensis* Mandov (Peregrinus- to Furcillata zones). On the other hand, typical Mediterranean indexes like *Saynoceras verrucosum*, *Neocomites peregrinus*

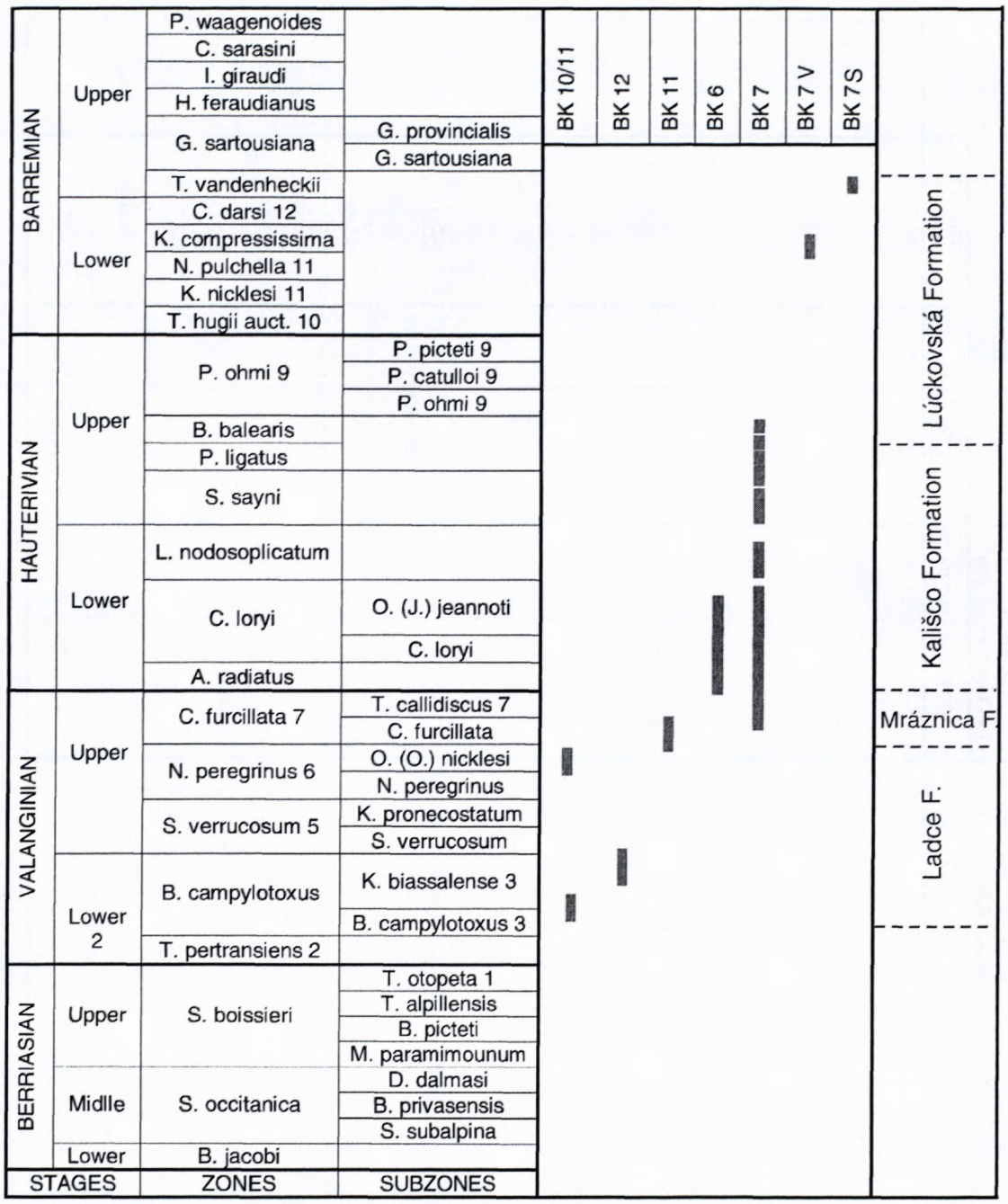

Figure 2.: Ammonite zonation of Lower Cretaceous with indication of documented zones in individual sections of the Butkov sequence

were not found in the Ladce Fm yet. The cephalopod distribution was correlated with the aptychi fauna collected in coeval strata. Twelve taxa of ribbed aptychi come from the Ladce Formation – for example *Lamellaptychus mortilleti mortilleti*, *L. aplanatus aplanatus*, *L. a. retroflexus*, *L. bermudensis*, *L. beyrichodidayi*, *L. symphysocostatus*; two taxa from this formation have been defined as new forms. Very interesting is the finding of *L. didayi* and *L. seranonis* at so low stratigraphical level – Campylotoxus Zone. Up to the present day was known that *L. didayi* and *L. seranonis* firstly appeared during Late Valanginian.

Marly limestones contain calpionellids and calcareous dinoflagellates of the Valanginian Calpionellites Standard Zone (Darderi- and Major Subzones). Calcareous nannofossil preservation is moderate to poor. *Nannoconus* spp. and *Watznaueria barnesae* constitute 40 – 90 % of rather low diverse assemblages. Calcareous nannofossils of the Ladce Formation allow to distinguish the Rucinolithus wissei NK-3A Subzone of the Calcicalathina oblongata NK-3 Zone. A very seldom, poorly preserved non-calcareous dinoflagellate association was ascertained in 34 - samples taken from the Ladce Fm for palynological (Spi) Zone with typical cosmopollitan forms like *Cometodiniumhabibii*, *Oligosphaeridium complex*, *Circulodinium Gonyaulacysta* and *Spiniferites*. The Verrucosum Zone on the 12th level of the Butkov quarry yielded no dinoflagellates at all.

		AMMONITE ZONATION Hoedemaeker et al. (2003) ZONES	LITOSTRATIGRAPHIC UNIT	DINOCYST ZONATION Leereveld (1995, 1997a,1997b)	CALPIONELLID ZONATION Reháková, Michalík (1997) ZONES	SUBZONES	NANNOFOSSIL ZONATION ZONES Thierstein (1973)	SUBZONES Bralower et al. (1995)	SEQUENCE STRATIGRAPHY Michalík (this study)
ALBIAN	Upper	Stoliczkaia (S.) dispar	Butkov Fm		not studied		Eiffellithus turriseiffelii	NC-10	
		Mortoniceras inflatum					not studied		
	Middle	Euhoplites lautus	Sedimentary gap						
		Euhoplites loricatus							
		Hoplites dentatus	Manín Fm						
	Lower	Douvilleiceras mammillatum							
		Leymeriella tardefurcata							
APTIAN	Upper	Hypacanthoplites jacobi	Podhorie Fm						
		Acanthohoplites nolani							
	Middle	Parahoplites melchioris							
		Epichelon subnodosocostatum	Sedimentary gap						
	Lower	Dufrenoyia furcata							
		Deshayesites deshayesi							
		Deshayesites weissi							
		Deshayesites tuarkyricus							
BARREMIAN	Upper	Martelites sarasini							
		Imerites giraudi							
		Hemihoplites feraudianus							
		Heinzia sartousiana							
		Ancyloceras vandenheckli	Lúčkovská Formation	Odontochitina operculata (Oop)					
	Lower	Coronites darsi		not studied					
		Kotetischvilia compressissima		Subtilisphaera scabrata (Sca)			Micratholithus hoschulzii	NC-5D	
		Nicklesia pulchella							
		Subpulchellia nicklesi		not studied				not studied	
		Spitidiscus hugii							
HAUTERIVIAN	Upper	Pseudothurmannia ohmi						NC-5B	Ha6
		Balearites balearis		?			Lithraphidites bollii		Ha5
		Plesiospitidiscus ligatus						not studied	Ha4
		Subsaynella sayni	Kališčo Fm						Ha3
	Lower	Lyticoceras nodosoptlicatum		Lithodinia stoveri (Lst)				NC-4B	
		Crioceratites loryi		Muderongia staurota (Mst)	Tintinopsella			NC-4A	Ha2
		Acanthodiscus radiatus							Ha1
VALANGINIAN	Upper	Criosarasinella furcillata	Mráznica Fm.	Cymososphaeridium validum (Cva)			Calcicalathina oblongata	NK-3B	
		Neocomites peregrinus	Ladce Fm	?				not studied	Va4
		Saynoceras verrucosum							
	Lower	Busnardoites campylotoxus		Spiniferites spp. (Spi)	Calpionellites	Major		NK-3A	
			Sedimentary gap	not studied		Darderi	not studied		Va3
		Thurmanniceras pertransiens							Va2

Ammonite zones supported by macrofauna Ammonite zones defined according dinoflagellate distribution

Figure 3.: Correlation of several parabiostratigraphic scales (based on ammonites, dinocysts, calpionellids and nannoplankton) and sequence stratigraphic elements of Lower Cretaceous resulting from the Butkov sequence study

2.3. The Mráznica Formation

The Mráznica Formation (the Peregrinus and Furcillata zones) has been insufficiently studied in detail due to poorer exposures and worse eustatic record. Therefore, the exact position of missing sequence boundaries (Va-5, 6 and two unnamed ones) is unknown. The formation sedimented under poorly stratified water column. The oxygen was transported by vertical currents and enabled life of infaunal organisms (bioturbation). However, the bottom was too soft and not enough consolidated for colonisation by benthic fauna. Moreover, local anoxia was caused by input of unoxidated organic matter. Temporal terrigeneous input indicates raised humidity. Condensation of the uppermost part of the sequence (Callidiscus Subzone) is probable, but not confirmed yet.

The boundary between the Ladce Fm and overlying it Mráznica Fm is not sharp. Abundant ammonite remnants (several hundreds of specimens) of the Furcillata Zone date Late Valanginian age of the Mráznica Fm: *Criosarasinella furcillata* Thieuloy, *C. mandovi* Thieuloy, *C. coniferus* Busnardo, *Teschenites subflucticulus* Reboulet. Higher part of the sequence yielded *Crioceratites heterocostatus* Mandov, *Teschenites subpachydicranus* Reboulet, *Olcostephanus densicostatus* (Wegner), *Oosterella cultratoides* (Uhlig). All the ammonite shells found are dominated by sculptured forms.

Marly limestone sequence contain very rare microfossils of the Tintinnopsella Zone, rare remaniellids indicate erosion of older deposits. Calcareous nannofossils belong to the Late Valanginian Tubodiscus verenae Subzone (NK–3). The nannofossils assemblages are composed of both cosmopolitan representatives (*Watznaueria barnesae, Cyclagelosphaera margerelii, Rhagodiscus asper, Zeugrhabdotus embergeri, Cretarhabdus* spp., *Micrantholithus* spp.) together with Tethyan taxa (*Conusphaera mexicana, Cyclagelosphaera deflandrei, Cruciellipsis cuvillieri* and *Nannoconus* spp.). Rare Upper Valanginian and Lower Hauterivian Boreal taxa has been noticed (*Micrantholithus speetonensis, Crucibiscutum salebrosum, Nannoconus pseudoseptentrionalis*). Rich and diverse association of Upper Valanginian non-calcareous dinoflagellates belongs to the *Cymososphaeridium validum* (Cva) Zone determined by Leereveld (1997a, b). *Cymososphaeridium validum, Dingodinium cerviculum, Oligosphaeridium asterigerum* and *Bourkidinium elegans* occurred for the first time here. The composition of dinoflagellate assemblages reflects original marine environment of several hundred meter depths (littoral to brackish types predominate, e.g. *Circulodinium, Muderongia*).

2.4. The Kališčo Formation

The formation starts with calciturbidite layer. Five Hauterivian sequence boundaries (Ha-1-5) have been recognized in the Kališčo Fm and one (Ha-6) in the basal part of the Lúčkovská Formation. Due to poorer exposures we do not know the exact position of the Ha-7 sequence boundary.

Thick-bedded limestones of the lowstand tracts (thickness of 1-3 m) contain brachiopod shells and crinoid calyces. Rich ammonite and nannofossils associations characterise transgressive system tracts. The radiolarians reached the maximum of abundance during maximum flooding intervals. Calcareous lamellaptychi are represented by thick-valved types dominated by *L. didayi* and *L. seranonis*. Highstand system tracts are build of thin bedded limestones with marly intercalations.

Ammonites *Teschenites flucticulus* Thieuloy, *Eleniceras tchechitevi* Breskovski, *Jeanthieuloyites nodosus* (Mandov), *Olcostephanus hispanicus* (Mallada) prove for earliest Hauterivian age (the Radiatus Zone, although zonal index was never found) of the Kališčo Formation base. More frequent criceraticone forms like *Crioceratites nolani* (Kilian) and *C. loryi* Thieuloy (zonal index) together with sole *Olcostephanus (Jeannoticeras) jeannoti* (d´Orbigny) occur higher up in the sequence. The Nodosoplicatum Zone was not documented (like nowhere in Western Carpathians) yet. The Sayni Zone was proved by findings of *Subsaynella sayni* (Paquier) co-occurring with *Ptychoceras meyrati* Ooster in pelagic chert limestone sequence of the Kališčo Fm. Plesiospitidiscus ligatus (d´Orbigny) accompanied by P. meyrati and Abrytusites thieuloyi Vašíček & Michalík dates Late Hauterivian Ligatus Zone (Fig.3). *Tintinnopsella carpathica* occurs sporadically in the Kališčo Fm. Calcareous nannofossils denote the NC-4A and NC-4B Subzones correlated with the onset of the Nodosoplicatum Ammonite Zone. Low content of nannoconids and the abundance of *Micrantolithus hoschulzii* is a characteristic feature of Early Hauterivian nannofossil associations. Association of non-calcareous dinoflagellates belongs to the *Muderongia staurota* (Mst) Zone, the span of which is correlated with the ammonite Radiatus and lowermost Nodosoplicatum zones. This assumption is estimated also by the first appearance of *Achomosphaera verdieri, Histiocysta outananensis, Florentinia* sp., *Coronifera oceanica* and by the presence of coeval nannofossils. *Lithodinia stoveri* (Lst) dinozone was identified in the uppermost Lower Hauterivian ammonite Nodosoplicatum Zone.

The lithology of upper part of the Kališčo Fm did not supported dinoflagellate preservation. It is worth of mention that the brackish species (*Muderongia*) of non-calcareous dinoflagellates dominated just during the lowstand conditions of global sea-level. On the other hand, neritic (*Oligosphaeridium, Spiniferites*) and oceanic (*Pterodinium*) dinoflagellate species prevailed during the transgressive and high stand intervals in the time of higher nannoplankton and microplankton diversity.

2.5. The Lúčkovská Formation

The sequence stratigraphic pattern of the Barremian part of the Lúčkovská Formation and of the „Urgonian" complex (Podhorie- and Manín formations) was not studied due to lack of undisturbed, fresh and properly oriented exposures (this part of the sequence is not quarried in the last time).

Although we were not successfull in searching for the *Pseudothurmannia balearis*, the index of the Late Hauterivian Balearis Zone, the ammonites found in the basal

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Figure 4.: Panoramic view on north-western slope of Mt Butkov with the Ladce Cement Works quarry.

part of well bedded grey micritic limestones of the Lúčkovská Fm use to be associated with it: frequent Barremites, Crioceratites ex gr. majoricensis Nolan, ?Discoidella vermeuleni Cecca, Faraoni et Martini. Neither Late Hauterivian Ohmi Zone nor several next Barremian ammonite indexes (Hugii, Nicklesi, lower part of Pulchella and Darsi Zones) were found. However, presence of the Compressissima Zone is supported by abundant barremitids, but also Nicklesia pulchella (d´Orbigny), Moutoniticeras nodosum (d´Orbigny), Dissimilites dissimilis (d´Orbigny), Patruliusiceras lateumbilicatum Avram, Parasaynoceras tzankiovi Avram, Metahoplites cf. nicklesi (Karakasch), Holcodiscus cf. gastaldii Kilian, Paraspiticeras sp. The ammonite finding of Toxancyloceras vandenheckii (Astier) coming from scree in the highest part of the Lúčkovská Fm sequence supports the presence of the basal Late Barremian Vandenheckii Zone.

The Upper Hauterivian aptychi association is characteristic of angulocostate lamellaptychi only (*L. angulocostatus angulocostatus*, *L. a. angulicostatus*). These valves represent stratigraphically youngest specimens within lamellaptychi associations studied.

Sporadic *Tintinnopsella carpathica* occurs in the lowermost part of the formation. The calcareous nannofossil assemblage belongs to the Litraphidites bollii Zone, NC-5B Subzone. If compared with Kališčo Fm, nannoconid abundance increased. The block from the eastern part of the 7th etage (BK-7/V) belongs to the Early Barremian Micratholithus hoschulzii Zone, NC-5D Subzone.

Rich palynomorphs were observed in the Lúčkovská Fm, although none specific dinozone could have been determinable in the lower part of sequence. Early Barremian *Subtilisphaera scabrata* (Sca) dinozone (with the first occurrence of *Cerbia tabulata*) and Late Barremian *Odontochitina operculata* (Oop) dinozone (with the first occurrence of *Prolixosphaeridium parvispinum*) were identified in the upermost part of the formation. Dinoflagelate cysts of littoral environment (*Cerbia, Tenua*) dominate over neritic types.

2.6. The Podhorie and Manín formations

Dark bituminous organodetrital cherty limestones of the Podhorie Fm contain bad preserved, corroded dinoflagellates, such as *Cerbia tabulata, Cleistosphaeridium clavulum, Oligosphaeridium dividuum*, which allow to suppose Late Barremian or younger age of the formation. Upwards, they pass into carbonate platform limestones of the Manín Formation (Michalík and Soták, 1990). These shallow water carbonate deposits have not been studied in detail, yet.

2.7. The Butkov Formation

Dark brown gray shales of the Butkov Formation rest with gap on the corroded condensed surface of the Manín Formation. They contain glauconite grains, plant debris and planktonic foraminifers (Boorová and Salaj, 1992). Dinoflagelate cysts of open neritic (*Achomosphaera, Litosphaeridium*) and pelagial associations (*Pterodinium*) dominate over acritarchs (*Wallodinium, Veryhachium*), bisaccate pollen grains and microforaminifers. The first occurrence of *Litosphaeridium siphoniphorum* coincides with Late Albian ammonite Inflatum Zone, the appearence of *Protoellipsodinium conulum* together with *Endoceratium dettmaniae* and *Ovoidinum verrucosum* coincides with the youngest Albian ammonite Dispar Zone. *Atopodinium perforatum, Dinopterigium cladoides, Pervosphaeridium pseudhystrichodinium, P. truncatum, Xiphophoridium alatum*, and other Albian forms are abundant in dinoflagellate associations. Very rare findings of *Eiffelithus*

turriseiffelii allow to suppose late Early Albian age of the formation or assign the base of the Eiffelithus turriseiffelii Zone (CC9) sensu Perch-Nielsen (1985).

3. Conclusions:

1. The pelagic limestone sequence of Mt Butkov exposed by the Ladce Cement Works quarry is the best documented representative Lower Cretaceous sequence in Western Carpathians at all.
2. Basal Berriasian gap represents a characteristic feature of the Manín Unit, it is connected with the paleogeographic setting of this unit in the basin.
3. The Ladce Formation comprises Campylotoxus-, Verrucosum- and Peregrinus ammonite zones correlable with calpionellid Calpionellites Zone and with lowermost part of the Tintinnopsella Zone.
4. The Mráznica Formation is a product of dysoxic episode spanning the ammonite Furcillata Zone – an equivalent of dinoflagellate Validum Zone.
5. The Kališčo Formation has been deposited during ammonite Radiatus-, Loryi-, Nodosoplicatum-, Sayni-, and Ligatus zones. The lower part of the formation belongs to dinoflagellate Staurota and Stoveri zones, dinocysts are poorly represented higher up in the sequence.
6. The Lúčkovská Formation was the last part of the Lower Cretaceous pelagic limestone sequence. Its lowermost part (? Balearis Zone) is poorly dated, higher part of the sequence belongs to Hugii-, Nicklesi-, Pulchella-, Compressissima-, and Vanderheckii zones. The last zone is comparable with dinocyst Operculata Zone.
7. The Podhorie and Manín formations represents products of „Urgonian" carbonate platform, which developed since Aptian to the end of Early Albian.
8. The Butkov Marl Formation is equivalent to nannoplankton Turriseiffelii Zone, compared with the duration of ammonite Inflatum and Dispar zones.
9. Correlation of ammonites, aptychi, calpionellids, dinocysts and nannoplankton gives clue to precisioning of biostratigraphic division of Lower Cretaceous sequences.

References:

Bergen J. A., 1994: Berriasian to Early Aptian calcareous nannofossils from the Vocontian trough (SE France) and deep sea drilling Site 534: new nannofossil taxa and summary of low-latitude biostratigraphic events. *Journal of Nannoplankton Research* 16, 2., 59-69.

Boorová D., Salaj J., 1992: Remarks on the biostratigraphy on the Butkov Formation in the Manín sequence. *Geologica Carpathica* 43, 2., 123-126.

Borza K., Michalík J. & Vašíček Z., 1987: Lithological, biofacies and geochemical characterization of the Lower Cretaceous pelagic carbonate sequence of Mt Butkov (Manín Unit, West Carpathians). *Geologický zborník Geologica Carpathica* 38,3., 323 - 348, 13 figs.

Bown P. R., Rutledge D.C., Crux J.A. & Gallagher L.T., 1998: Lower Cretaceous. In: Bown P. R. (ed.): Calcareous nannofossil biostratigraphy. *Chapman and Hall*, 86-131.

Bralower T.J., Monechi S., Thierstein H.R., 1989: Calcareous Nannofossil Zonation of the Jurassic - Cretaceous Boundary Interval and Correlation with the Geomagnetic Polarity Timescale. *Marine Micropal.* 14., 153-235.

Detraz H., Mojon P.-O., 1989: Évolution paléogéographique de la marge jurassienne de la Téthys du Tithonique-Portlandien au Valanginien: corrélations biostratigraphiques et séquentielles des facies marins à continentaux. *Eclogae geol. Helvetiae 82, 1.*, 37-112.

Hardenbol J., Thierry J., Farley M.B., Jacquin T., de Graciansky P.C. & Vail P.R., 1998: Mesozoic and Cenozoic sequence stratigraphy of European basins. *SEMP, Spec. Publ.* 60.

Hoedemaeker Ph. J., 2002: 11. Correlating the uncorrelatables: A Tethyan-Boreal correlation of Pre-Aptian Cretaceous strata. *In*: Michalík J. (ed.): Tethyan/Boreal Cretaceous Correlation. Mediterranean and Boreal Cretaceous paleobiogeographic areas in Central and Eastern Europe. *Veda*, 235-284. Bratislava.

Hoedemaeker P. J., Reboulet S. (eds.) & 17 co-authors, 2003: Report on the 1st International Workshop of the IUGS Lower Cretaceous Ammonite working Group, the "Kilian Group" (Lyon, 11 July 2002). *Cretaceous Research* 24., 89-94.

Jan du Chene R., Busnardo R., Charollais J., Clavel B., Deconninck J.-F., Emmanuel L., Gardin S., Gorin G., Manivit H., Monteil E., Raynaud J.-F., Renard M., Steffen D., Steinhauser N., Strasser A., Strohmenger C. & Vail P.R., 1993: Sequence – stratigraphic interpretation of upper Tithonian-Berriasian reference sections in SE France: a multidisciplinary approach. *Bull. Centre Rech. Ex.-Prod. Elf-Aquitaine* 17, 151-181.

Leereveld H., 1995: Dinoflagellate cysts from the Lower Cretaceous Río Argos succession (SE Spain). *Lab. Palaeobot. Palynol. Contr. Ser.* 2., 1-175.

Leereveld H., 1997a: Upper Tithonian – Valanginian (Upper Jurassic – Lower Cretaceous) dinoflagellate cyst stratigraphy of the western Mediterranean. *Cretaceous Research* 18., 385-420.

Leereveld H., 1997b: Hauterivian – Barremian (Lower Cretaceous) dinoflagellate cyst stratigraphy of the western Mediterranean. *Cretaceous Research* 18., 421-456.

Michalík J. & Vašíček Z., 1987: Geológia a stratigrafia ložiska spodnokriedových vápencov Butkov (manínska jednotka, stredné Považie). *Mineralia Slovaca* 19,2., 115 - 134.

Michalík J. , Gašparíková V., Halásová E., Peterčáková M. & Ožvoldová L., 1990: Mikrobiostratigrafia vrchnojurských a spodnokriedových súvrství manínskej jednotky v profile Butkov pri Ladcoch, Strážovské Vrchy, Centrálne Západné Karpaty. *Knihovna Zemního plynu a nafty* 9 b., 23 - 55.

Skupien P., Vašíček Z., Reháková D., Halásová E. 2003: Biostratigraphy of Lower Cretaceous of the Manín Unit (Butkov Quarry, Strážovské vrchy Mts., Western Carpathians). *Sbor. věd. Prací Vys. Školy báňské -TU, Ř. horn.-geol., 1, 49. 91-97.*

Thierstein H. R., 1973: Lower Cretaceous calcareous nannoplankton zonation. *Eclogae Geol. Helvetiae* 64, 459-488.

Vail P.R., Hardenbohl J. & Todd R.G., 1984: Jurassic unconformities, chronostratigraphy and sea-level changes from seismic stratigraphy and biostratigraphy. *Amer. Assoc. Petrol. Geologists Memoirs* 36., 129-144.

Vašíček Z. & Michalík J., 1986: Lower Cretaceous ammonites of the Manín Unit (Mt Butkov, W. Carpathians). *Geologický zborník Geologica Carpathica* 37,4., 449 - 481.

Vašíček Z., Michalík J., Reháková D., 1994: Early Cretaceous stratigraphy, paleogeography and life in Western Carpathians. *Beringeria* 10., pp. 1-170.

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A contribution to the tectonics of the Periklippen zone near Zázrivá (Western Carpathians)

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Abstract. Field structural evidences of southvergent reverse faulting (i.e. backthrusting in relation to the polarity of the orogen) were observed and analysed within the Periklippen zone of the Orava segment of the Pieniny Klippen Belt near Zázrivá village. The studied area is situated at the northern rim of the Central Western Carpathians affected by transpressional tectonic regime operating in the Pieniny Klippen Belt zone dividing the Central and Outer Western Carpathians. The sediments of the Central Carpathian Paleogene Basin rimming the Pieniny Klippen Belt from the south are tectonically deformed. Miocene (post-Oligocene) folding and backthrusting is recorded in meso-scale structures observed in the outcrops, as well as it results from the analysis of bedding attitudes of the Paleogene sediments. The backthrust tectonic style of the area is evident from the map-scale structures and deep reflection seismic profile, too. A tectonic slice of the Paleogene sediments, tectonically incorporated along south-vergent large-scale thrusts to the Mesoszoic nappe units is interpreted in the geological map. Structural interpretation of 2T seismic profile shows distinctive south-vergent (north dipping) reflectors as well. The reflectors have been interpreted as crustal-scale backthrusts.

Key words: Pieniny Klippen Belt, backthrusting, transpression, folds, paleostress, Neoalpine tectonics

Introduction

Alpine-type fold and thrust belts usually show distinctive polarity of tectonic transport within the orogen. Plate convergence results in shortening, usually realized by orogenic front vergent folding and/or thrusting. The evident vergence of tectonic movement towards the orogenic front can be explained by an active propagation of hinterland towards the stable foreland. Meso-Neoalpine tectonic evolution of the Western Carpathians was controlled by long lasting (Upper Cretaceous – recent) squeezing between the North European Platform and promoted the Apulia-Adria microcontinent pushed by the Africa lithospheric plate to the north. It led to the strong dominance of the north-verging tectonic structures within the Central, as well as Outer Western Carpathians (Flysch Belt) where asymmetric accretionary orogenic wedge was created due to consumption of a quasi-oceanic Peninic (Vahic) crustal slab. Nevertheless, south-verging, high-angle thrusts have been already described in the eastern part of the Pieniny Klippen Belt (Nemčok & Rudinec, 1990; Plašienka et al., 1998). The south vergent reverse faulting in studied area has been first described by Matějka (1931) in the Medzirozsutce saddle and later accepted in tectonic interpretation of the area (Haško & Polák, 1978).

During the last years, we have had an opportunity to study systematically the zone of tectonic junction of the Central and Outer Western Carpathians in the eastern part of the Malá Fatra Mts. and the Kysucké vrchy Mts (Fig. 1). From detailed geological mapping and structural analysis resulted that the geological structure in tight contact with the Pieniny Klippen Belt zone is also strongly affected by backthrusting. The studied area is extended south of the Pieniny Klippen Belt around Zázrivá village. The wider area is occupied by four tectonic units listed from the north to the south (Fig. 2): a) Pieniny Klippen Belt; b) Central Carpathian Paleogene Basin, c) Fatric and Hronic units, d) Tatric unit. The background knowledge concerning the geology and tectonics of the area has come from the geological maps and investigations of Andrusov & Kuthan (1943), Haško & Polák (1978), Potfaj (1974, 1979, 1998), Samuel & Haško (1978), Rakús (1984), Aubrecht et al. (2004), Marko et al. (2004).

The presence of backthrusting within the studied area has been already suggested by Haško & Polák (1978) according the map scale structures arrangement. We submit herein structural-tectonic evidences and geodynamical interpretation of south vergent reverse faulting in the Periklippen zone near Zázrivá village.

Geological settings

Studied area occupies the junction zone of Central and Outer Western Carpathians. The geological structure of the Central Western Carpathians is created by several superposed Meso-Alpine Tectonic Units (e.g. Tatric, Fatric and Hronic Units). Neo-Alpine structure of the Outer Western Carpathians is represented by the Magura nappe, the northernmost unit within the tectonic profile (Fig. 2). Overall tectonic style of the studied area is con-

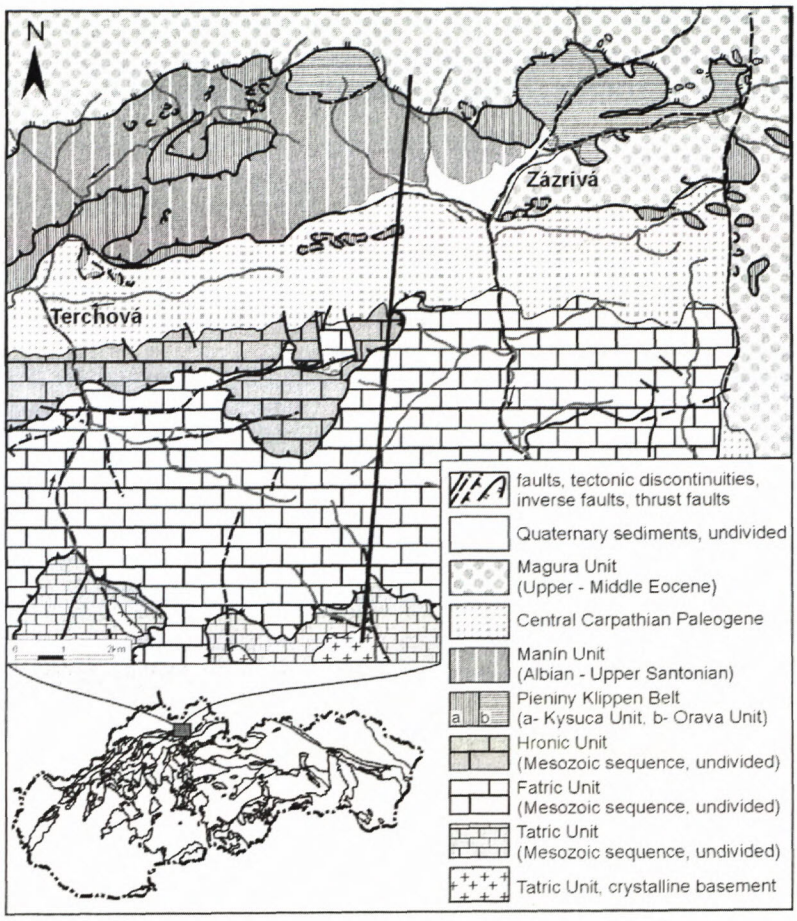

Fig. 1: Tectonic sketch of the Zázrivka River valley according to Haško & Polák (1978) with the line of the tectonic cross-section, slightly modified.

trolled by paleodynamics of the Pieniny Klippen Belt, zone of extreme shortening and shearing, accommodating convergence and translation of two stacking principal Neo-Alpine systems of the Western Carpathians – the Outer Carpathian accretionary wedge and the Central Western Carpathian orogenic backstop.

The Tatric superunit

The Variscan basement of the Tatric superunit is formed by biotitic and mica granites with authometamorphosed granodiorites, and biotitic and quartzitic diorites to granodiorites (Haško & Polák, 1978). The Tatric basement is covered by the sedimentary sequence that starts with the Scythian detrital sediments, the Middle Triassic carbonates and the Upper Triassic shales and quartzites of the Carpathian Keuper Formation. The Jurassic sequence is represented mostly by the Lias facies and "Fleckenmergel" facies. The Dogger and Malm sediments are formed predominantly by radiolarian limestones. The marly cherty limestones with intercalations of shales are typical formation of the Tithonian-Neocomian age, overlain by Aptian marly limestones, Albian synorogenic flysch sediments and Cenomanian silicic clastic sediments.

The Fatric superunit

The Fatric superunit (Krížna nappe) represents the lowest nappe system, which overthrusts the Tatric superunit. Stratigraphic ranging is from the Anisian to the Albian. The lowermost member of the Krížna nappe are the Anisian Gutenstein limestones. The Triassic sequence is predominantly carbonatic (limestones and dolomite). This is disconnected by the Lunz sandstones and claystones during the Lower Carnian and by quartzitic sandstones, claystones and dolomites of the Carpathian Keuper Formation. The Jurassic to Lower Cretaceous sequence of the Krížna nappe is represented by the deep-water Zliechov succession dominated by hemipelagic marly limestones and radiolarites, terminated by the Mid-Cretaceous flysch.

The Hronic superunit

The Hronic superunit (Choč nappe) represents the highest nappe system, which overthrusts the Krížna nappe. It forms of two separate tectonic duplexes: a) the Veľký Rozsutec duplex and b) the Malý Rozsutec duplex. The Choč nappe mostly consists of carbonate platform sediments ranging from the Anisian to Norian. The dominant sediments are dolomites that form the main mass of the Choč nappe. The rock sequence starts with the Gutenstein limestones and finish with the Hauptdolomite in the Norian. The carbonatic sequence is intercalated by the Lunz event, represented by clastic sedimentation of sandstones and sandy claystones.

The Central Carpathian Paleogene Basin

The sediments of the Central Carpathian Paleogene Basin are extended on the northern slopes of Malá Fatra Mts. They are dissected by the Pieniny Klippen Belt from north and by Párnica sigmoid structure from east. Its stratigraphic range is from the Upper Paleocene to the Upper Eocene. The sedimentary succession was also considered to the Žilina-Hričovské Podhradie Paleogene Basin (Haško & Polák, 1978; Samuel & Haško, 1978). The Eocene shallow to deep-marine sediments transgressive overlying the Mesozoic rocks of the Malá Fatra Mts. are preserved in surroundings of Zázrivá village. The sedimentary succession is represented by sediments of the Borové, Huty, Zuberec Formations and the Pucov Member (sensu Gross et al., 1984). The Borové Formation consists of the carbonate conglomerates, breccias, sandstones and organodetrical limestones. It represents shallow marine transgressive finning and deepening upward sedimentary succession. The overlying Huty Formation consists of the massive mudstones alternating with sandstone and siltstone intercalations deposited in mud-rich submarine fan. Sandstones are predominantly thin-bedded with the Bouma's Tc-d intervals (Bouma, 1962), coarse-grained and thick-bedded sandstones with basal Bouma's interval are uncommon. In the lowermost part of

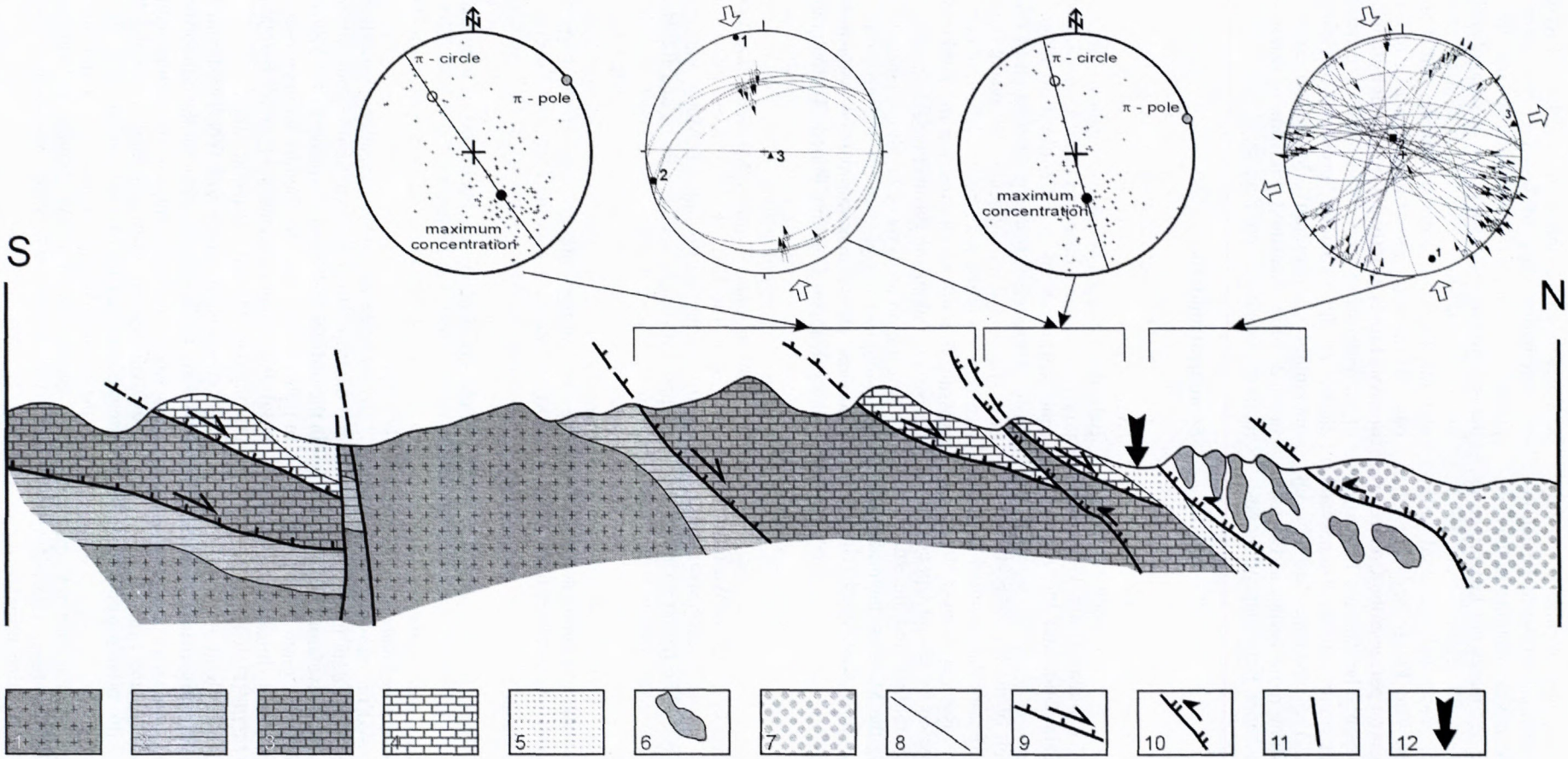

Fig. 2: Idealised tectonic cross-section of the Central and Outer Western Carpathian junction area along Zázrivka River valley (according to Haško & Polák 1978, addapted). 1) The crystalline of the Tatric supernit; 2) the Mesozoic cover of the Tatric superunit; 3) The Fatric superunit (Krížna nappe); 4) The Hronic superunit (Choč nappe); 5) The Central Carpathian Paleogene Basin sediments; 6) The Pieniny Klippen Belt; 7) The Magura supernit; 8) Lithological boundaries; 9) Meso-Alpine thrust, 10) Neo-Alpine thrust, 11) fault; 12) Localization of the outcrop Zázrivá/Terchová road crossing.

the Huty Formation, deposits of the Pucov Member are preserved. The Member composes of unsorted boulder conglomerates, sometimes with sandstone intercalations. The red colour of conglomerates is changing to grey one in upward direction. These sediments are interpreted as submarine canyon or channel fill (Gross et al., 1982), however, they have probably deposited in incised valley and fan-delta environments. The Pucov body cuts the Borové Formation and in central part also the Cretaceous Formation of the Krížna nappe. The Zuberec Formation consists of mudstones alternating with sandstones and locally with conglomerates. The sandstones are thin- up to thick-bedded and they show more complete Bouma's intervals. The sandstone/mudstone ratios depend on position in a submarine fan.

The Pieniny Klippen Belt

The Pieniny Klippen Belt within the studied area is formed by the Hettangian to Lower Maastrichtian Kysuca Unit, the Lotharingian to Neocomian Orava Unit, Aalenian to Neocomian Czertezik Unit, and the Albian to Lower Santonian Manín Unit.

The Pieniny Klippen Belt of the Kysucké vrchy displays a complex tectonic structure that resulted from its special geotectonic position. Rock sequences of the Pieniny Klippen Belt are affected by strong Upper Cretaceous to Lower Paleocene folding and thrusting and Miocene wrenching. During the Miocene tectonic activity, mostly brittle fault structures developed (Haško & Polák, 1978).

The Magura nappe

The Magura nappe belongs to the Outer Western Carpathians and is represented by the Eocene sediments of the Bystrica and Krynica Units. The Krynica Unit is extended in surroundings of Zázrivá village, both, north from Pieniny Klippen Belt and in narrrow belt tectonically incorporated between two branches of the Pieniny Klippen Belt. This unit is formed by alternated glauconitic sandstones a grey claystones, occasionally are developed red claystones.

Methods

The methodology applied during the research included detailed geological mapping (scale 1:10 000) and structural investigation focused on mesoscale fault and fold analysis. The measured fault data have been processed by analytical paleostress inversion method (Angelier 1989, 1994), using software application Tectonics FP (by F. Reiter & P. Acs, Univ. Innsbruck, Austria) and software package TENSOR (Delvaux, 1993, Delvaux and Sperner, 2003). The crucial step in the field structural research of faults was kinematical analysis of fault slips, based upon the evaluation of asymmetric structures of slickenside surfaces and evaluation of outcrop-scale structures genetically related to the fault dynamics.

Analysis of folds orientation in the Central Carpathian Paleogene Basin sediments has been realized using mesoscale fold data as well as bedding attitudes of measured during geological mapping. The paleostress field and backthrust tectonic style have been determined using the orientation data of bedding, fold axes and axial planes. The principal deformational axes have relation to the fold geometry. A strain axis is parallel with the direction of the maximum elongation, C strain axis is parallel with the direction of the shortening, and B strain axis is parallel with direction of fold axis (axis of rotation). Geometry of folds exactly defines relations to the orientation of the paleostress axes. Fold axes are generally perpendicular to the maximum principal paleostress axis σ_1 (maximum compression). Macrofold axes were constructed from measured fold limbs using the π pole method (construction of β axes).

Structural analysis

The field investigation was focused on structural records of deformation events south of the Pieniny Klippen Belt along the Zázrivka river valley. Meso-scale structural records were observed in the Upper Eocene – Oligocene sediments of the Central Carpathian Paleogene Basin. Attitudes of bedding, orientation of fold axes and fault slip data were collected. All available outcrops are localised along the trace of the structural/tectonic profile crossing in north-south direction the Periklippen Central Carpathian Paleogene Basin (Fig. 2).

Orientation analysis of bedding planes measured during geological mapping in the Paleogene and Mesozoic sediments shows that sedimentary sequences near the Pieniny Klippen Belt are folded. Tectonograms display arrangement of bedding poles, typical for tautozonal set of planes – limbs of tectonic folds. Constructed fold axes are subhorizontal with WSW-ENE azimuths, gently plunging to the ENE (Fig. 2). Axial planes of folds are mostly steeply north dipping. Many axial planes have steeper and shorter southern limbs and flatter and longer northern limbs. Except constructed macrofolds, there were observed and measured meso-scale folds in the sediments of the Central Carpathian Paleogene Basin (Fig. 3). We studied the Paleogene sediments exposed along a short N-S defilé across the Huty and Zuberec formation. According to the presence of the well developped Bouma´s intervals (Bouma, 1962), the north dipping flysch sedimentary sequences are in a normal position. Sandstone beds are folded, fold axes have ENE-WSW up to E-W direction and axial planes are dominantly north dipping.

Meso-scale slickenside lineations were studied in several outcrops along the structural/tectonic profile (Fig. 2) in the bedrock Paleogene sequences of the Zázrivka River in tight contact with the Pieniny Klippen Belt, and in the basal Paleogene sequences (Borové Formation) transgreding over Mesoalpine nappe units.

A conjugate population of WNW-ESE and NNE-SSW strike-slip faults was described in the outcrops of the Zázrivka River, in the vicinity of the Pieniny Klippen Belt. This fault system was activated under the NNW-SSE compression and ENE-WSW tension (Fig. 2). Southerly, in the basal Paleogene sequences (Čremoš hill), a dominant population of NNW dipping reverse slickensides, activated under NNW-SSE compression was observed (Fig. 2).

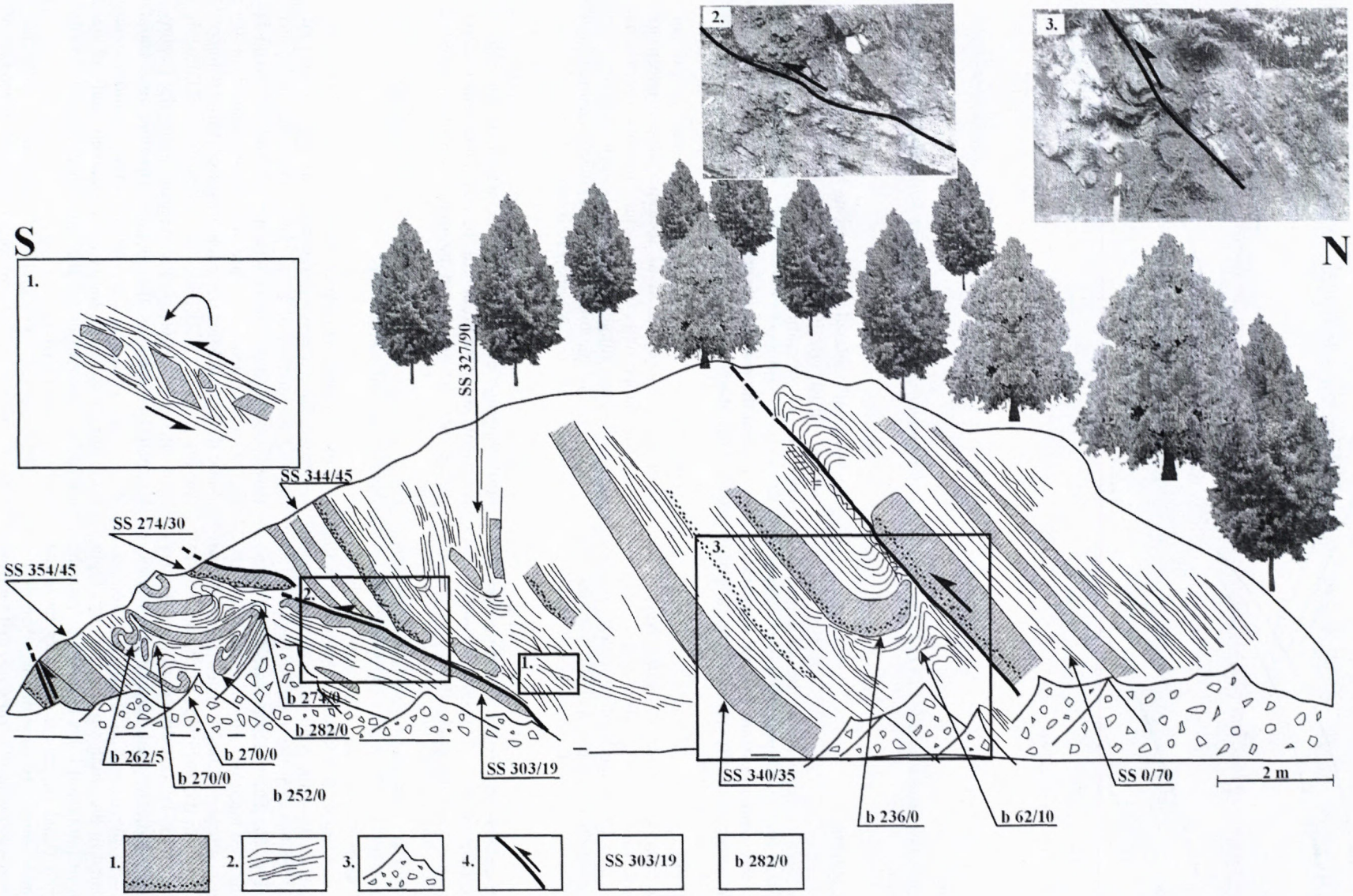

Fig. 3: Defilé across the Zuberec flysch formation of the Central Carpathian Paleogene Basin sediments (Locality Zázrivá/Terchová road crossing). 1) graded sandstone beds, occasionally with fine-graded conglomerates on their bases; 2) claystones, 3) recent debris; 4) interpreted reverse faults, 5) dip direction and dip of bedding , 6) azimuth and plunge of fold axis.

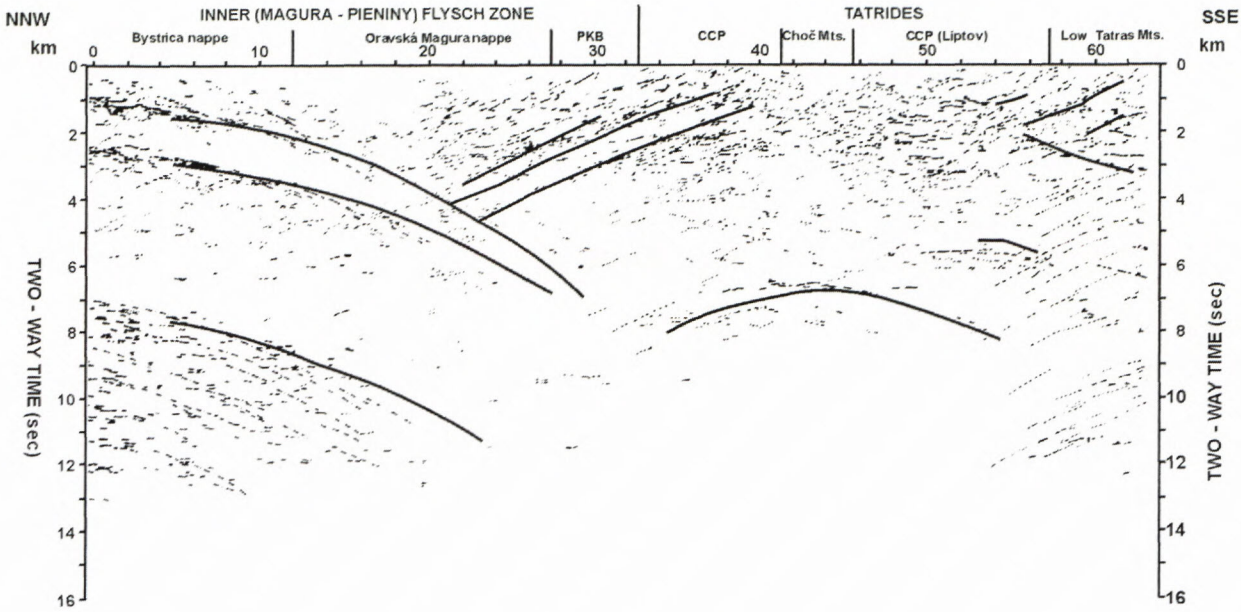

Fig. 4: Deep reflection seismic profile 2T (Tomek et al., 1987) with highlighted dominant reflectors interpreted as crustal-scale backthrusts.

Tectonic interpretation

Structural research realized along the structural/tectonic profile south of Pieniny Klippen Belt in the Zázrivá valley shows that the sediments of the Central Carpathian Paleogene Basin geodynamically representing a post-nappe unit are fairly strongly affected by tectonic faulting and folding. Both, faults and folds could have been generated during the same tectonic event, under NNW-SSE oriented maximum principal stress axis σ_1.

Processing of data by methods of structural analysis allowed to determine character and tectonic regimes operating during the deformational events. It follows, from analysis of fault-slip data; the change of the tectonic regime from the north to the south has occurred. The dominant strike-slip transpressional tectonic regime operated near the Pieniny Klippen Belt. Towards the south, the transpressional tectonic regime gradually changed up to the pure compressional tectonic regime producing reverse faulting (Fig. 2). The most distinctive and numerous population of meso-scale faults represents south vergent reverse faults. The most spectacular locality which has rendered the evident proof of southern vergency (top to the south) of these faults is the road cut just at the road crossing (Zázrivá/Terchová) at the southern periphery of Zázrivá village (Fig. 3). The outcrop-scale faults alone and their kinematics are interpreted there according to the presence and the geometry of fault-related folds. These folds even a drag fold in the right side of the outcrop as well as constructed folds from bedding attitudes display asymmetry generally indicating southern vergency (especially in the case of macrofolds (Fig. 2). We interpret these folds as related to the south vergent faulting. Tight genetical relation of faults and folds come also from the fact, that they both could be generated under the same maximum principal stress axis orientation, that means during the same tectonic event. We suppose, that faulting and folding observed south of the Pieniny Klippen Belt are genetically related to large-scale backthrusting (south vergent thrusting). It resulted from transpressional tectonic regime operating between the Outer and Central Western Carpathians.

Except the meso-scale structures, there are map-scale, even crustal-scale evidences of backthrusting within the wider area. An interpretation of Central Carpathian Paleogene Basin sediments occurence as the narrow belt tectonically incorporated as tectonic slice between the Mesozoic nappe units (see structural/tectonic profile) fits well with above suggested backthrust tectonic style.

Large-scale picture of the backthrust tectonic style south of the Pieniny Klippen Belt emerges from the deep reflection 2T seismic profile (Tomek et al., 1987; Tomek, 1993). There are recorded very distinctive crustal-scale north-dipping reflectors (Fig. 4), which as we believe represents southern branch of the post-Paleogene positive flower structure developed due to the shearing in between the Outer and the Central Western Carpathians.

Discussion and conclusions

Poles to bedding of both the Paleogene and Mesozoic sediments have a very similar array, so the style of folding and orientation of folds seems to be the analogous. However, the question is whether all folds observed in the Mesozoic sequences are genetically related to the above-described Miocene backthrusting. Another important question is the distance to which the backthrusting (generated by transpressional shearing along the Pieniny Klippen Belt) affects the tectonic structure of Central Western Carpathians. The answer to this question would need further research focussed to detailed study of deformation events along the structural/tectonic profile south of Zázrivá village.

The observed folds and folds constructed from attitudes of bedding planes are regarded to be a product of compressional tectonics. The outcrop Zázrivá/Terchová

road cross renders also crucial evidences of south vergent reverse faulting in the Central Carpathian Paleogene rocks. Nevertheless, folds in sandstone beds observed in the left part of exposure are most probably product of a submarine slump event that should have preceded the tectonic backthrusting.

In summary of our investigation we conclude that distinctive map and the outcrop-scale structural record of compressional tectonics have been observed south of the Pieniny Klippen Belt zone in a broader vicinity of Zázrivá village. This deformation structures are genetically related to the large-scale backthrusting (i.e. south vergent thrusting) represented by reverse faults and asymmetric south vergent folds.

The backthrusting was connected with the strike-slip tectonic activity along the Pieniny Klippen Belt due to the sinistral transpressional regime operating in between the Central and Outer Western Carpathians from the Karpatian up to the Middle Badenian (Marko et al., 1995, Kováč & Hók, 1996). This process led to the development of a positive flower structure, which is visible in the deep reflection seismic profiles (Tomek et al., 1987; Tomek, 1993).

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References

Angelier, J., 1989: From orientation to magnitudes in paleostress determinations using fault slip data. Journal of Structural Geology, Vol. 11, No.1/2, 37-50.

Angelier, J., 1994: Fault slip analysis and palaeostress reconstruction. In: Hancock P. L. (Ed.): Continental deformation. Pergamon Press, University of Bristol (U. K.), London, 53-100.

Aubrecht, R., Gaži, P., Bučová, J., Hlavatá, J., Sestrienka, J., Schlogl, J. & Vlačiky, M., 2004: On the age and nature of the so-called Zázrivá beds (Pieniny Klippen Belt, Western Carpathians). Min. slovaca, 36, 1, 1-7

Bouma, A. M., 1962: Sedimentology of some flysh deposits. Amsterdam, Elsevier, 168 p.

Gross, P. Köhler, E. & Borza, K., 1982: Conglomerate submarine fans in Central-Carpathian Paleogene near Pucov. Geologické práce, Správy 77, Bratislava, 75-86.

Gross, P., Köhler E. & Samuel, O., 1984: New lithostratigraphic dividing of the Inner Carpathian Paleogene. Geologické práce, Správy 81, 113-117 (in Slovak).

Delvaux, D. F., 1993: The TENSOR program for paleostress reconstruction: examples from the east African and the Baikal rift zones. - TERRA nova, 5, suppl n°1, Proceedings of EUG VII, Strasbourg, 4-8 April., s. 216.

Delvaux, D. & Sperner, B., 2003: New aspects of tectonic stress inversion with reference to the TENSOR program. In: Nieuwland D. A. (Ed.): New Insights into Structural Interpretation and Modelling. Geological Society, London, Special Publications, 212, 75-100.

Haško, J. & Polák, M., 1978: Geological map of the Kysucké vrchy and Kriváňska Malá Fatra Mts. GSSR, Bratislava.

Kováč, P. & Hók, J., 1996: Tertiary Development of the Western Part of Klippen Belt. Slovak Geol. Mag., 2, 137-149.

Matějka, A., 1931: La partie orientale de la Malá Fatra. In Matějka A. & Andrusov D. (eds): Guide des excursions dans les Carpathes occidentales. Knih. St. geol. ústavu Čs. rep., 13A, 303–316.

Marko, F., Plašienka, D. & Fodor, L., 1995: Meso-Cenozoic stress fields within the Alpine-Carpathian transition zone: A review. Geol. Carpath., 46, 1, 19-27.

Marko, F., Vojtko, R., Plašienka, D., Sliva, L., Starek, D., Reichwalder, P. & Jablonský, J. 2004: Structural record of backthrusting within the Orava segment of the periklippen zone (Zázrivá, Western Carpathians) ESSEWECA 2004 abstracts, PriF UK, Bratislava.

Nemčok, J. & Rudinec, R. 1990: The Čergov Mts. – one of key areas of the Flysch Belt in Eastern Slovakia as to the oil content. Min. slovaca, 22, 175-178. (In Slovak).

Plašienka D., Soták J. & Prokešová R., 1998: Structural profiles across the Šambron-Kamenica Periklippen Zone of the Central Carpathian Paleogene Basin in NE Slovakia. Mineralia Slov., 29, 173–184.

Potfaj, J., 1974: Geological structure of the area northerly of Zazrivá village. Diploma thesis, archive Dept. of Geology and Paleontology, Comenius University, Bratislava, 54p. (In Slovak).

Potfaj, J., 1979: Tectonic Profile of the contact between the Klippen belt and Oravská Magura in the Oravská Magura region. In: Maheľ, M. (Ed.): Tectonic profiles through the West Carpathians. GÚDŠ, Bratislava, 37-40. (In Slovak).

Potfaj, M. 1998: Geodynamics of the Klippen Belt and Flysch Belt of the Western Carpathians. In: M. Rakús edit.: Geodynamic development of the Western Carpathians. GSSR, Bratislava, 143-154.

Rakús, M. (Ed.) 1984: Guide to geological excursion in the West Carpathians Mts., GÚDŠ Bratislava, 95pp.

Samuel, O. & Haško, J. 1978: New data on the Paleogene of the northeastern part of the Žilinská kotlina depression. Geol. práce, Správy 70, GÚDŠ Bratislava, 83-90.

Tomek, Č., Dvořáková, L., Ibrmajer, I., Jiříček, R. & Koráb, T. 1987: Crustal profiles of active continental collisional belt: Czechoslovak deep seismic reflection profiling in the West Carpathians. Geophys. J. R. astr. Soc., 89, 383-388.

Tomek, Č., 1993: Deep crustal structure beneath the central and inner West Carpathians. Tectonophysics, 226, 417-431.

Slovak Geol. Mag., 11, 1 (2005), 45 – 58

Benthic agglutinated foraminifera and organic-walled dinoflagellate cysts from Late Cretaceous oceanic deposits at Kalwaria Zebrzydowska, Flysch Carpathians, Poland: biostratigraphy and palaeoenvironment

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Abstract. Microfossil analysis of Late Cretaceous oceanic deposits exposed in vicinity of Kalwaria Zebrzydowska (Silesian Nappe, Polish Flysch Carpathians) has been carried out. Samples from the variegated shales and the Godula beds have been analysed for their agglutinated foraminifera and organic-walled dinocyst content. Age-assessment of the sediments in question suggests Early Turonian-Early Santonian age of the variegated shales and Late Santonian-Early/Middle Campanian age of the Godula beds. Palaeoenvironmental analysis of foraminifera and dinocysts shows a significant change during Late Cretaceous in this part of the Silesian basin. Sedimentation of hemipelagic/pelagic variegated shales was associated with limited organic matter supply, which resulted in aerobic conditions both in bottom waters and in sediment. Beginning of turbiditic sedimentation of the Godula beds resulted in increased influx of organic matter to the deeper parts of the basin, which caused oxygen depletion in sediment. Changes in dinocyst assemblage composition in the Godula beds succession reflect increasing resedimentation from marginal areas of the Silesian basin.

Key words: foraminifera, dinoflagellate cysts, palaeoecology, oceanic deposits, biostratigraphy, Late Cretaceous, Flysch Carpathians

Introduction

Non-calcareous pelagic/hemipelagic deposits characterized by predominantly reddish colour – the so-called "variegated shales" are typical for Upper Cretaceous of the Flysch Carpathians. This facies has been distinguished as several lithostratigraphic units such as the Malinowa Shale Formation (Magura Nappe; Birkenmajer & Oszczypko, 1989) originally described from the Grajcarek Unit of the Pieniny Klippen Belt (Birkenmajer, 1977), the variegated shales or the Godula shales of the Silesian and the Sub-Silesian nappes (e.g., Ślączka, 1959). The "variegated shales" occur also locally in the Late Cretaceous successions of the Skole and Dukla nappes (Ślączka & Kaminski, 1998). Red-coloured fine-grained deposits are also known from the Pieniny Klippen Belt: the Macelowa Marl Member and the Pustelnia Marl Member (Birkenmajer, 1977; see also Bąk, 1998).

These "variegated shales" (reddish shales intercalated with greenish ones) were deposited in Carpathian basin during period of deep marine, oceanic sedimentation below the local calcite compensation depth (CCD; see e.g., Leszczyński & Uchman, 1991). Tectonic movements of the Laramian phase divided uniform Carpathian basin into several basins separated by uplifted areas of intrabasinal ridges. Palaeorelief and tectonic activity were the reasons of increased flysch sedimentation that terminated in large areas of Carpathian basins the sedimentation of hemipelagic/pelagic variegated facies. Turbiditic Godula beds followed by the lower Istebna sandstone were deposited in the Silesian Nappe, the Jarmuta Formation and the Inoceramian beds in the Magura Nappe (Birkenmajer & Oszczypko, 1989; Oszczypko, 1992) and the siliceous marls and the Inoceramian (Ropianka) beds in the Skole Nappe (Kotlarczyk, 1985).

This considerable change of sedimentation mode during Late Cretaceous in deep Carpathian basin has significantly altered the environmental conditions. Our study of foraminifera and organic-walled dinoflagellate cysts (hereafter dinocysts) from both hemipelagic/pelagic and turbiditic facies is an attempt to add new information on reconstruction of the change of depositional environments during Late Cretaceous. Its main advantage is tracing the relation between the organic matter supply to the basin (palynofacies and dinocysts) and the bottom water conditions (agglutinated foraminifera). In this purpose we have studied palynology (PG) and foraminifera (AL) from the same set of samples consisting of reddish, greenish and greyish fine-grained lithofacies representing the Late Cretaceous variegated shales and the Godula beds exposed in vicinity of Kalwaria Zebrzydowska.

Geological setting

Kalwaria Zebrydowska is situated in Pogórze Lanckorońskie (Fig. 1A), which geologically represents the Silesian Nappe. The Silesian Nappe east of Skawa dislocation consists of two series. The southern series repre-

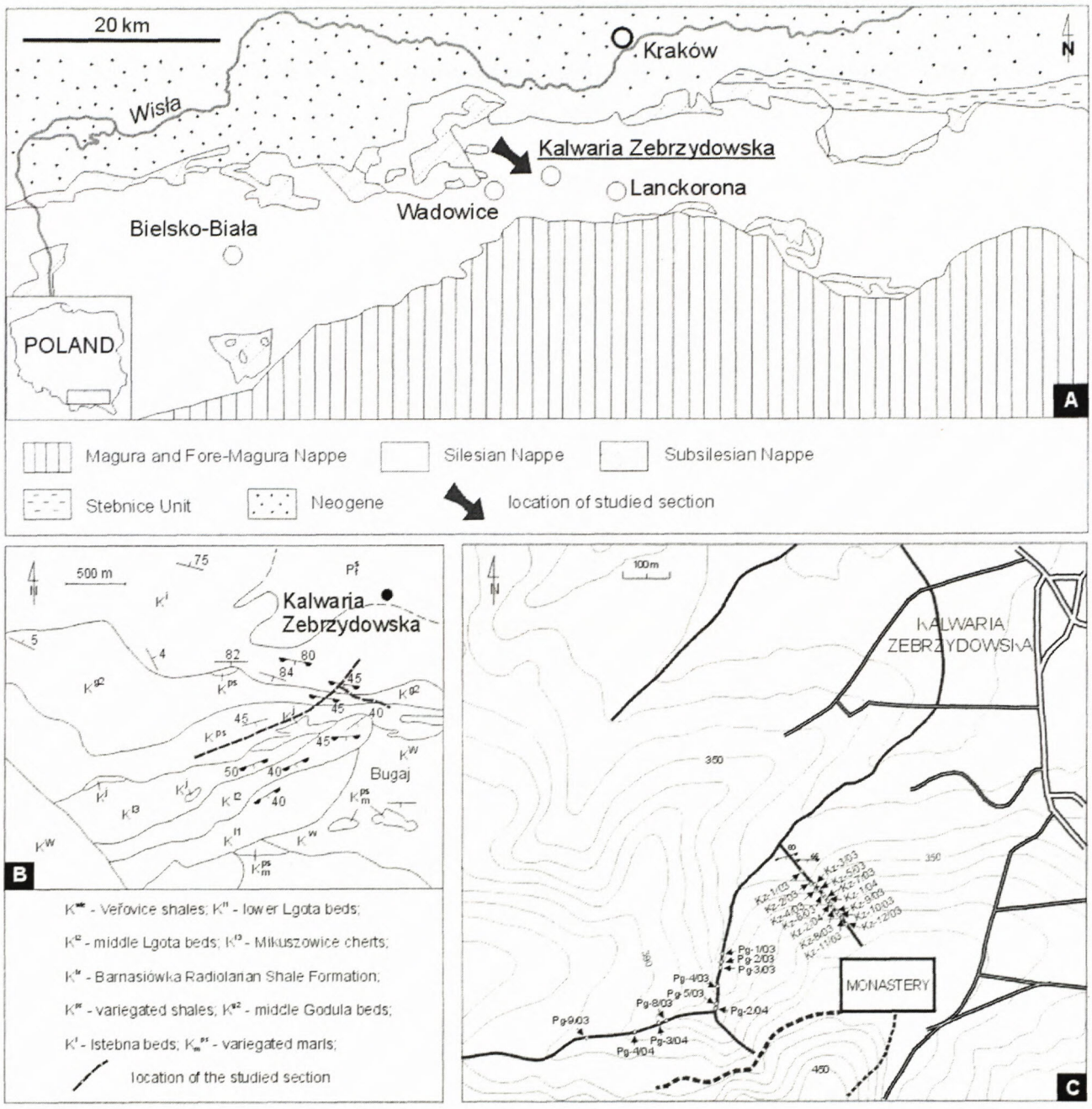

Fig. 1. Location of study area. A – Geological sketch-map of western part of Polish Carpathians with location of studied section (after Szymakowska & Żytko 1965); B – Geological map of Kalwaria Zebrzydowska vicinity with location of studied section (after Szymakowska & Żytko 1965); C – Location of studied outcrops.

sents Palaeogene strata (mainly the Krosno beds) whereas the northern one (i.e. the Pogórze Lanckorońskie) consists mainly of Cretaceous deposits (Książkiewicz., 1951, 1972; Słomka, 1995). The Upper Cretaceous of the northern series includes uppermost part of the Lgota beds, the Barnasiówka Radiolarian Shale Formation, the variegated shales, the Godula beds and the lower Istebna sandstones (Fig. 1B). The Godula beds in this area are developed as thin-bedded fine-grained deposits and/or the variegated shales (Fig. 2). Such development of the Godula beds is distinguished as the Lanckorona facies, contrary to the Godula beds west of the Skawa disclocation, which consist mainly of thick-bedded sandstones and reach thickness exceeding 2000 m (Książkiewicz, 1951, 1972).

The oldest deposits of the Late Cretaceous succession of the Pogórze Lanckorońskie are the uppermost part of the Lgota beds and locally occurring marly deposits (Fig. 3). They are followed by the Late Cenomanian-earliest Turonian Barnasiówka Radiolarian Shale Formation, which consists of thin-bedded glauconitic siliceous sandstones and light-greenish and green non-calcareous shales (Bąk *et al.*, 2001). This lithostratigraphic unit is overlied by the variegated shales consisting of brick-reddish shales and subordinar intercalations of green shales (Fig. 3). Thin-bedded glauconitic sandstones occur occasionally.

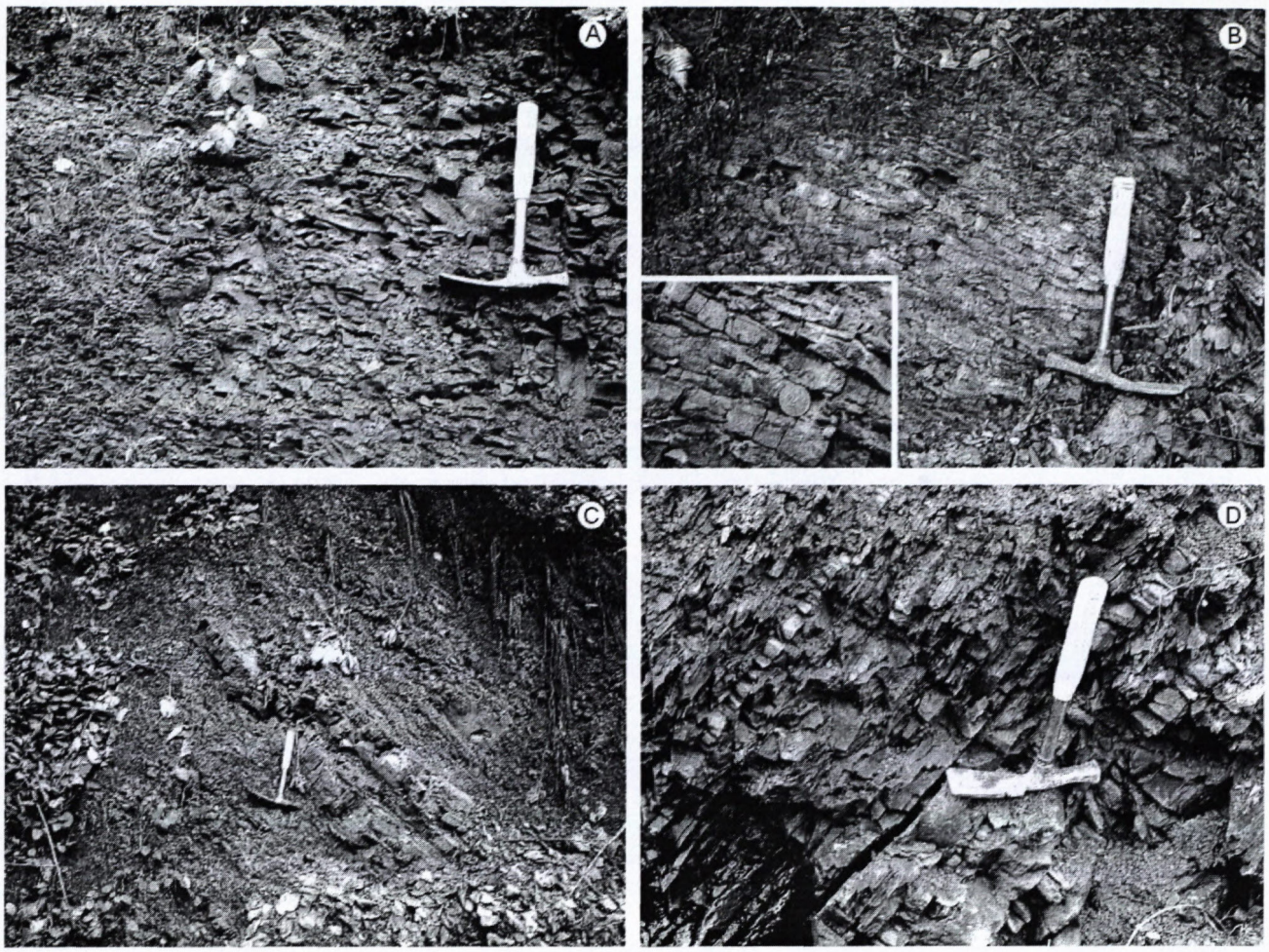

Fig. 2. Lithology of studied variageted shales and Godula beds exposed at northern slopes of Góra Lanckorońska Hill (photo: P. Gedl). A – clayey variegated shales; B – variegated shales with frequent thin-bedded sandstones (coin diameter = 18 mm); C – medium-bedded sandstone within upper part of variegated shales; D – thin-bedded turbiditic Godula beds.

Increasing number of thin-bedded glauconitic sandstones and mainly greenish-grey colour of shales characterize lower part of the succeeding Godula beds. Red shales are thin and infrequent here, whereas they occur more frequently in the upper part of the Godula beds. In the area of study the thickness of the variegated shales is about 150-250 meters (Książkiewicz, 1951) and that of the Godula beds reaches from 200 to 600 meters (Słomka, 1995). The youngest deposits exposed in studied area are the lower Istebna sandstones (Fig. 3).

Material and methods

The studied samples have been collected from outcrops in a small unnamed creek and its tributary that cuts the northern slopes of the Lanckorońska Góra Hill south of Kalwaria Zebrzydowska (Fig. 1C). The variegated shales exposed in studied section consist of non-calcareous reddish shales with intercalations of non-calcareous greenish shales (Fig. 2A). Thickness of the latter is variable, from few millimetres to 30 centimetres. Thin-bedded (mainly up to 2 cm – Fig. 2B, occasionally up to 10 cm – Fig. 2C) fine grained sandstones occur within this lithostratigraphic unit. The Godula beds in the studied section consist of thin- and middle-bedded glauconitic sandstones, which are interlayered by greyish, grey-greenish non-calcareous shales (Fig. 2D). Infrequent red shales occur in the topmost part of the Godula beds in this section. Thirty samples have been collected from red and green shales of the variegated shales and grey-greenish and red shales of the Godula beds. Their position is shown in Figure 3.

Samples for foraminifera, about 0.5 kg each, have been processed following standard method including boiling with Glaubert salt, freezing and washing through sieves with mesh diameters > 63 μm. 300 specimens of foraminifera have been picked out from each sample and mounted on cardboard microscope slides. For morphogroup analysis of fragments of tubular species and multichambered, uniserial forms (*Reophax*, *Caudammina*) were counted individually and then their number was recalculated taking into account dimensions of unchanged forms. Scanning electron microscope photomicrographs have been taken in the Laboratory of Field Emission Scanning Electron Microscopy and Microanalysis in the Institute of Geological Sciences of the Jagiellonian University.

The same set of samples was processed for palynology. 30 g of cleaned and crushed rock was taken for each

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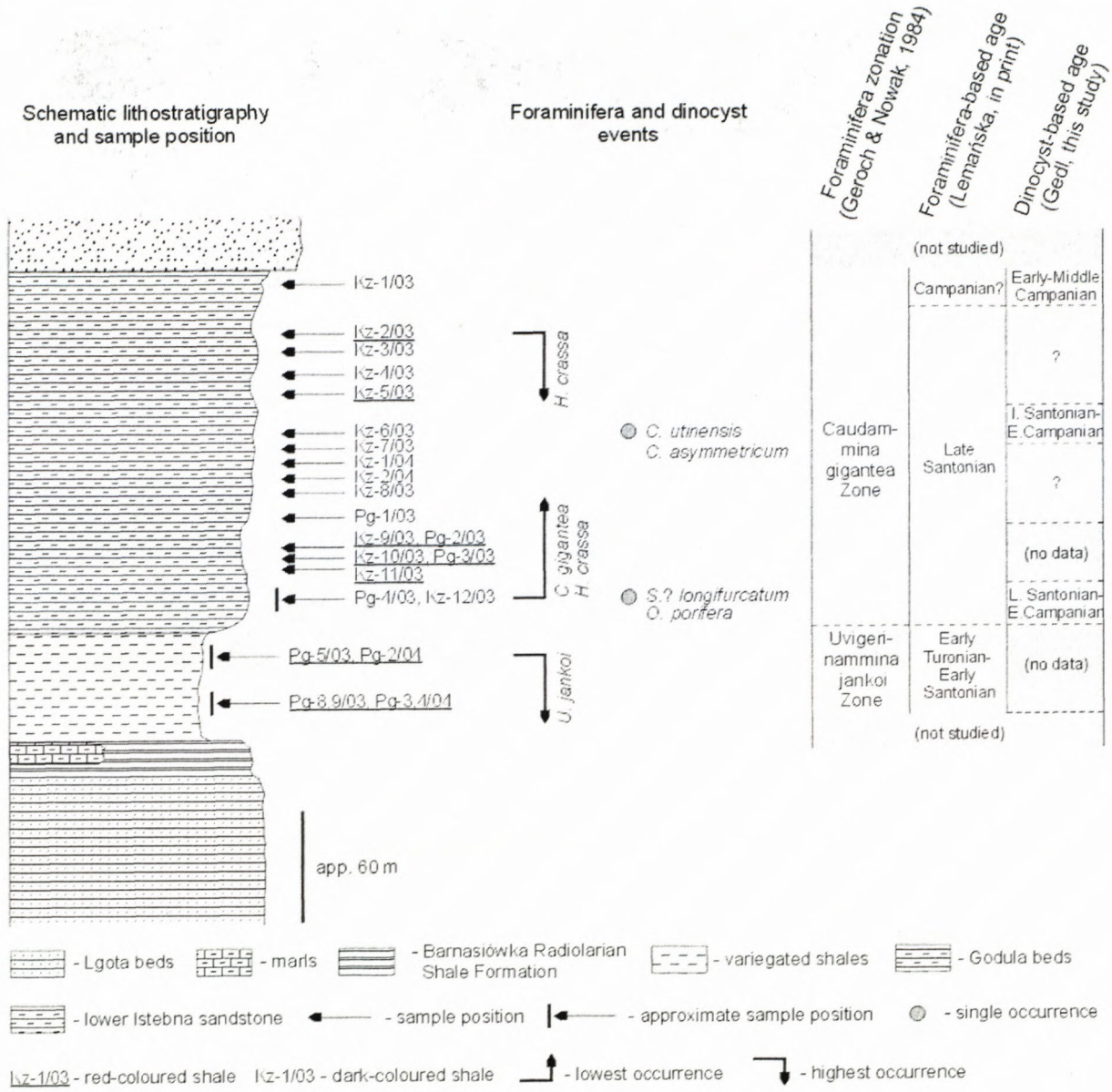

Fig. 3. Schematic lithostratigraphical column of studied deposits. Sample positions are indicated tentatively due to tectonics and non-continuous exposures. Foraminifera and dinocyst events indicated. Abbreviations: *C. gigantea – Caudammina gigantea*; *H. crassa – Hormosina crassa*; *U. jankoi – Uvigerinammina jankoi*; *C. utinensis – Cannosphaeropsis utinensis*; *C. asymmetricum – Callaiosphaeridium asymmetricum*; *S.? longifurcatum – Surculosphaeridium? longifurcatum*; *O. porifera – Odontochitina porifera*; l. Santonian – latest Santonian; L. Santonian – Late Santonian; E. Campanian – Early Campanian.

sample. Samples were subjected to standard palynological procedure including 38% hydrochloric acid (HCl) treatment, 40% hydrofluoric acid (HF) treatment, heavy liquid ($ZnCl_2$+HCl; density 2.0 g/cm^3) separation, ultrasound for 10-15 s and sieving at 15 μm nylon-mesh. Two slides were made from each sample using glycerine jelly as a mounting medium. The rock samples, palynological residues and slides are all stored in the collection of the Institute of Geological Sciences, Polish Academy of Sciences, Kraków.

Results

Variegated shales. Foraminifera assemblage from this lithostratigraphic unit is composed of agglutinated species only (Pl. 1). The poor assemblage consists of badly preserved small-sized specimens including *Rhabdammina*, *Rhizammina*, *Bathysiphon*, *Ammodiscus*, *Glomospira*, *Haplophragmoides*, *Trochamminoides*, *Recurvoides* and *Trochammina*. Relatively frequent are also *Gerochammina stanislawi*, *Gerochammina obesa* and *Uvigerinammina jankoi*. Foraminifera are associated with frequent sponge spicules and radiolaria. The variegated shales, both the red and greenish shales, are devoid of dinocysts.

Godula beds. Foraminifera from the Godula beds are also representing by the agglutinated forms only (Pl. 1, 2). However, their assemblage is characterized by higher taxonomic diversity. In contrast to the assemblage from the variegated shales, the foraminifera from the Godula beds consist mainly of large-sized coarse-grained genera. The

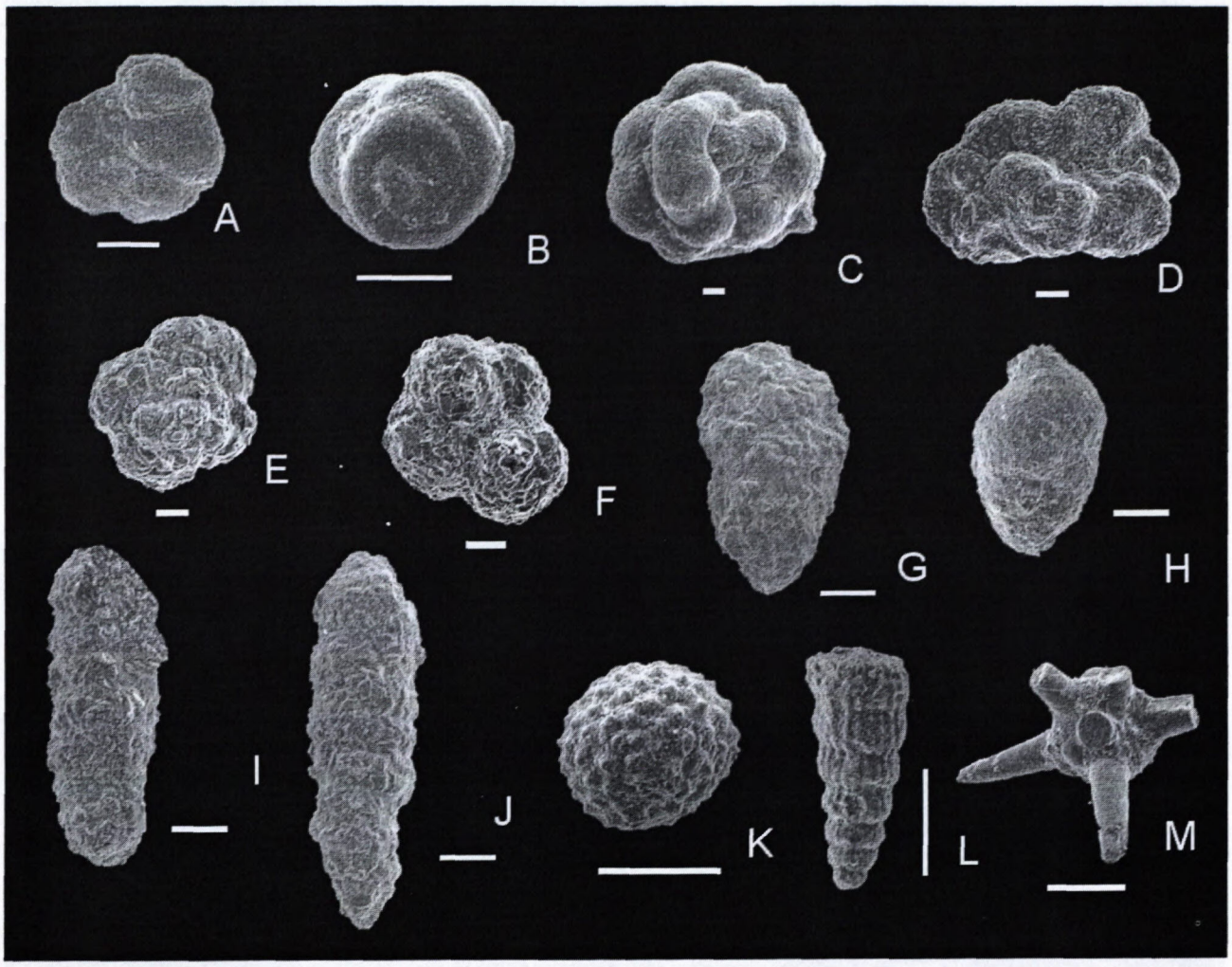

Plate. 1. Agglutinated foraminifera from variegated shales and Godula beds at Kalwaria Zebrzydowska (scale bar – 100 μm). **A** – *Haplophragmoides miatliuke* (Maslakova), Pg-8/03 (variegated shales); **B** – *Glomospira charoides* (Jones & Parker), Pg-8/03 (variegated shales); **C** – *Paratrochamminoides olszewskii* (Grzybowski), Kz-2/03 (Godula beds); **D** – *Paratrochamminoides irregularis* (White), Kz-10/03 (Godula beds); **E, F** – *Trochammina globigeriniformis* (Jones & Parker), Kz-10/03 (Godula beds); **G** – *Gerochammina obesa* (Neagu), Kz-9/03 (Godula beds); **H** – *Uvigerinammina jankoi* (Majzon), Pg-3/04 (variegated shales); **I** – *Gerochammina conversa* (Grzybowski), Kz-2/03 (Godula beds); **J** – *Gerochammina stanislawi* (Neagu), Kz-2/03 (Godula beds); **K, L** – radiolaria, Pg-5/03 (variegated shales); **M** – sponge spicule, Pg-5/03 (variegated shales).

most frequent are the representatives of *Rhabdammina*, *Nothia*, *Psammosphaera* and *Reophax*. *Caudammina gigantea* (Geroch) and *Caudammina ovulum* (Grzybowski) occur frequently whereas other taxa like *Bathysiphon*, *Ammodiscus*, *Glomospira*, *Trochammina*, *Trochamminoides* and *Paratrochamminoides* are less frequent. Single specimens of *Hormosina crassa* (Geroch) have been found in the Godula beds too.

Greenish and greyish shales from the Godula beds contain dinocysts (Pl. 3-6). Their assemblage consists of very well preserved specimens characterized by pale-yellow colour as well forms showing features of mechanical damage and maturity changes (dark yellow, brownish colour). The most frequent dinocyst taxa found in the Godula beds represent Gonyaulacoids: these are mainly chorate forms like *Spiniferites ramosus*, and less frequent *Achomosphaera* spp., *Exochosphaeridium* spp., *Tanyosphaeridium* spp., *Hystrichodinium* spp. and *Hystrichosphaeridium* spp. Relatively frequent *Pterodinium* spp. dominates among the proximochorate Gonyaulacoids. Peridinioids are much less frequent in sediments in question. *Palaeohystrichophora infusorioides* occurs frequently in samples from the basal (samples Pg/4/03 and Kz/12/03) part of the Godula beds where the red shales occur, *Palaeoperidinium cretaceum*, *Cerodinium* sp. and *Subtilisphaera* sp. occur subordinarly. Rare specimens of *Chatangiella* and small-sized *Isabelidinium* have been found.

Biostratigraphy

Foraminifera biostratigraphy of deposits in question was studied by Lemańska (in print). According to her, the variegated shales exposed in the creek at the Lanckorońska Góra Hill represents the Uvigerinammina jankoi Zone *sensu* Geroch & Nowak (1984) whereas the Godula beds represent Caudammina gigantea Zone *sensu* Geroch & Nowak (1984). The age of the younger

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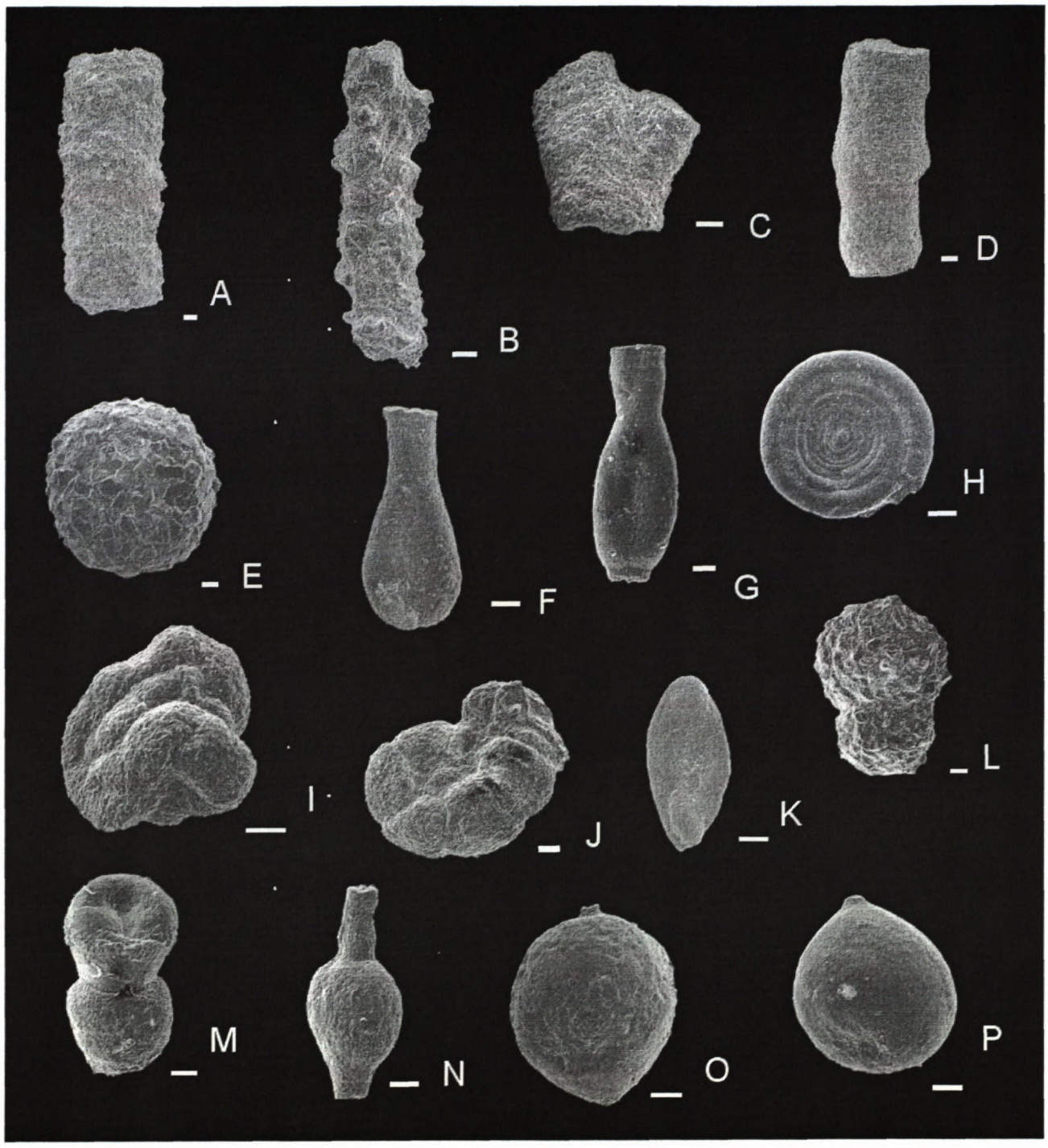

Plate. 2. Agglutinated foraminifera from Godula beds at Kalwaria Zebrzydowska (scale bar – 100 μm). **A** – *Rhabdammina* sp., Kz-10/3; **B** – *Rhabdammina cylindryca* (Glaessner), Kz-10/03; **C** – *Nothia excelsa* (Grzybowski), Kz-8/03; **D** – *Bathisiphon microrhaphidus* (Samuel), Kz-8/03; **E** – *Psammosphaera fusca* (Schultze), Kz-7/03; **F** – *Hyperammina elongata* (Brady), Kz-8/03; **G** – *Kalamopsis grzybowskii* (Dylążanka), Pg-3/03; **H** – *Ammodiscus cretaceous* (Reuss), Kz-4/03; **I** – *Glomospira irregularis* (Grzybowski), Kz-2/03; **J** – *Trochamminoides proteus* (Karrer), Kz-6/03; **K** – *Rzehakina minima* (Cushman & Renz), Kz-6/03; **L** – *Reophax duplex* (Grzybowski), Kz-6/03; **M** – *Hormosina velascoensis* (Cushman), Pg-3/03; **N** – *Hormosina crassa* (Geroch), Pg-2/03; **O, P** – *Caudammina gigantea* (Grzybowski), Kz-1/03.

foraminifera assemblage with *Caudammina gigantea* (Geroch) was estimated as Late Santonian (Fig. 3). This was based on the co-occurrence of the index species, which is known to appear throughout Late Santonian-Early Campanian (Olszewska, 1997) and *Hormosina crassa* (Geroch), which stratigraphic range is Barremian-early Senonian (Morgiel & Olszewska, 1981). However, the latter species has not been found in the stratigraphically highest sample Kz-1/03. This may suggest Campanian age of the topmost part of the Godula beds exposed in vicinity of Kalwaria Zebrzydowska. The age of the variegated shales in studied section was estimated on Early Turonian-Early Santonian (Lemańska, in print). This is based on the stratigraphic range of

Uvigerinammina jankoi (Majzon), which first appearance is known from Early Turonian (Geroch, 1957; Geroch, & Nowak, 1984; Kuhnt, 1992; Bąk, 1998).

Dinocyst age-assessment of the Godula beds (the variegated shales contain no dinocysts) in the area of study based on dinocyst must be treated as preliminary only (Fig. 3). Dinocysts have been only found in few samples representing dark-coloured lithofacies where stratigraphically important species occur as very rare specimens. Their occurrences generally confirm the age interpretation of this lithostratigraphic unit based on foraminifera.

The base of the Godula beds contains *Odontochitina porifera*, species that according to several authors (e. g., Stover *et al.*, 1996) appeared during Coniacian and Early Santonian. However, most recently Williams *et al.* (2004) proposed Late Santonian-Late Campanian range of this species in mid-latitudes of northern hemisphere. In the same rock interval *Surculosphaeridium*? *longifurcatum* was found. This species appears for the last time during Early Campanian (Williams *et al.* (2004). Hence, depending on the range interpretation of *O. porifera*, Coniacian-Early Santonian or Late Santonian-Early Campanian beginning of the Godula beds sedimentation in this area of Silesian basin can be suggested. The latter interpretation coincides with foraminifera datations based on first appearance of *Caudammina gigantea* in basal part of the Godula beds (Fig. 3).

Another stratigraphically important dinocyst species found in sediment in question is *Cannospahaeropsis utinensis*, which occurs in middle part of the Godula beds (sample Kz-6/03; Fig. 3). According to Williams *et al.* (2004) this species appeared for the first time during latest Santonian in mid-latitudes of the northern hemisphere. In the same sample *Callaiosphaeridium asymmetricum* has been found. This species has last appearance during the Early or Middle Campanian (Stover et al., 1996; Williams *et al.*, 2004, respectively). Co-occurrence of these dinocyst species suggests that sedimentation of the middle part of the studied Godula beds took place during latest Santonian-Early/Middle Campanian.

Several dinocyst species from the topmost part of the Godula beds (sample Kz-1/03) are long ranging with stratigraphic top-ranges limited to earliest-Early Maastrichtian (e. g., *Palaeohystrichophora infusorioides*, *Xenascus ceratioides*, *Laciniadinium arcticum*; Stover *et al.*, 1996). However, single specimen of *Odontochitina* sp. A *sensu* Kirsch (1991) has been found here. Range of this species was estimated by Kirsch (1991) as Early-Middle Campanian. This would suggest that sedimentation of the Godula beds in this part of the Silesian basin terminated during Early-Middle Campanian.

Summarising, interpretation of our data suggests that sedimentation of the Godula beds in this part of the Silesian basin lasted throughout Late Santonian and was presumably terminated during the Early-Middle Campanian (Fig. 3).

Reconstruction of palaeoenvironment

Microfossils that have been found in the variegated shales during our studies consist of agglutinated foraminifera, sponge spicules and radiolaria. Neither dinocysts nor phytoclasts have been found. Detailed analysis of foraminifera assemblage from this lithostratigraphic unit (Lemańska, in print) shows dominance of epifaunal and shallow and deep infaunal forms whereas suspension feeding forms comprise 10% of the assemblage. Their life strategy – living buried in the sediment (based on e. g., Kaminski *et al.*, 1995; Nagy *et al.*, 1995; Kuhnt *et al.*, 1996; Bąk *et al.*, 1997), was interpreted as indicative for well oxygenated bottom waters, low sedimentation rate and limited food supply (Lemańska, in print). This interpretation agrees well with interpretation of palynological data: lack of dinocysts and phytoclasts suggests highly aerobic environment resulting from very slow sedimentation rate and limited organic matter supply. Red-green colour variations of the variegated shales, which result from Fe^{3+}/Fe^{2+} ratio depending on amount of organic matter (e. g., Potter *et al.*, 1980), are not reflected in palynological content: samples representing both lithotypes contain no palynological organic matter (i. e., organic particles larger that 15 μm). This suggests that even during sedimentation of greenish shales, which presumably represent hemipelagic sediment of diluted turbidite currents (see Leszczyński & Uchman, 1996), oxygen content in bottom waters was high enough to oxidize organic matter.

Beginning of the Godula beds sedimentation, i. e. increase of flysch-type sedimentation in this part of the Silesian basin, resulted in major change of bottom environment. Agglutinated formaninifera assemblage from this lithostratigraphic unit consists mainly of suspension feeding forms – 45%. Epifaunal forms represent 32% of the whole benthos whereas infaunal forms comprise only 16% (Lemańska, in print). Such assemblage, composed predominantly of coarse-grained large-sized foraminifera, suggests high flux of organic matter, which seems to be resedimented from more proximal areas. This is indicated by the occurrence in dark-coloured shales of the Godula beds of dinocysts, which inhabit mainly the near-shore waters. However, their ratio is variable. It is the lowest in the samples taken from the basal part of the Godula beds, which contain frequent dinocyst that lived in offshore waters (*Spiniferites ramosus*, *Pterodinium* spp.). Moreover, frequent occurrence in this part of succession of *Palaeohystrichophora infusorioides*, a species distinguished by very good state of preservation, may be related to blooms of its motile stage in oceanic waters. This might be a record of *in situ* primary productivity of oceanic waters, which has not been masked by resedimentation – palynofacies of these samples consist of black opaque phytoclasts, typical component of pelagic deposits. Frequent occurrence of Peridinioids in pelagic/hemipelagic deep-water deposits was described by Gedl (2004) from Maastrichtian of Flysch Carpathians in Moravia. Higher up the section, the frequency of near-shore dinocysts increases. It is a result of increased resedimentation from marginal parts of the basin. Another record of this resedimentation is increasing occurrence of land plant tissue remains. Its maximum is evidenced in the top-most part of the Godula beds where dinocyst diversity is the highest and near-shore species (e. g., *Odon-*

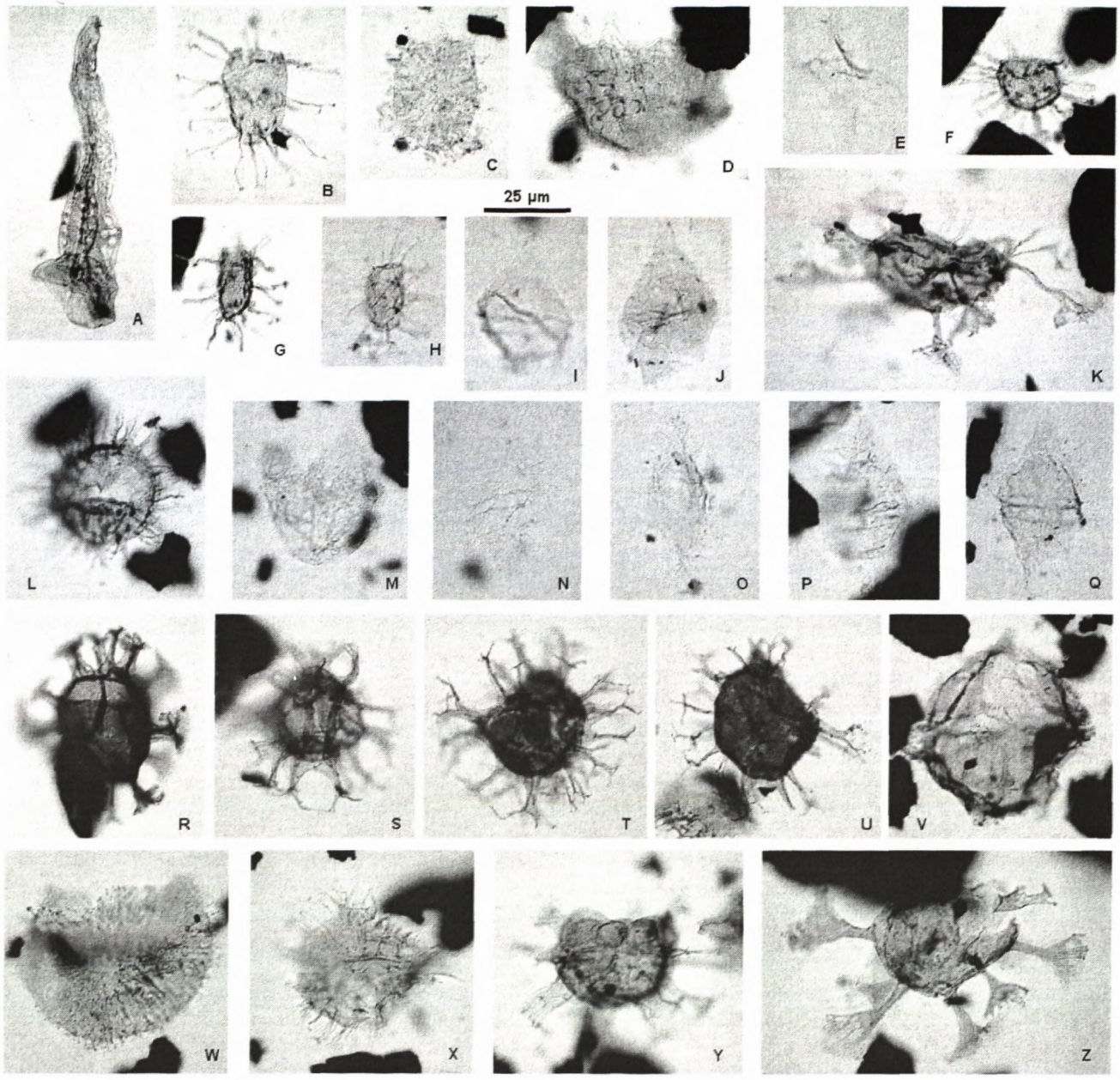

Plate 3. Dinoflagellate cysts from Godula beds at Kalwaria Zebrzydowska. **A** – *Odontochitina porifera*, Pg-4/03; **B**, **G**, **H** – *Tanyosphaeridium* sp., B: Kz-6/03, G, H: Kz-12/03; **C** – *Prolixosphaeridium* sp., Pg-4/03; **D** – *Systematophora* sp., Pg-4/03; **E** – *Palaeotetradinium silicorum*, Pg-4/03; **F** – *Dapsilidinium* sp., Kz-12/03; **I**, **J** – *Subtilisphaera* sp., Pg-4/03; **K** – *Stiphrosphaeridium anthophorum*, Pg-4/03; **L** – *Pervosphaeridium* sp., Kz-6/03; **M** – *Kallosphaeridium* sp., Pg-4/03; **N-Q** – *Palaeohystrichophora infusorioides*, Kz-12/03; **R** – *Achomosphaera* sp., Kz-12/03; **S-U** – *Spiniferites ramosus*, Kz-12/03; **V** – *Cribroperidinium* sp., Pg-4/03; **W** – *Circulodinium distinctum*, Pg-4/03; **X** – *Exochosphaeridium* sp., Pg-4/03; **Y** – *Hystrichosphaeridium* sp., Pg-4/03; **Z** – *Oligosphaeridium pulcherrimum*, Pg-4/03

tochitina sp.) occur frequently. Also land derived plant remains (phytoclasts and sporomorphs) are the most frequent here.

Higher influx of organic matter during turbiditic sedimentation of the Godula beds caused also changes in chemistry of sediment. Lower oxygen concentration in sediment than it was during sedimentation of the variegated shales is indicated by low amounts (16%) of infaunal forms. It results from bacterial decay of larger amounts of organic matter and causes green colour of sediment related to the Fe^{3+}/Fe^{2+} ratio. The red colour of sediment appears when this ratio is high whereas the green colour is associated with low ratio (Dominik, 1977; Potter *et al.*, 1980).

The Fe^{3+}/Fe^{2+} ratio depends on oxidation conditions within sediment, which, in turn, is controlled by organic matter amount. Our study shows that dark coloured shales of the Godula beds in vicinity of Kalwaria Zebrzydowska contain relatively high amounts of organic matter of marine and land origin. Reddish shales of this lithostratigraphic unit must have been deposited during periods of calm, hemipelagic/pelagic sedimentation with limited supply of organic matter from marginal areas of the Silesian basin. Contrary, the differences in sedimen-

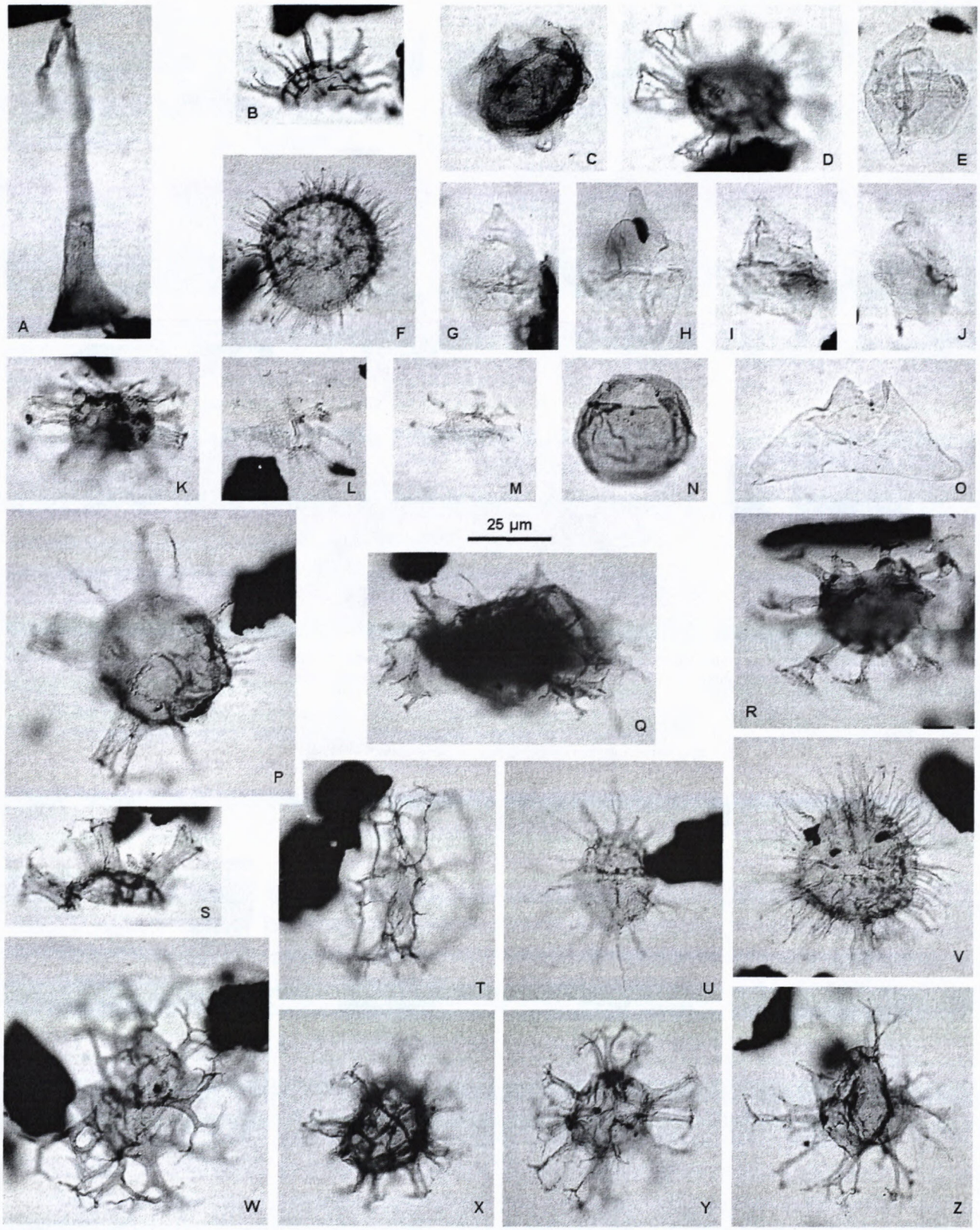

Plate 4. Dinoflagellate cysts from Godula beds at Kalwaria Zebrzydowska. **A** – *Odontochitinia operculata*, Kz-6/03; **B** – *Surculosphaeridium*? *longifurcatum*, Kz-12/03; **C** – *Senoniasphaera rotundata*, Kz-12/03; **D** – *Hystrichosphaerina*? sp., Pg-4/03; **E** – *Ovoidinium*? sp., Pg-4/03; **F** – *Operculodinium* sp., Kz-6/03; **G-J** – *Isabelidinium* spp., Pg-4/03; **K-M** – *Hystrichosphaeridium* spp., K, L: Kz-6/03, M: Pg-4/03; **N** – "round-brown", Kz-12/03; **O** – *Trigonopyxidia ginella*, Pg-4/03; **P** – *Florentinia* sp., Kz-6/03; **Q** – ?*Palynodinium* sp., Kz-6/03; **R** – *Hystrichosphaeridium tubiferum*, Kz-6/03; **S** – *Callaiosphaeridium asymmetricum*, Kz-6/03; **T** – *Cannosphaeropsis utinensis*, Kz-6/03; **U** – *Hystrichodinium pulchrum*, Kz-6/03; **V** – *Exochosphaeridium* sp., Kz-6/03; **W, Z** – *Achomosphaera* sp., Kz-6/03; **X, Y** – *Spiniferites ramosus*, Kz-6/03

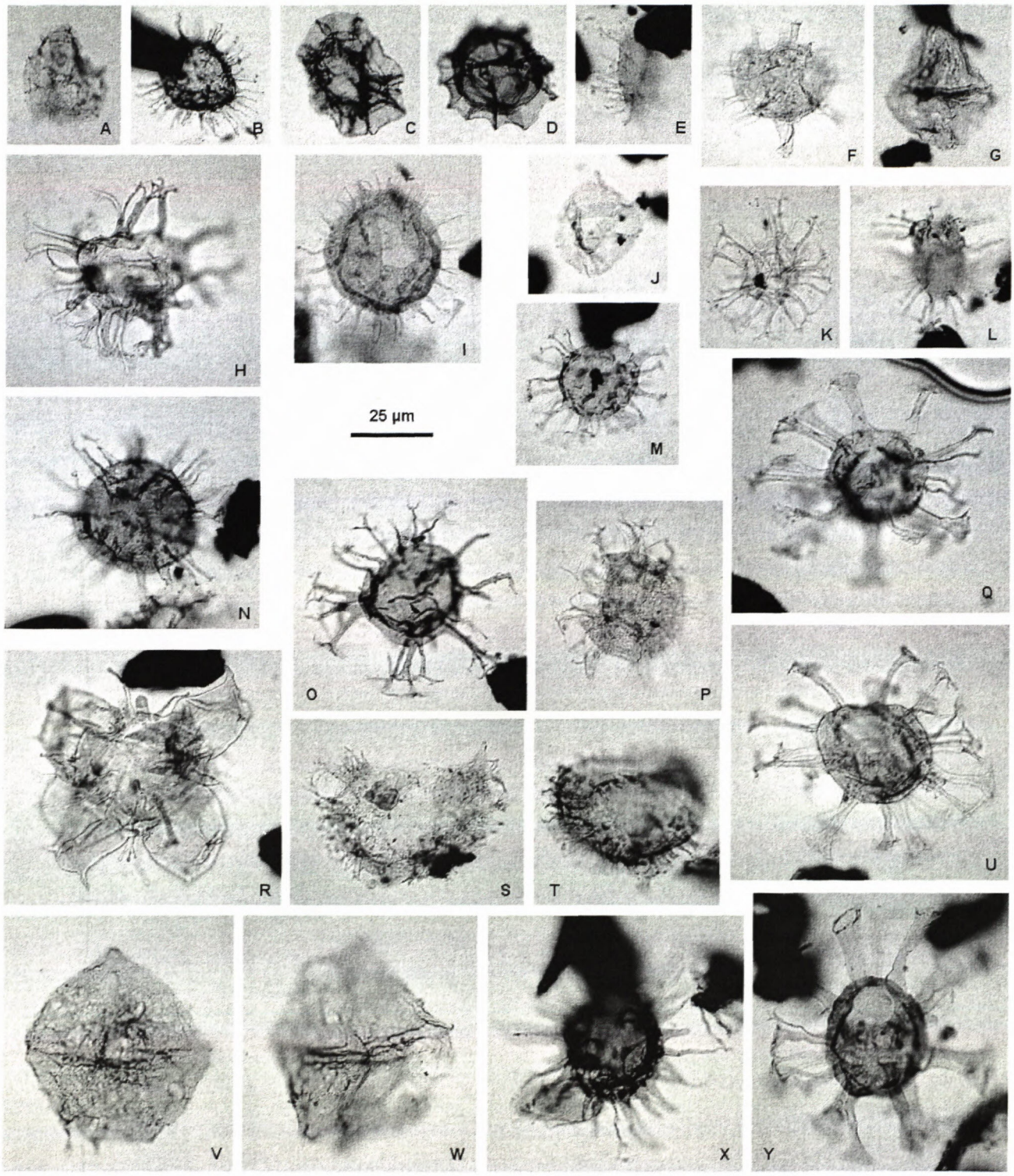

Plate 5. Dinoflagellate cysts from Godula beds at Kalwaria Zebrzydowska. **A** – *Impagidinium* sp., Kz-6/03; **B** – *Kiokansium polypes*, Kz-6/03; **C, D** – *Pterodinium cingulatum*, Kz-6/03; **E, L** – *Tanyosphaeridium* sp., Kz-6/03; **F** – *Diphyes* sp., Kz-1/03; **G** – *Alisogymnium euclaense*, Kz-6/03; **H** – *Surculosphaeridium belowi*, Kz-1/03; **I** – *Operculodinium* sp., Kz-6/03; **J** – dinocyst indet., Pg-4/03; **K** – *Spiniferites ramosus*, Kz-1/03; **M** – ?*Taleisphaera hydra*, Kz-6/03; **N** – *Pervosphaeridium* sp., Pg-1/03; **O** – *Achomosphaera* sp., Pg-1/03; **P** – *Spiniferites crassipelis*, Pg-1/03; **Q, U** – *Hystrichosphaeridium salpingophorum*, Kz-1/03; **R** – *Hystrichokolpoma cinctum*, Kz-1/03; **S** – *Glaphyrocysta ordinata*, Kz-1/03; **T** – *Circulodinium distinctum*, Kz-1/03; **V, W** – *Palaeoperidinium cretaceum*, Kz-12/03; **X** – *Hystrichodinium* sp., Kz-12/03; **Y** – *Kleithriasphaeridium* sp., Pg-4/03

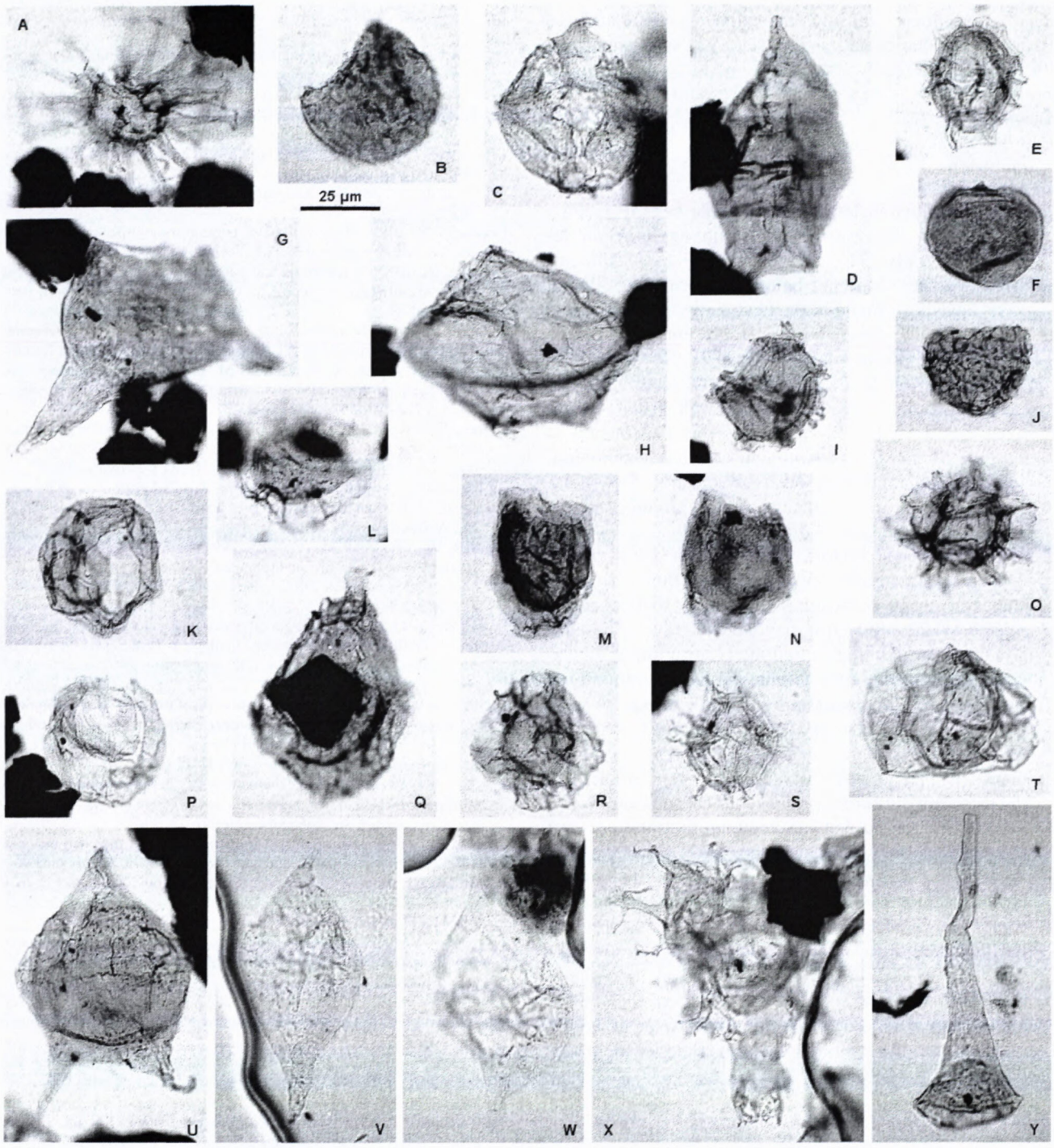

Plate 6. Dinoflagellate cysts from Godula beds at Kalwaria Zebrzydowska. **A** – *Dapsilidinium* sp., Pg-1/03; **B** – dinocyst indet., Kz-1/03; **C**, **Q** – *Cribroperidinium* spp., C: Kz-1/03, Q: Pg-1/03; **D** – *Chatangiella* sp., Pg-1/03; **E**, **I** – *Pterodinium* sp., E: Pg-1/03, I: Kz-1/03; **F** – *Apteodinium* sp., Pg-1/03; **G** – *Odontochitinia* sp. A *sensu* Kirsch (1991), Kz-1/03; **H** – *Palaeoperidinium cretaceum*, Pg-1/03; **J** – *Valensiella reticulata*, Pg-1/03; **K**, **P**, **T** – *Disphaeria* sp., K, P: Pg-1/03, T: Kz-1/03; **L** – *Eatonicysta ursulae sensu* Mahreinecke (1992), Kz-6/03; **M**, **N** – *Leberidocysta chlamydata*, Pg-1/03; **O**, **R** – *Pterodinium aliferum*, Pg-1/03; **S** – *Pterodinium cingulatum*, Kz-1/03; **U** – *Cerodinium* sp., Kz-1/03; **V**, **W** – *Laciniadinium arcticum*, Kz-1/03; **X** – *Xenascus ceratioides*, Kz-1/03; **Y** – *Odontochitina costata*, Kz-1/03

tary environments during deposition greenish and red shales of the variegated shales were not so pronounced. In both cases organic matter content is very low and it was presumably sedimentation rate responsible for colour origin.

Conclusions

1. The variegated shales and the Godula beds in vicinity of Kalwaria Zebrzydowska contain agglutinated foraminifera only. This suggests that these sediments were deposited at depth below the local CCD. Dinocysts have been found in the Godula beds only.
2. The studied variegated shales represent Uvigerinammina jankoi Zone *sensu* Geroch & Nowak (1984) whereas the Godula beds represent Caudammina gigantea Zone *sensu* Geroch & Nowak (1984). Their ages, based on foraminifera, have been estimated as Early Turonian-Early Santonian and Late Santonian-Early Campanian? respectively. Late Santonian-Early/Middle Campanian age of the Godula beds is suggested on the base of dinocysts.
3. Well oxygenated bottom water and surface sediment column characterises deposition of the variegated shales in question. Scarcity of organic matter supply related to oceanic setting beyond the reach of intense flysch sedimentation resulted in colonisation of the basin bottom by the epifunal and infaunal foraminifera. Increased resedimentation from more proximal areas (turbiditic sedimentation of the Godula beds), recorded also in dinocyst assemblages altered bottom environments. Higher amounts of organic matter supplied to the sea floor by turbiditic currents caused better food availability for suspension feeding foraminifera and oxygen depletion within sediment.
4. Changes in dinocyst assemblages from the Godula beds reflect intensity of resedimentation from marginal areas of Silesian basin during Late Santonian-Early/Middle Campanian. Presumably *in situ* and offshore dinocysts occur in the basal part of the Godula beds. Higher up the succession, near-shore species begin to dominate. They are the most frequent in the topmost part of the Godula beds overlaid by the lower Istebna sandstone.

Acknowledgements

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References

Bąk, K., 1998: Planktonic foraminiferal biostratigraphy, Upper Cretaceous red pelagic deposits, Pieniny Klippen Belt, Carpathians. *Studia Geologica Polonica*, 111: 7-92.

Bąk, K., Bąk, M., Geroch, S., Manecki, M., 1997: Biostratigraphy and paleoenvironmental analysis of benthic foraminifera and radiolarians in Paleogene Variegated Shales in Skole Unit, Polish Flysch Carpathians. *Annales Societatis Geologorum Poloniae*, 67(2,3), 135 p.

Bąk K., Bąk M., Paul Z., 2001: Barnasiówka Radiolarian Shale Formation – a new lithostratigraphic unit in the Upper Cenomanian-lowermost Turonian of the Polish Outer Carpathians (Silesian Series). *Annales Societatis Geologorum Poloniae*, 71, p. 75-103.

Birkenmajer, K., 1977: Jurassic and Cretaceous lithostratigraphic units of the Pieniny Klippen Belt, Carpathians, Poland. *Studia Geologica Polonica*, 45: 1-159.

Birkenmajer, K. & Oszczypko, N., 1989: Cretaceous and Palaeogene lithostratigraphic units of the Magura Nappe, Krynica Subunit, Carpathians. *Annales Societatis Geologorum Poloniae*, 59, 145-181.

Corliss, B.H., 1985: Microhabitats of benthic foraminifera within deep-sea sediments. *Nature*, 314, p. 435-478.

Dominik, J., 1977: A mineralogical-petrographical study of variegated shales from Magura nappe (the Carpathians). *Prace Mineralogiczne*, 53: 1-86.

Gedl, P., 2004: Dinoflagellate cyst record of the deep-sea Cretaceous-Tertiary boundary at Uzgruň, Carpathian Mountains, Czech Republic. *In*: Beaudoin, A. B. & Head, M. J. (eds), The Palynology and Micropalaeontology of Boundaries.*Geological Society, London, Special Publications*, 230: 257-273.

Geroch, S. & Nowak W., 1984: Proposal of Zonation for the late Tithonian – late Eocene, based upon arenaceous foraminifera from the outer Carpathians, Poland. In: Oertli, H. (ed.). *Benthos `83; 2nd International Symposium on Benthic Foraminifera Pau (France), April 11-15, 1983*. Elf Aquitaine, ESSO REP and TOTAL CFP, Pau & Bourdeaux, p. 225-239.

Jones R. W., Charnock M. A., 1985: "Morphogroups" of agglutinating foraminifera. Their life positions and feeding habits and potential applicability in (paleo)ecological studies. *Revue de Paleobiologie*, 4, p. 311-320.

Kaiho, K., 1991: Global changes of Paleogene aerobic/anaerobic benthic foraminifera and deep-sea circulation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 83, p. 65-88.

Kaminski M. A. & Kuhnt W., 1995: Tubular agglutinated foraminifera as indicators of organic carbon flux. In: Kaminski, M. A., Geroch, S., & Gasiński, M. A., (eds.), *Proceedings of the Fourth International Workshop on Agglutinated Foraminifera*. Grzybowski Foundation Special Publication, no. 3, p. 141-144.

Kirsch, K.-H. 1991: Dinoflagellatenzysten aus der Oberkreide des Helvetikums und Nordultrahelvetikums von Oberbayern. *Münchner geowissenschaftliche Abhandlungen* (A), 22: 306 pp.

Kotlarczyk, J., 1985: An outline of the stratigraphy of marginal tectonic units of the Carpathian orogen in the Rzeszów-Przemyśl area. In: Kotlarczyk, J. (ed.), Geotraverse Kraków- Baranów-Ustrzyki Dolne-Komańcza-Dukla. Guide to Excursion 4. Carpatho-Balkan Geological Association XIII Congress, Cracow, Poland 1985, p. 39-64.

Książkiewicz M., 1951: *Objaśnienie arkusza Wadowice*. Ogólna mapa geologiczna Polski w skali 1:50 000. Państwowy Instytut Geologiczny, Warszawa, 283 p.

Kuhnt W., Moullade M., Kaminski M. A., 1996: Ecological structuring and evolution of the deep sea agglutinated foraminifera – a review. Rev. Micropaleont, 39 (4),p. 271-281.

Lemańska, A., in print: Comparison of deep-water agglutinated foraminifera from hemipelagic variegated shales (Early Turonian-Early Santonian) and turbiditic Godula beds (Late Santonian-Campanian) in the Lanckorona-Wadowice area; Silesian Nappe (Polish Outer Carpathians). *Studia Geologica Polonica*, 124.

Leszczyński, S. & Uchman A., 1991: To the orgin of variegated shales from flysch of the Polish Carpathians. *Geologica Carpathica*, 42: 279-289.

Nagy J., Gradstein F. M., Kaminski M. A., Holbourn A. E., 1995: Foraminiferal morphogroups, paleoenviroments and new taxa from Jurassic to Cretaceous strata of Thakkhola, Nepal. In: Kaminski, M. A., Geroch, S., & Gasiński, M. A. (eds), *Proceedings of the Fourth International Workshop on Agglutinated Foraminifera*. Grzybowski Foundation Special Publication, no. 3, p. 181-209.

Oszczypko, N., 1992. Late Cretaceous through Paleogene evolution of the Magura Basin. *Geologica Carpathica*, 43: 333-338.

Potter, P. E., Maynard, B. J. & Pryor, W. A., 1980. Sedimentology of Shale. Study Guide and Reference Source. Springer-Verlag, New York, 310 pp.

Słomka T., 1995: Głębokomorska sedymentacja silikoklastyczna warstw godulskich Karpat (summary: Deep-marine siliciclastic sedimentation of the Godula Beds, Carpathians). *Prace Geologiczne*, 139: 1-132.

Stover, L. E., Brinkhuis, H., Damassa, S. P., de Verteuil, L., Helby, R. J., Monteil, E., Partridge, A. D., Powell, A. J., Riding, J. B., Smelror, M. & Williams, G. L., 1996: Mesozoic-Tertiary dinoflagellates, acritarchs and prasinophytes. *In*: Jansonius, J. & McGregor, D. C. (eds), Palynology: principles and applications. *American Association of Stratigraphic Palynologists Foundation*, 2: 641-750.

Szymakowska, F. & Żytko, K. (eds), 1965: *Szczegółowa Mapa Geologiczna Polski (bez utworów czwartorzędowych) 1:50000. Rejon Karpat i Przedgórza. Arkusz Kalwaria Zebrzydowska.* Wydawnictwa Geologiczne, Warszawa.

Ślączka, A., 1959: Stratygrafia serii śląskiej łuski Bystrego na południe od Baligrodu (summary: Stratigraphy of the Bystre scale [Middle Carpathians]). *Instytut Geologiczny, Biuletyn*, 203-286.

Ślączka, A. & Kaminski, M. A., 1998: Guidebook to Excursions in the Polish Flysch Carpathians. *Grzybowski Foundation Special Publication*, 6: 171 + x pp.

Tyszka J., 1994: Response of Middle Jurassic benthic foraminiferal morphogroups to dysoxic/ anoxic conditions in the Pieniny Klippen Basin, Polish Carpathians. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 110: 55-81

Williams, G. L., Brinkhuis, H., Pearce, M. A., Fensome, R. A. & Weegink, J. W., 2004: Southern Ocean and global dinoflagellate cyst events compared: index events fro the Late Cretaceous-Neogene. In: Exon, N. F., Kennett, J. P. & Malone, M. J. (eds), *Proc. ODP, Sci. Results*, 189: 1-98.

APPENDIX

An alphabetical listing of agglutinated foraminifera and dinocyst taxa found in the Kalwaria Zebrzydowska section is provided below. Numbers in parentheses refer to the appropriate photomicrographs in Plates 1 to 2 (foraminifera) and 3 to 6 (dinocysts).

Foraminifera:

Ammodiscus cretaceus (Reuss, 1845) [Pl. 1H]
Ammodiscus irregularis (d'Orbigny)
Ammodiscus sp.
Bathysiphon microrhaphidus (Samuel, 1977) [Pl. 1D]
Bathysiphon sp.
Caudammina gigantea (Geroch, 1960) [Pl. 1O, P]
Caudammina ovulum (Grzybowski, 1896)
Gerochammina conversa (Grzybowski, 1901) [Pl. 2I]
Gerochammina obesa (Neagu, 1990) [Pl. 2G]
Gerochammina stanislawi (Neagu,1990) [Pl. 2J]
Glomospira charoides (Jones et Parker, 1860) [Pl. 2B]
Glomospira diffundens (Cushman et Renz, 1946)
Glomospira glomerata (Grzybowski, 1898)
Glomospira gordialis (Jones et Parker, 1860)
Glomospira irregularis (Grzybowski, 1898) [Pl. 1I]
Glomospira serpens (Grzybowski, 1898)
Glomospira sp.
Haplophragmoides mjatliuke (Maslakova, 1955) [Pl. 2A]
Haplophragmoides sp.
Hormosina crassa (Geroch, 1966) [Pl. 1N]
Hormosina velascoensis (Cushman, 1926) [Pl. 1M]
Hyperammina elongata (Brady, 1878) [Pl. 1F]
Hyperammina sp.
Kalamopsis grzybowskii (Dylążanka, 1923) [Pl. 1G]
Karrerulina horrida (Mjatliuk, 1970)
Nothia excelsa (Grzybowski, 1898) [Pl. 1C]
Paratrochamminoides irregularis (White, 1928) [Pl. 2D]
Paratrochamminoides olszewskii (Grzybowski, 1898) [Pl. 2C]
Paratrochamminoides sp.
Psammosphaera fusca (Schultze, 1875) [Pl. 1E]
Psammosphaera sp.
Recurvoides spp.
Reophax duplex (Grzybowski, 1869) [Pl. 1L]
Reophax pilulifer (Brady, 1844)
Reophax sp.
Rhabdammina cylindrica (Glaessner, 1937) [Pl. 1B]
Rhabdammina linearis (Brady)
Rhabdammina sp. [Pl. 1A]
Rhizammina sp.
Rzehakina minima (Cushman et Renz, 1946) [Pl. 1K]
Rzehakina sp.
Saccammina sp.
Trochammina globigeriniformis (Jones et Parker, 1865) [Pl. 2E, F]
Trochammina spp.
Trochamminoides folius (Grzybowski, 1898)
Trochamminoides grzybowskii (Kaminski et Geroch, 1993)
Trochamminoides proteus (Karrer, 1866) [Pl. 1J]
Trochamminoides sp.
Uvigerinammina jankoi (Majzon, 1943) [Pl. 2H]

Dinocysts:

Achomosphaera sp. [Pl. 3R; Pl. 4W, Z; Pl. 5O]
Alisogymnium euclaense (Cookson et Eisenack, 1970) Lentin et Vozzhennikova, 1990 [Pl. 5G]
Apteodinium sp. [Pl. 6F]
Callaiosphaeridium asymmetricum (Deflandre et Courteville, 1939) Davey et Williams, 1966 [Pl. 4S]
Cannosphaeropsis utinensis O. Wetzel, 1932 [Pl. 4T]
Cerodinium sp. [Pl. 6U]
Chatangiella sp. [Pl. 6D]
Circulodinium distinctum (Deflandre et Cookson, 1955) Jansonius, 1986 [Pl. 3W; Pl. 5T]
Cribroperidinium sp. [Pl. 3V; Pl. 6C, Q]
Dapsilidinium sp. [Pl. 3F; Pl. 6A]
Diphyes sp. [Pl. 5F]
Disphaeria sp. [Pl. 6K, P, T]
Eatonicysta ursulae sensu Marheinecke, 1992 [Pl. 6L]
Exochosphaeridium sp. [Pl. 3X; Pl. 4V]
Florentinia sp. [Pl. 4P]
Glaphyrocysta ordinata (Williams et Downie, 1966) Stover et Evitt, 1978 [Pl. 5S]
Hystrichodinium pulchrum Deflandre, 1935 [Pl. 4U]
Hystrichodinium sp. [Pl. 5X]
Hystrichokolpoma cinctum Klumpp, 1953 [Pl. 5R]
Hystrichosphaeridium salpingophorum (Deflandre, 1935) Deflandre, 1937 [Pl. 5Q, U]
Hystrichosphaeridium tubiferum (Ehrenberg, 1838) Deflandre, 1937 [Pl. 4R]
Hystrichosphaeridium sp. [Pl. 3Y; Pl. 4K-M]
Hystrichosphaerina? sp. [Pl. 4D]
Impagidinium sp. [Pl. 5A]
Isabelidinium spp. [Pl. 4G-J]
Kallosphaeridium sp. [Pl. 3M]
Kiokansium polypes (Cookson et Eisenack, 1962) Below, 1982 [Pl. 5B]
Kleithriasphaeridium sp. [Pl. 5Y]
Laciniadinium arcticum (Manum et Cookson, 1964) Lentin et Williams, 1980 [Pl. 6V, W]
Leberidocysta chlamydata (Cookson et Eisenack, 1962) Stover et Evitt 1978 [Pl. 6M, N]
Odontochitina costata Alberti, 1961 [Pl. 6Y]
Odontochitina operculata (O.Wetzel, 1933) Deflandre et Cookson, 1955 [Pl. 4A]
Odontochitina porifera Cookson, 1956 [Pl. 3A]
Odontochitinia sp. A *sensu* Kirsch (1991) [Pl. 6G]
Oligosphaeridium pulcherrimum (Deflandre et Cookson, 1955) Davey et Williams, 1966 [Pl. 3Z]
Operculodinium sp. [Pl. 4F; Pl. 5I]
Ovoidinium? sp. [Pl. 4E]

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Palaeohystrichophora infusorioides Deflandre, 1935 [Pl. 3N-Q]
Palaeoperidinium cretaceum Pocock, 1962 [Pl. 5V, W; Pl. 6H]
Palaeotetradinium silicorum Deflandre, 1936 [Pl. 3E]
?*Palynodinium* sp. [Pl. 4Q]
Pervosphaeridium sp. [Pl. 3L; Pl. 5N]
Prolixosphaeridium sp. [Pl. 3C]
Pterodinium aliferum Eisenack, 1958 [Pl. 6O, R]
Pterodinium cingulatum (O. Wetzel, 1933) Below, 1981 [Pl. 5C, D; Pl. 6C]
Pterodinium sp. [Pl. 6E, I]
Senoniasphaera rotundata Clarke et Verdier, 1967 [Pl. 4C]
Spiniferites crassipelis (Deflandre et Cookson, 1955) Sarjeant, 1970 [Pl. 5P]
Spiniferites ramosus (Ehrenberg 1838) Loeblich et Loeblich, 1966 [Pl. 3S-U; Pl. 4X, Y; Pl. 5K]
Stiphrosphaeridium anthophorum (Cookson et Eisenack, 1958) Lentin et Williams, 1985 [Pl. 3K]
Subtilisphaera sp. [Pl. 3I, J]
Surculosphaeridium belowi Yun, 1981 [Pl. 5H]
Surculosphaeridium? *longifurcatum* (Firtion, 1952) Davey et al., 1966 [Pl. 4B]
Systematophora sp. [Pl. 3D]
?*Taleisphaera hydra* Duxbury, 1979 [Pl. 5M]
Tanyosphaeridium sp. [Pl. 3B, G, H; Pl. 5E, L]
Trigonopyxidia ginella (Cookson et Eisenack, 1960) Downie et Sarjeant, 1965 [Pl. 4O]
Valensiella reticulata (Davey, 1969) Courtinat, 1989 [Pl. 6J]
Xenascus ceratioides (Deflandre, 1937) Lentin et Williams, 1973 [Pl. 6X]
"round-brown" [Pl. 4N]

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The fish fauna from the ŠVM - 1 borehole (Tajná village, Slovakia)

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Abstract: Following taxa were identified in structural borehole ŠVM – 1, Tajná village (Mochovce, Danube Basin): *Alosa* sp., Clupeidae, Engraulidae, Gobiidae and Triglidae. Fragments of bones were found in Middle Sarmatian clay sediments. The spectrum of fish species corresponds to a typical marine shallow water association of to subtropical up to temperate zone.

Key words: paleoecology, Middle Sarmatian, marine shallow-water, fish fauna, Danube Basin

Introduction

Neogene sediments from the Danube Basin yield rich assemblages of fossil fish, which records evolution of Tertiary fish fauna in a broad area. Neogene fish assemblages of Danube Basin were described from several localities – Smolenice, Skalka near Štúrovo and from Rišňovce depression (Holec, 1973, 1974; Fordinál & Nagy, 1997; Fordinál, 2000). Fish remains of *Alosa* sp., Clupeidae, Engraulidae, Gobiidae and Triglidae were determined from structural borehole ŠVM-1 (Fig. 1), which was drilled SW from Tajná village in the Danube Basin. Neogene sediments of Sarmatian to Dacian age were drilled in (211 m depth) this borehole. Fish fauna was contained in grey-green laminated claystones (121.45 up to 142.30 m) of Vráble Fm. This relative thin section, can be lithologically and faunistically correlated with other Sarmatian localities in the Danube and in the Vienna Basin as well as.

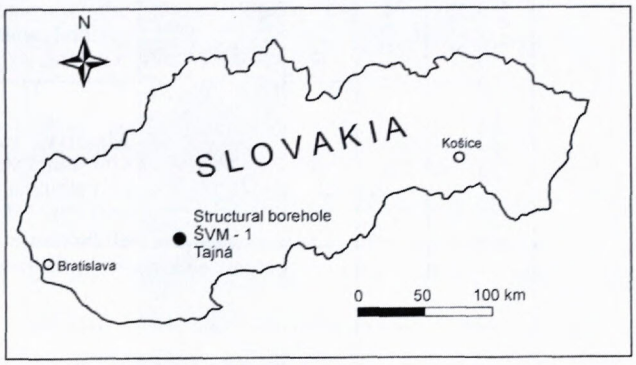

Fig. 1: Localization of the borehole ŠVM – 1 Tajná.

Geological setting

Broad area around the Mochovce village is build by Neogene deposits of the Danube Basin (Fig. 2). Neogene sequence in this area consists of Pliocene Volkovce Fm, Pontian Beladice Fm, Pannonian Ivánka Fm, Sarmatian Vráble Fm, Badenian Ruskov Fm, Svinná Fm, Pozba Fm and Madunice Fm (Harčár et al., 1988).

The borehole proper consists of the Volkovce Fm in the interval 1.00 up to 24.00 m, which also crops out on the surface. The formation is composed of complex of sands, pebble sands and gravels. Silty clays with layer of siltstones occur in the interval 12.15 – 16.18 m (Andrejeva-Grigorovič et al., 2001).

Sediments of the Ivánka Fm (l.c.) are developed in the interval 24.00 up to 111.70 m. According to biostratigraphy and lithological structure this formation is divided into the Pannonian E (interval 24.00 - 61.00 m), Pannonian C/D (interval 61.00 - 75.00 m) and Pannonian B (75.00 - 111.7 m). The Pannonian E informal member interval is composed of dark-grey silty clays and coarse till fine-grained sandstones, sometimes also pebble sandstones. The underlying deposits of the Pannonian C/D are mainly in the clays trend. These clays are richer on the residual of shell fauna. Deposits of the Pannonian B were deposited in freshwater low dynamic environment. This member is composed from relatively hard and cracky claystones, the silts laminas are very seldom (109.00 –109.50 m). Claystones with a lot of ostracods (Andrejeva – Grigorovič et al., 2001) in overlying part of the Pannonian B.

The Sarmatian sequence is represented by the Vráble Fm (l.c.) in the interval 111.70 up to 211.00 m. Biostratigraphically the Vráble Fm was divided into Upper (111.70 – 120.60 m), Middle (120.70 – 173.15 m) and Lower Sarmatian (173.15 – 211.00 m) parts. Upper and Middle Sarmatian deposits are practical identical, their boundaries are very gradual and they are distinguishable biostratigraphically only. At this boundary, laminated to massive claystones alternate with more expressively claystones and claystones with frequent chalk laminas. Distinctively laminated claystones are dominating. The fish fauna was found in the last mentioned lithologies. The results of biostratigraphical research indicated on sedimentation in brackish environment up to 20 m depth. The change of markedly and indistinctively laminated claystones signified occasional stratification of water column with anoxic layer near the bottom. Synse-

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AGE		FORMATION	DEEP (m)	LITOLOGY	INTERPRETATION
PLIOCENE	Dacian	*Volkovce Fm.*	0 - 24	Fine to coarse grained sands, pebble sands and fine to medium grained gravels, occasionaly are occur clays with admixure and thin beds of silt,without fosill remnant.	Deposits of the coarse-grained fan delta. Sedimentary facies of delta front and alluvial part of delta topset.
					hiatus
PANNONIAN	E	*Ivánska Fm.*	24 - 61	Dark gray, calcareous clays, with high amount of silt and thick beds of coarse to fine grained sand, silt, occasionally too with fine grained gravel. They are aranged to thickening upward trends. Remnants of the fossil flora and fauna are preserved.	Basinal sediments of the shallow brackish environment (mainly clays). Occasionally are developed local deltas deposits (delta front sands and prodelta silts).
	C/D		61 - 75	Gray, gray-green to green clays with admixure and thin intercalations of fine grained sands and silts. Shell and plant remnants are preserved.	Shelf deposits of the shallow marine brackish environment. (gray clays). Occasionally are developed lagunar clays or local deltas deposits (prodelta silts)
					hiatus
	B		75 - 106	Massive, calcareaous brown-green claystones with very fine silt admixure and abundant ostracoda fauna. Strong tectonic deformation, abundant slicken-sides. Upper boundary is discordant, lower one is conforms.	Basinal facies of the extremely brakish environment. Neritic deposits without deltaic sand and silt.
					hiatus
SARMATIAN	Upper	*Vráble Fm.*	106 - 120.6	Mainly green- brown and brown-green calcareaous very fine silty claystones. Alternating of diffuse and sharp laminated claystones. White tuff and tuffite lamina are common. Occasionally are developed small synsedimentary deformations. Clays are tectonic deformated, bed dip is 10 - 30°. Shell, fish and plant remnants are quite common.	Deep shelf deposits of the brackish environment. Rare, thin, laminated tuffites suggests to minimal influx of the silty and sandy material. Clays are both, aeolian (vulcanosedimentry) and sedimentary origin. Synsedimentary deformations suggest to seizmic activity of the region, dipping lamina suggest to postdiagenetic deformation of rocks.
	Middle		120.6 - 173.1		
	Lower		173.1 - 211	Massive, occasionally laminated brown-green to gray-green claystones. Redeposited shell fragment and volcanic lappilas are common. Thin andesite layer are interpreted as clast in claystones. Lowermost part of borehole is form by porphyric andesite (Čifáre type).	Shoreface, transgressive deposits of brackish environment with volcanic clasts in claystones. Tuff and tuffite beds suggest to volcanic activity of area. In upper part of section is documented abrupt deepening and increase of salinity connected with marine ingression. Andesites in lowermost part are interpreted as part of subaquaceous lava flow.

Fig. 2: General litological and sedimentological description of borehole ŠVM – 1 Tajná.

dimentary deformations were observed locally suggesting seismic activity in broad area.

On the interface of Middle and Lower Sarmatian, in biostratigraphy proved sea ingression into very isolated sedimentary environment. In the sedimentary record this event could be indicated by presence of claystones rich in destroyed shells (transgressive shell bed lag), which rapidly pass into deep-water laminated clays. These transgressive sediments are frequent mainly at the base of deposits.

Lower Sarmatian part of sequence consists of laminated claystones. Massive claystones which often contain admixture of pyroclastic rocks prevail. Lower Sarmatian sequence is typical by occurrence of andesite blocks as well as by tuffites and rare also by biotite tuffs. In the lowermost part of core more than 22 m thick andesitic lava flow (Andrejeva – Grigorovič et al., 2001) occurs.

Methods and terminology

Morfometric measurement was made in binocular microscope with precision of 0.5 mm, length data was measured on the vertical line with the axis of body.

Abbreviations used: SL – standard length, LCa – head length, LM – length of the jaw, DO – eye length, PO – preorbital length, PD – predorsal length, PP – prepectoral length, PV – prepelvic length, PA – preanal length, LD – length of the base of the dorsal fin, LA – length of the base of the anal fin, AC – body depth, AP – least depth of the caudal peduncle
D – dorsal fin, V – pelvic fin, P – pectoral fin, A – anal fin, C – tail fin, Vert. – number of vertebra

Systematics

Superorder Clupeomorpha
Order Clupeiformes
Suborder Clupeoidei CUVIER, 1817
Family Clupeidae BONAPARTE, 1831

Clupeidae gen. indet.

Plate 2a

Materials: One incomplete skeleton (without the head), tail part is destroyed too; body with cycloid scales (number of sample 3 TA).

Description: The fish body is prolate and on the transverse section is oval with abdomen keel. The lower jaw-bone is shorter as upper jaw-bone. This specimen has big eyes. The dorsal fin is short; it consists of 17-20 relatively high rays. The tail fin is cut out deeply, having the shape of the "V" letter. The pelvic fins begin in the middle of the fish body. Clupeidae have expressive separate big cycloid scales. The size of the body reaches up to 36 cm.

Paleoecology: The modern counterparts of this fish are social, herd living in epicontinental sea water, in little depth subtropical to arctic areas.

Stratigraphic range: Eocene – Pleistocene of the Europe (Romer, 1967).

Occurrence: Structural borehole ŠVM – 1, depth 123.00 m (number of sample 3 TA), Rohožník locality (Holec, 1973, 1974).

Genus *Alosa* Linck, 1790

***Alosa* sp.**

Plate 1a, Plate 2b, c

Materials: One incomplete skeleton with spinal column and tail (number of sample 4 TA) and one complete fish (number of sample 7 TA).

Dimensions:
Vert. 40, SL 36.0 mm, LCa 10.5 mm, PD 13.0 mm, AP 2.0 mm.

Tab. 1: Principal metrical parameters (mm) of the specimens n. 7 TA Alosa sp. (% SL in paranthesis).

Number	SL	LCa	PD	AP
7 TA	36.0	10.5 (29.1)	13.0 (36.1)	2.0 (5.56)

Description: The body is prolate with big head part. The abdomen keel is apparent in generally oval transverse section. There are big eyes and broad mouth on the head. The lower jaw-bone is shorter then the upper jaw-bone. The dorsal fin is high and short, it begins before the pelvic fins. It consists of 15-17 rays. The pelvic fins are short (6-7 rays). The tail fin is deeply cut out in "V" shape. Cycloid scales could have been easily lost. The size of the body is different, it reaches 75 cm in length.

Paleoecology: This has social, herd fish living in brackish and normal salinite both shallow littoral water as well as in mesopelagial.

Stratigraphic range: Oligocene – Pliocene of the Europe (Romer, 1967).

Occurence: Structural borehole ŠVM – 1, depth 138.00 m (number of sample 4 TA) and depth 137.50 m (number of sample 7 TA).

Family Engraulidae

Engraulidae gen. indet.

Plate 1b, Plate 2d

Materials: One incomplete skeleton with spinal column with vertebra and tail (number of sample 2 TA) and one no complete tail (number of sample 5b TA).

Description: The fish body is very slim, laterally flattened. The lower jaw-bone is very broad (extending well behind eyes). The upper jaw-bone is long. The dorsal fin begins in the middle of the fish body and it has 15-18 soft rays. The anal fin begin in 2/3 length of the fish body and it has to 26 soft rays. The pelvic fins begin before the middle of the fish body, before the base of dorsal fin. There are two scales on the base of tail fin. The total size of the body attains 25 cm, but it is usually smaller than 18 cm.

Paleoecology: This is bevy fish, herd fish living in mostly of shallow coastal waters and estuaries in tropical and temperate areas.

Stratigraphic range: Eocene – Miocene of the Europe (Romer, 1967).

Occurrence: Structural borehole ŠVM – 1, depth 142.30 m (number of sample 2 TA) and in the depth 139.40 m (number of sample 5b TA).

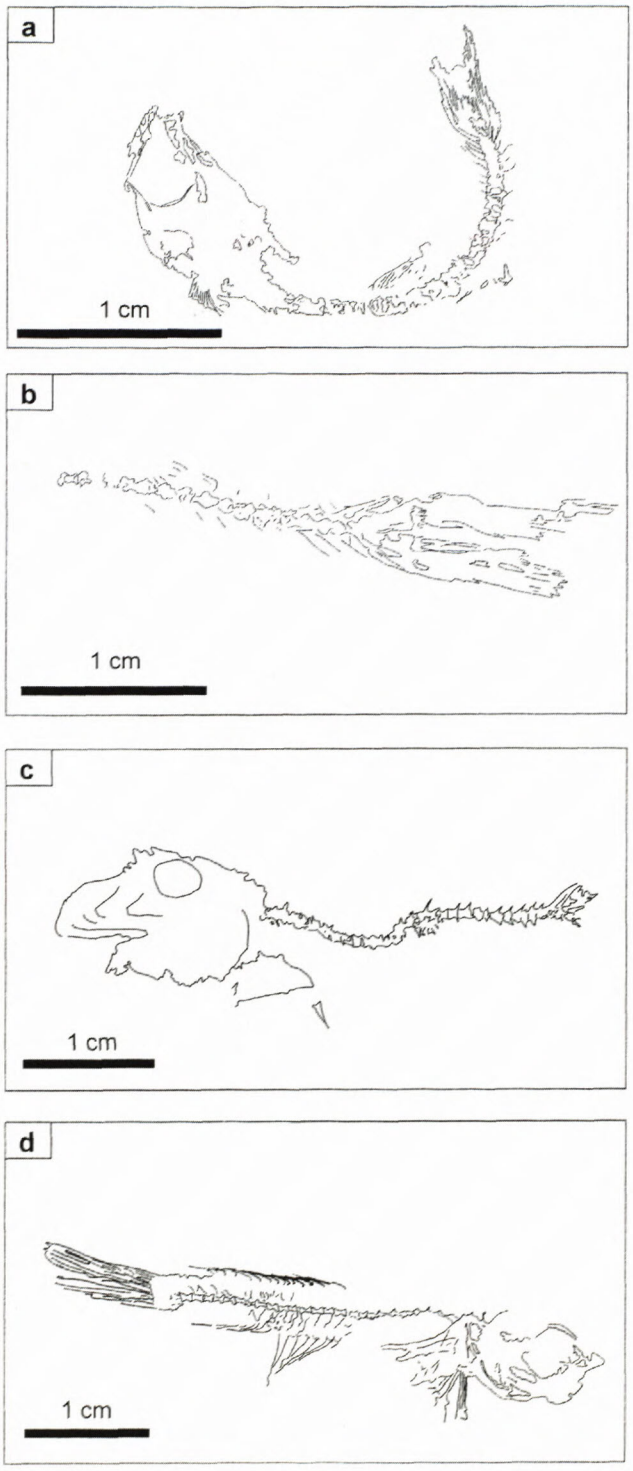

Plate 1
a - *Alosa* sp. (number of sample 7 TA)
b - Engraulidae gen. indet. (number of sample 2 TA)
c - Triglidae gen. indet. (number of sample 1 TA)
d - Gobiidae gen. indet. (number of sample 6 TA)

Superorder Acanthopterygii
Order Scorpaeniformes NELSON, 1994
Suborder Scorpaenoidei
Family Triglidae
Triglidae gen. indet.

Plate 1c, Plate 2e

Materials: One incomplete skeleton with the head and vertebra, but with fragment of tail (number of sample 1 TA).

Dimensions:
Vert. 29, SL 32.0 mm, Lca 12.0 mm, LM 5.0 mm, DO 3.0 mm, PO 5.0 mm, AP 1.0 mm.

Tab. 2: Principal metrical parameters (mm) of the specimens n. 1 TA Triglidae gen. indet. (% SL in paranthesis).

number	SL	LCa	LM	DO	PO	AP
1 TA	32.0	12.0 (37.5)	5.0 (15.6)	3.0 (9.4)	5.0 (15.6)	1.0 (3.1)

Description: The fish body is prolate with big head part. Compact bony cover is on the head. Triglidae have a big eyes and large jaws. The body has two dorsal fins, there are 8-10 hard rays on the first and 15-18 soft rays on the second one. The pectoral fins are big and ranging on 3-4 ray of the anal fin. The anal fin has 14-17 of soft rays. The size of the body is changeable, it reaches 25-50 cm in length.
Paleoecology: Triglidae are living over muddy, sandy and gravelly background, usually in 5-300 m. The young fish is living near the beach, especially in or near by the deltas (also in the fresh water) in tropical to temperate areas.
Stratigraphic range: Eocene – Miocene of the Europe (Romer, 1967)
Occurrence: Structural borehole ŠVM – 1, depth 128.20 m (number of sample 1 TA).

Order Perciformes
Suborder Gobioidei
Family Gobiidae
Gobiidae gen. indet.

Plate 1d, Plate 2f

Materials: One complete skeleton (number of sample 6 TA).
Dimensions:
Vert.29, V 9, A 13, C 14, SL 23.0 mm, LCa 7.0 mm, DO 2.8 mm, PO 1.0 mm, PP 8.0 mm, PV 7.0 mm, PA 14.0 mm, LD 6.0 mm, LA 5.0 mm, AC 2.5 mm, AP 2.0 mm.

Tab. 3: Principal metrical parameters (mm) of the specimens n. 6 TA Gobiidae gen. indet. (% SL in paranthesis)

Number	SL	LCa	DO	PO	PP	PV
6 TA	23.0	7.0 (30.4)	2.8 (12.2)	1.0 (4.3)	8.0 (34.8)	7.0 (30.4)

Number	PA	LD	LA	AC	AP
6 TA	14.0 (60.9)	6.0 (26.1)	5.0 (21.7)	2.5 (10.9)	2.0 (8.7)

Description: The fish body is prolate, little flattened laterally with long tail. The eyes are usually large and it situated near top of the head. Gobiidae have two separately dorsal fins, the first one with 7 (few with 8 hard rays), the second one with 1 hard and 9-10 soft rays. The

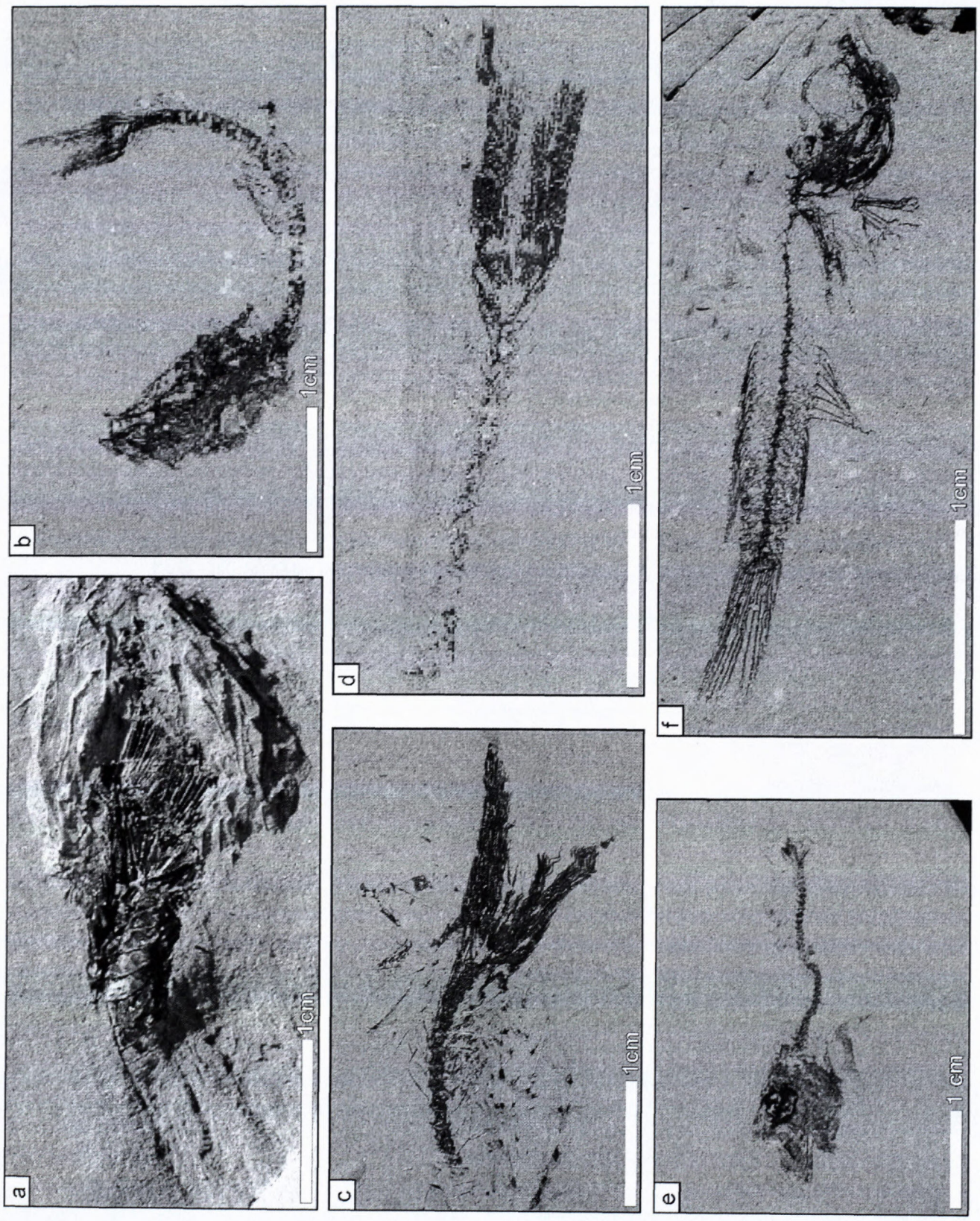

Plate 2:
a - Clupeidae gen. indet. (number of sample 3 TA)
b - *Alosa* sp. (number of sample 7 TA)
c - *Alosa* sp. (number of sample 4 TA)
d - Engraulidae gen. indet. (number of sample 2 TA)
e - Triglidae gen. indet. (number of sample 1 TA)
f - Gobiidae gen. indet. (number of sample 6 TA)

pectoral fins are big, without loose rays. The pelvic fins are accreting. The back of the tail fin is even. Gobiidae have expressive cycloid or ctenoid scales. The maximum length attains 50 cm, most specimens are smaller than 10 cm.

Paleoecology: Herd fish living in brackish and normal saline shallow coastal waters in tropical to subtropical areas.

Stratigraphic range: Middle Miocene - Recent of the Europe (Romer, 1967)

Occurrence: Structural borehole ŠVM– 1, depth 121.45 m (number of sample 6 TA).

Conclusions

This paper brings new data on occurrence of fish fauna from the borehole ŠVM – 1. From this borehole seven remnants were determined belonging to *Alosa* sp., Clupeidae, Engraulidae, Gobiidae and Triglidae. The study material comes from of Vráble Fm, from 121.45 up to 142.30 m interval.

The fish remains found document relatively shallow-water conditions – the sublittoral, open shelf zone or shallow, protected bays, with stratified water column. Tropical up to temperate climate could be confirmed by analysis of other fauna found (calcareous nannofossils, foraminifera and ostracods). This fauna which is also of brackish character indicates sedimentation in 30 – 40 m depth. The lack of carbonate in the water could be interpreted by the volcanic activity and by strong terrigenic debris support. In this period (Middle Sarmatian), the restriction of the basin was interrupted, which can be evidenced by immigration of Clupeidae.

References

Fordinál, K., 2000: Pannonian fauna of the northern part of the Danube Basin (Slovakia). Slovak Geological Magazine, 6, 2-3, 127-129.

Fordinál, K. & Nagy, A: 1997: Hlavina Mb – marginal Upper Pannonian deposits of the Rišňovce depression. Mineralia Slovaca, 6, 29, 401-406 (in Slovak).

Grigorovič, A. A., Fordinál, K., Halásová, E., Hudáčková, N., Slamková, M. & Sliva. Ľ., 2001: The lithological, sedimentological and biostratigraphical interpretation of ŠVM - 1 (Tajná) borehole Manuscript, PriF UK Bratislava, 65 pp (in Slovak).

Harčár, J., Priechodská, Z., Karolus, K., Karolusová, E., Remšík, A. & Šucha, P., 1988: Explanations of geological map 1 : 50 000 of north-east Danube Basin. GUDŠ, Bratislava, 114 pp (in Slovak).

Holec, P., 1973: Fisch-Otolithen aus dem Oberen Baden (Miozän) des Nordöstlichen Teiles des Wiener Beckens (Gebiet von Rohožník). Geologica Carpathica, Bratislava, 24, 2, 393-414.

Holec, P., 1974: The Badenian fish otoliths (Miocene) of north part the Vienna and Danube Basins. Manuscript, PriF UK Bratislava, 88 pp (in Slovak).

Romer, A. S., 1967: Vertebrate paleontology. The University of Chicago Press (Chicago and London), 468 pp.

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The structure of the gypsum-anhydrite dome at Alsótelekes

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Abstract. The Alsótelekes gypsum open pit works since 1987 and gives an insight to special features of evaporite tectonics in the Rudabánya Mountains. The evaporitic gypsum-anhydrite deposit was formed in the Upper Permian but the structure evolved during the Early Miocene movements of the Darnó sinistral strike-slip zone. The diapiric dome uplifted in an extension phase was overprinted by the imbrication of a later closure. These events produced a deposit in an advantageous thickness and position for the mining.

Keywords: evaporite tectonics, Darnó Zone, gypsum

Introduction

The Rudabánya Mountains is a SW-NE striking elongated chain of hills in the NE part of Hungary (Fig. 1). It lies in the Darnó Zone, a major tectonic boundary (Zelenka et al. 1983) which is about 4-5 km wide here. The metasomatic ores of the mountains, mainly copper and iron, were mined since the medieval times but nowadays all ore mining activities are stopped.

The evaporite complex was first found by drillings of an iron ore survey in 1950 in the outskirts of Alsótelekes. In 1952, the Perkupa-I. borehole explored a stack of anhydrite horses with imbricated serpentinized volcanic bodies in the Bódva Valley which was interpreted as a SE-verging overthrust structure (Mészáros 1957). Between 1957 and 1985, from the four-level underground mine of Perkupa anhydrite was exploited for melioration.

In 1968 the At-478 borehole at Alsótelekes (drilled for exploration of the tectonic structure) penetrated a gypsum-anhydrite body with more than 400 m thickness. When the Hungarian Geological and Geophysical Institutes (MÁFI and ELGI) examined the complex geological characteristics of the Aggtelek-Rudabánya Mountains (Less et al. 1988) from 1980 and made a gypsum-anhydrite prospect for the area (Grill & Szentpétery 1988), the shallow penetration high-frequency seismic profiles indicated the near-surface occurrence of the evaporitic complex eastwards from Alsótelekes (Albu et al. 1984). In 1986 the exploration drillings also confirmed the advantageous position of a gypsum body, covered by only few meters of other sediments in the Nagy Valley. After that, the area fit for open pit mining was explored by drilling along profiles and then in a network. Since then, 230 exploration boreholes, surface geoelectric (resistance, IP) surveys (Verő & Milánkovich 1983) and an open pit opened in 1987 explored the gypsum-anhydrite-shale-sandstone complex showing a diapiric evaporite tectonics in an area of 0,25 km^2 between the +160 and +205 m levels. Almost 2 million tons of raw materials were exploited. From the crystalline gypsum of better quality (>70% $CaSO_4$ x $2H_2O$) burnt gypsum (Paris plaster) and plaster boards are made. Gypsum of poorer quality and the anhydrite are used in the cement industry (Table 1).

So the pit (Fig. 2) offers a unique opportunity for studying the structural features of the evaporite. Our surveys covered the geological documentation of the drill cores (Kovács-Gál et al. 1987) and the pit walls with structural measurements. The aim was to get a picture about the structural details of the gypsum-anhydrite body and to build up a model for the formation of them with respect to the regional tectonics, first of all to the movements of the Darnó Zone.

Geological settings

The Darnó Zone consists of several individual fault blocks. The Telekes Valley itself indicates a fault parallel with the main strike of the zone (Fig. 1). On the SE side of this fault at Alsótelekes Gutenstein Dolomite crops out, the NW side is covered by neogene sediments. Surface geoelectronical (resistivity and IP) measurements proved the presence of the evaporite complex under 20-50 m cover next to the NW side of the Alsótelekes dolomite quarry (Verő & Milánkovich 1983). The gypsum open pit in the Nagy Valley lies some hundred meters away from that fault.

Stratigraphically the evaporitic formation can be considered the lowermost known unit of the Silicikum, named Perkupa Anhydrite Formation of Upper Permian age (Fülöp 1994). The Silica Nappes were detached from their basement in the incompetent material of this formation which acted as a décollement horizon (Less 2000). It is a typical lagoon facies sediment with sabkha-like conditions on the higher and reductive conditions on the deeper parts. There are three textural types of gypsum layers: brecciated, selenitic (coarse-grained) and laminitic. The lenticular, outwedging strata of the tidal zone

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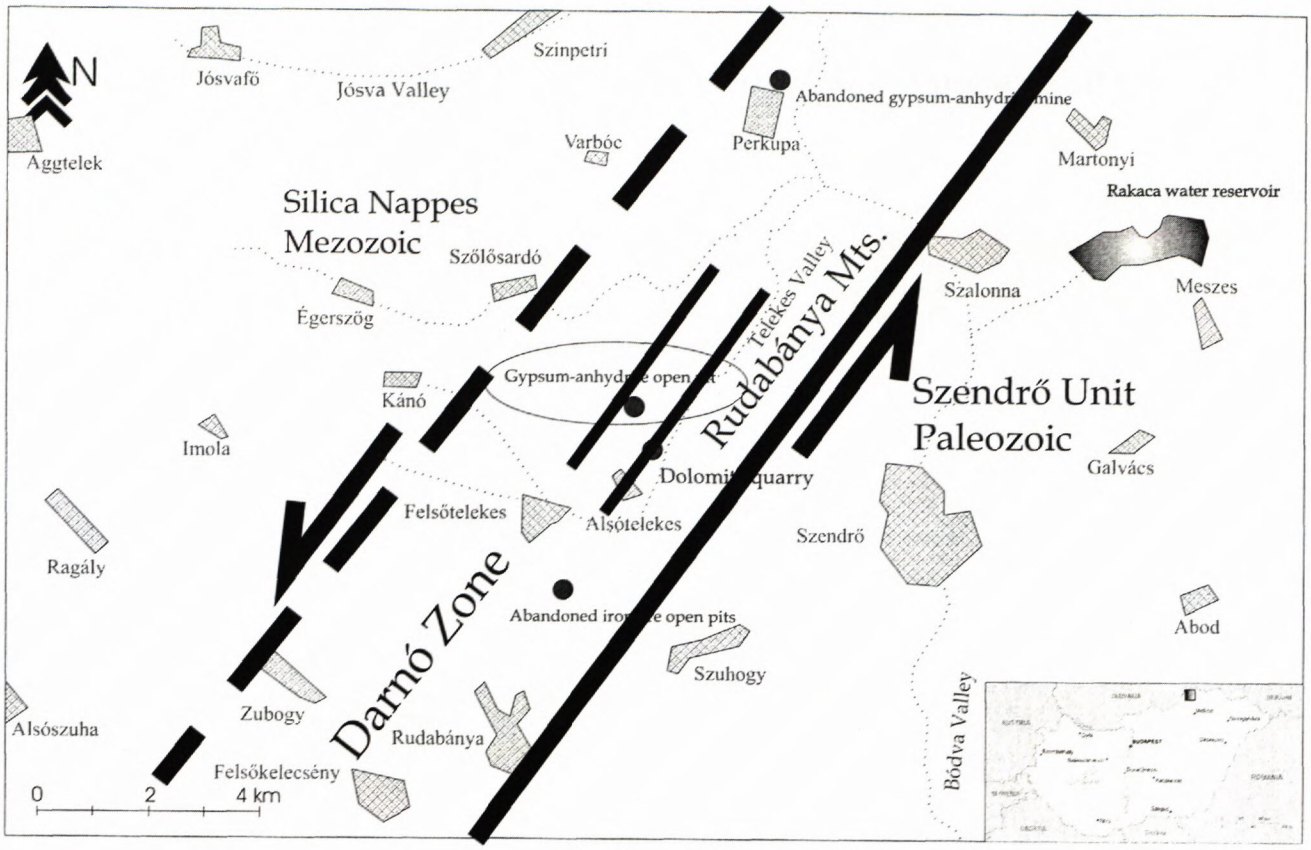

Fig. 1. Sketch map of the Rudabánya Mountains with the major tectonic elements.

Table 1. Chemical and mineralogical composition of the gypsum types at Alsótelekes. Chemical data measured in the Rudabánya laboratory, mineralogical data in the Eger laboratory of the OÉÁ (Hungarian Ore- and Mineral Mining Co) in 1987.

Chemical composition, %	**Laminitic gypsum**	**Selenitic gypsum**	**Brecciated gypsum**
SiO_2	1,2 – 8,6	2,2 – 3,55	4,05 – 10,05
Al_2O_3	0,1 – 0,52	0,12 – 0,26	0,12 – 1,01
CaO	26,63 – 31,54	28,7 – 32,53	25,23 – 29,44
MgO	1,61 – 2,72	0,4 – 2,81	1,92 – 6,35
CO_2	2,17 – 4,02	1,17 – 2,57	1,95 – 14,60
SO_3	36,70 – 43,50	40,3 – 44,05	30,39 – 40,13
Fe	0,2 – 1,0	0,2 – 0,8	0,20 – 1,10
Izz. veszt. 60°C	0,02 – 0,25	0,04 – 0,07	0,07 – 0,15
Izz. veszt. 225°C	15,18 – 18,71	16,98 – 18,38	12,43 – 16,79
K_2O water soluble	0,2 – 1,0	0,2 – 0,9	1,0 – 1,35
Na_2O water soluble	0,01 – 0,02	0,01 – 0,02	0,01 – 0,02
Mineralogical composition, %			
gypsum	77 – 92	85 – 93	64 – 85
anhydrite	0,5 – 6	0,5 – 5	1 – 7
carbonate	4	0,5	4 – 15
magnesite	4 – 5	3 – 4	5
muscovite	10	5 – 7	10 – 13
plagioclase	3	1 – 2	3
quartz	2	1 – 2	1 – 10
pyrite	-	-	1
serpentine	-	-	2 – 10

Fig. 2. SE-looking overwiev of the Alsótelekes gypsum-anhydrite open pit, 2004.

contain sand and cm-scale, slightly rounded, flat pebbles of anhydrite precipitated before and torn up by the wawes. On the highest parts elevated over the tide level lenses of red clay with iron oxides were formed. The strata formed beneath the tidal zone are dark, sometimes bituminous shales, sulphates and carbonates with fine scattered pyrite grains. Anhydrite occurs either with shale inclusions or with dolomite interlayering. The frequent alternation of the different rock types shows the undulation of the water level during the sedimentation. The microlayering of the dolomitic anhydrite indicates (probably seasonal) changes in temperature.

In the survey area and in the pit all contacts of the gypsum-anhydrite body are discordant. The direct cover is a continental red clayish sediment with debris and lenticular bodies of limestone breccia and resedimented black or purple clay of the evaporitic complex. The material often contains acicular gypsum crystals and veins. This sediment can be classified by its facies and material in the Lower Miocene Zagyvapálfalva Clay Formation, which is widely distributed in North Hungary. On the NW side of the pit large (10 m scale) blocks of dark and bright Steinalm Limestone are present, not directly on the gypsum but on the continental sediment and on black shale. This unmetamorphosed Steinalm Limestone is considered to belong to the succession of the Silica Nappes (Less 2000). There are also separate blocks of black shale, sandstone, dolomite and limestone of unidentified origin enclosed by the gypsum. Dark carbonates may have come from the Gutenstein Formation (underlying the Steinalm Limestone) but may be of Paleozoic origin as well. Black shale is most prevalent on the NW side not only in lateral contact with the gypsum but also with the continental sediment and between limestone blocks. Several blocks of black and bright limestone occur in a NE-SW striking zone on the SE side of the pit. This limestone is karstified and it contained considerable amount of water. The gypsum itself has become karstified on the top here too, with dolomite debris in the caverns (Fig. 3).

The uppermost beds are Pannonian fine-grained lacustric and limnic sediments with several lignite beds. The bedding is subhorizontal but seems to be inclined over the highest parts of the gypsum body.

Structure of the gypsum-anhydrite body

The present open pit explores the western side of a NE-SW elongated dome structure. In the upper 30-35 m of the evaporitic complex in the pit mainly gypsum with laminated black mudstone and anhydrite stripes can be found while under it there is a laminated dolomite-striped anhydrite. Several diapirs or mushroom-shaped intrusions of 10-20 m diametre with steep or vertical lamination are explored (Fig. 4). The laminated gypsum (which is the most prevalent type) shows at every part of the pit well-developed signs of ductile flow. Although the lamination may be an original sedimentary feature it is wholly transposed containing isoclinal or nearly isoclinal, dm-scale

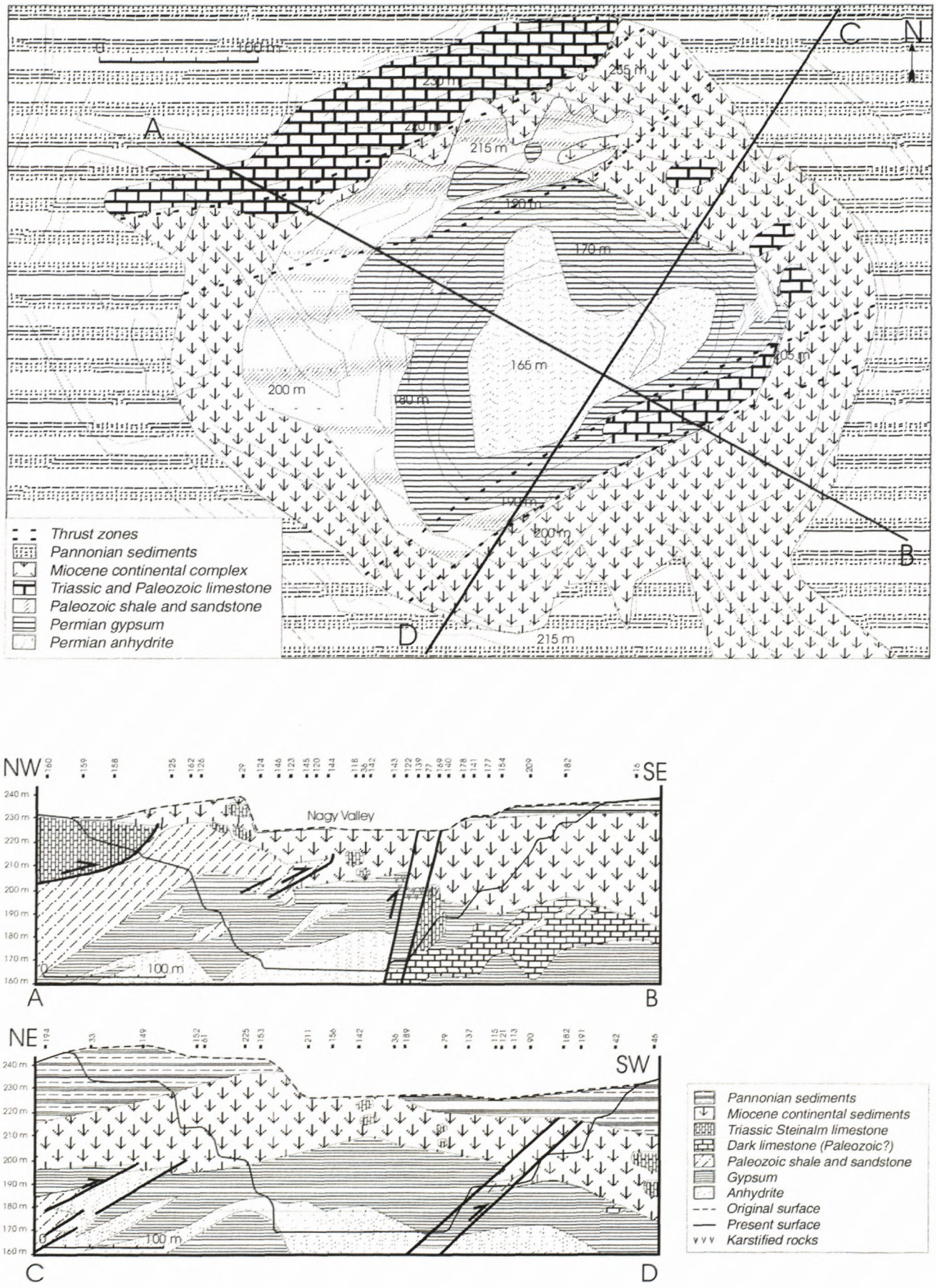

Fig. 3. Geological map (a) and profiles (b) across the Alsótelekes gypsum-anhydrite open pit.

Fig. 4. Diapir-structure in laminated gypsum.

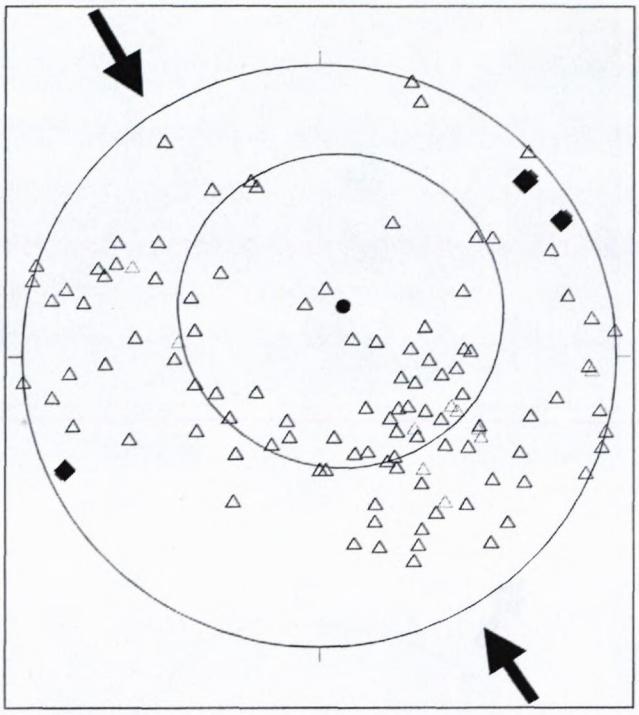

Fig. 6. Stereogram of the gypsum lamination dips. Triangles indicate lamination plane poles, qadrangles indicate second phase fold axes, best-fit small circle with dot indicates axis and folding angle of the dome (a conical fold), arrows show second phase compression.

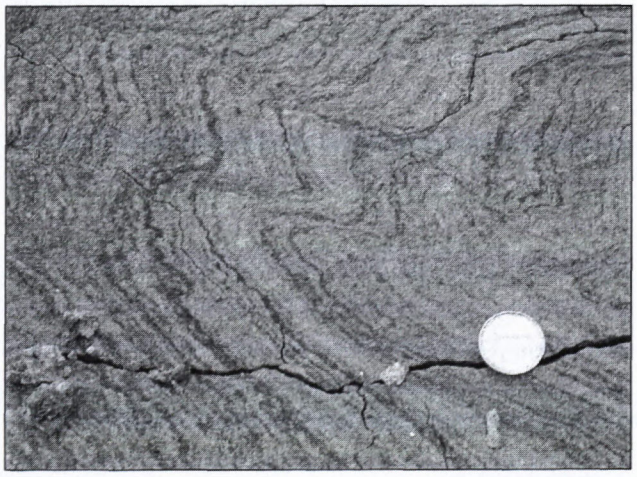

Fig. 5. Folding in laminated gypsum.

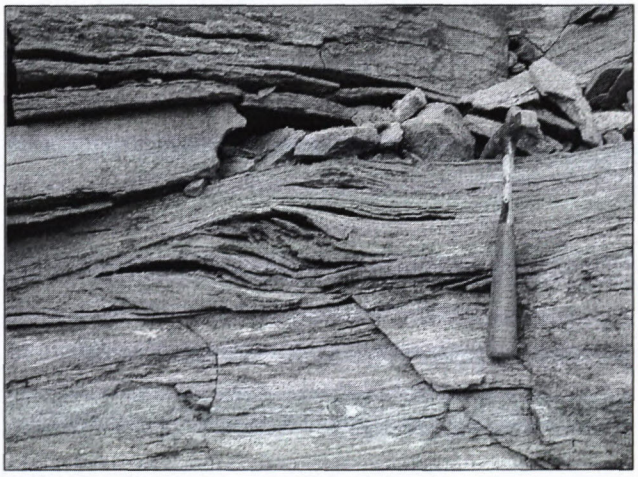

Fig. 7. Slightly bended anhydrite layers. The hammer is 28 cm long.

similar folds (this is the third-order folding here) (Fig. 5). These folds may seem to be cylindrical in their profiles but typically they are conical sheath folds. The laminae are continuous in general but truncated at enclosed limestone, sandstone or shale bodies. The dip angle has sudden changes from moderate to almost vertical in some zones. The pattern of the dips measured in the pit outlines a set of conical folds with subvertical axes (a diapiric structure) which corresponds to the second-order folding of a dome (Fig. 6). On the top of the diapirs the lamination is almost horizontal and bends over the top of the diapir like over a bootlast.

Anhydrite is also laminated but small-scale third-order folding is rare and of different style: the lamination bends with a gentle curvature, there are no sharp hinges (Fig 7). When it occurs together with gypsum, it acts as a competent material. Anhydrite pebbles in the laminated gypsum have in some cases δ-tails showing the direction of the tectonic transport (Fig. 8). Brecciated gypsum appears together with dark carbonate or sandstone clasts in the core of m-10m scale sheath folds (Fig. 9). It also seems to be competent in contrast to the laminated kind. Around these folds the laminated gypsum is jointed with curved surfaces reminding of onion

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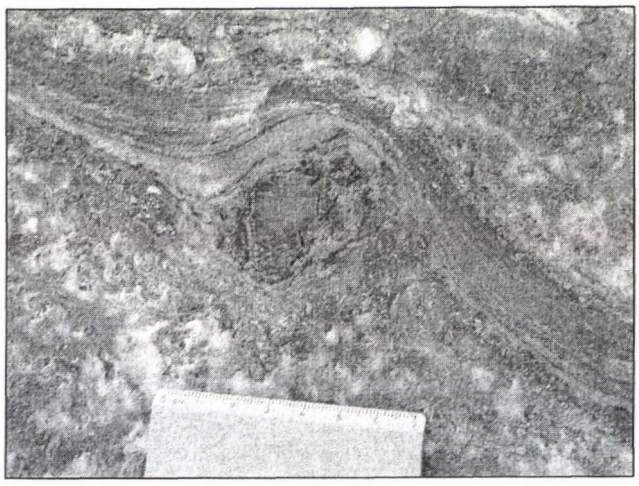

Fig. 8. Anhydrite clast with δ-tails in laminated gypsum.

Fig. 9. Sheath fold with limestone in the core.

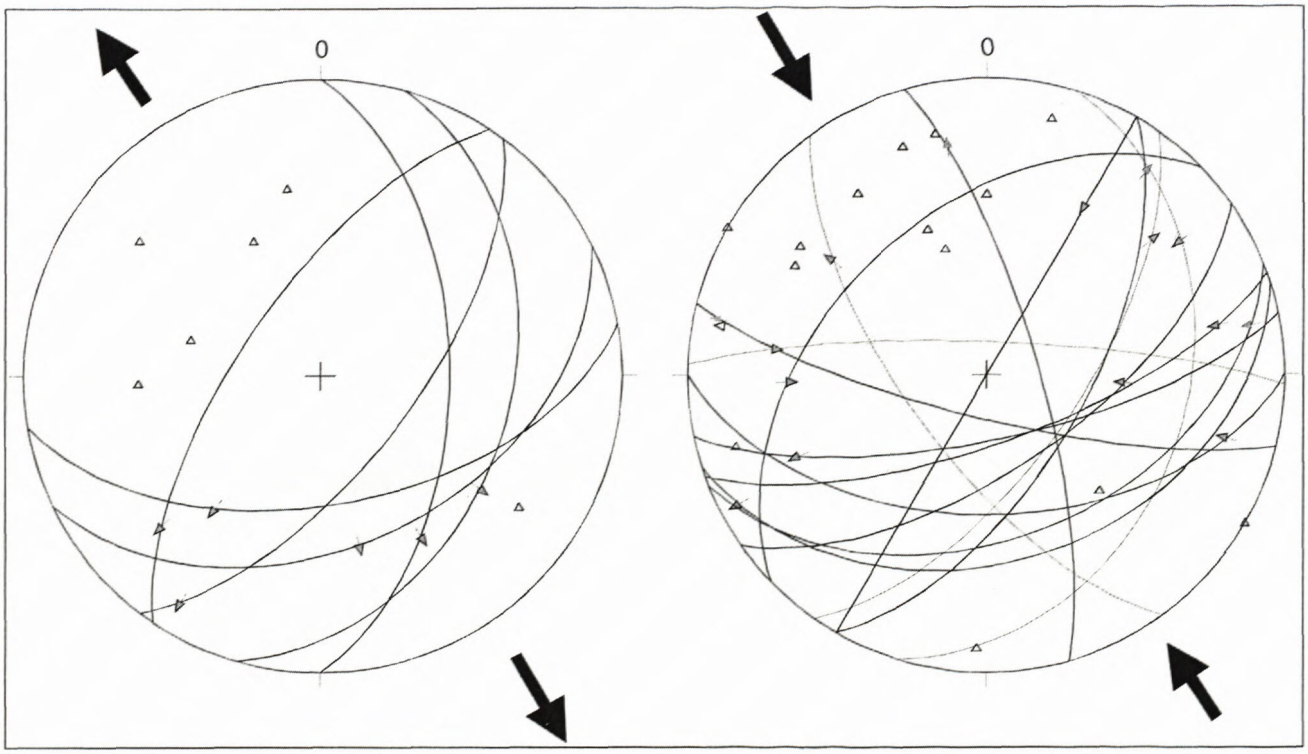

Fig. 10. Stereogram of the movements in the Steinalm limestone in the NW part of the pit. Major circles indicate planes, arrows indicate movement directions.

skin. The typical axis direction of these folds is horizontal around the 60°-240° strike corresponding to the elongation of the dome. When they occur together with vertical diapiric folds of the same scale, it causes a wavy interference pattern. The folding of the laminated gypsum is often associated with formation of brittle shear joints in the included or adjacent rock bodies.

In the S part of the pit there is a NNW-dipping fault zone with several blocks of dark limestone and with serpentinite-diabase clasts similar to the rocks reported from Perkupa (Mészáros 1957). Gypsum is brecciated at the contact and the movement planes on the limestone have slickenlines indicating a S-vergent overthrust. In the gypsum on the N side of this zone there is a 10 m-scale SSE-vergent antiform. In the core of this fold there is brecciated gypsum with several shear joints parallel with the axial plane of the fold and with slickenlines corresponding to the shear sense necessary to accommodate to the fold shape, forming an axial plane spatial cleavage with dm-scale domains. These joints are filled with acicular gypsum, and the fibres are perpendicular to the movement direction.

On the NW side the Steinalm limestone blocks are also in an overthrusted position and contain several movement planes with slickenlines. The older set of slickenlines indicates a NNW-SSE extension with normal faulting, while the younger set shows shortening in the same direction, corresponding to the present position of the blocks (Fig. 10).

Deformation history

The evaporitic diapirism at Alsótelekes is connected with the Miocene sinistral strike-slip dislocation of the Darnó Zone (Fig 1). The formation of the dome started with the opening of a zone-parallel elongated pull-apart basin along the NNE-SSW striking Telekes Valley fault in the Lower Miocene. The incompetent material of the evaporitic complex were moving toward this zone by ductile flow under the load of the overlying Mezozoic rocks and produced an anticline by its thickening. The remnants of the Mezozoic cover were uplifted and partly embedded in the evaporites while other blocks slipped aside. As the anhydrite became the outcropping layer on the surface, it was partly transformed into gypsum with karst features on the top. Meanwhile in the basin thick continental debris was accumulated, burying step by step the dome.

In a next phase, maybe still in the Lower Miocene the basin was inverted and closed by a NNW-SSE transpression. This phase is characterized by SSE-vergent thrusting of the competent blocks with folding of the gypsum, forming an uplifted, imbricated structure. The area took up a geographically high position as younger sediments are missing up to the Pannonian and these lie on an irregular sedimentation surface.

The Upper Pannonian lignite-bearing formation is unaffected by the evaporite tectonics, though its layers show slight bending above the gypsum diapir due to later extensions. In a cm-scale view, this bending is realized by several microfaults (Fig. 11). This subsidence can be derived either from solution processes or the slow ductile flow of the gypsum towards the Nagy Valley.

Conclusions

The Alsótelekes gypsum-anhydrite body is a diapiric dome structure intruded into a pull-apart basin of the Darnó Zone, overprinted by imbrication during the closure of this basin. The pit exposes the SW side of this anticline. The gypsum shows typical features of evaporite tectonics with structures of the ductile flow, while the deformation of other rocks was characteristically brittle. The most probable time of the main deformation events is Lower Miocene which is the supposed main period of activity of the Darnó sinistral strike-slip faulting.

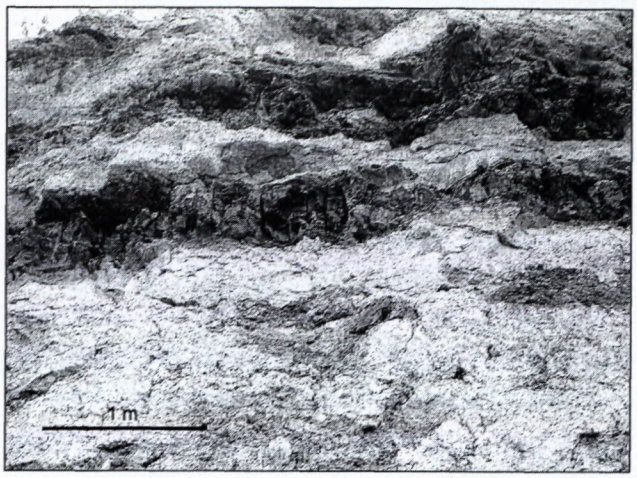

Fig. 11. Lignite beds with vertical joints.

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References

Albu, I., Nagy, E., Verő, L. & Zelenka, T., 1984: Geophysical survey of the Alsótelekes evaporite occurence. *Annual Report of the MÁELGI of 1983.*, p. 33-35. (in Hungarian)

Fülöp, J., 1994: *Geology of Hungary. Paleozoikum II.* Budapest: Akadémiai Kiadó, p. (in Hungarian)

Grill, J. & Szentpétery, I., 1988: Prospecting for gypsum-anhydrite deposits in the Aggtelek Karst and the Rudabánya Mts, N Hungary. *Annual Report of the Hung. Geol. Inst. of 1986*, p. 441-450. (in Hungarian)

Kovács-Gál, E., Kaló, J., Szilágyi, J. & Zelenka, T., 1987: The Aggtelek-Rudabánya Mountains gypsum survey. *Final report, in manuscript* (in Hungarian)

Less, Gy, Grill, J., Szentpétery, I., Róth, L. & Gyuricza, Gy., 1988: *1:25000 geological map of the Aggtelek-Rudabánya Mts.* MÁFI, Budapest

Less, Gy., 2000: Polyphase evolution of the structure of the Aggtelek-Rudabánya Mountains (NE Hungary), the southernmost element of the Inner Western Carpathians – a rewiev. *Slovak Geol. Mag.* vol. 6, no. 2-3, p. 260-268.

Mészáros, M., 1957: Geological features of the Perkupa gypsum-anhydrite occurence. *MÁFI Annales* vol. XLIX, no 4, p. 939-949. (in Hungarian)

Verő L. & Milánkovich, A., 1983: Report of the geoelectric survey in the outskirts of Alsótelekes in 1983. *MÁELGI Report T 15108. IV., in manuscript* (in Hungarian)

Zelenka, T., Baksa, Cs., Balla, Z., Földessy, J. & Jánnyi-Földessy, K., 1983: Is the Darnó lineament a mezozoic palaeogeographical boundary? *Földtani Közlöny* vol. 113, p. 27-37. (in Hungarian)

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Beránek, B., Leško, B. & Mayerová, M., 1979: Interpretation of seismic measurements along the trans-Carpathian profile K III. In: Babuška, V. & Plančár, J. (Eds.): *Geodynamic investigations in Czecho-Slovakia*. Bratislava: VEDA, p. 201-205.

Lucido, O., 1993: A new theory of the Earth's continental crust: The colloidal origin. *Geol. Carpathica*, vol. 44, no. 2, p. 67-74.

Pitoňák, P. & Spišiak, J., 1989: Mineralogy, petrology and geochemistry of the main rock types of the crystalline complex of the Nízke Tatry Mts. MS – Archiv GS SR, Bratislava, 232 p. (in Slovak).

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