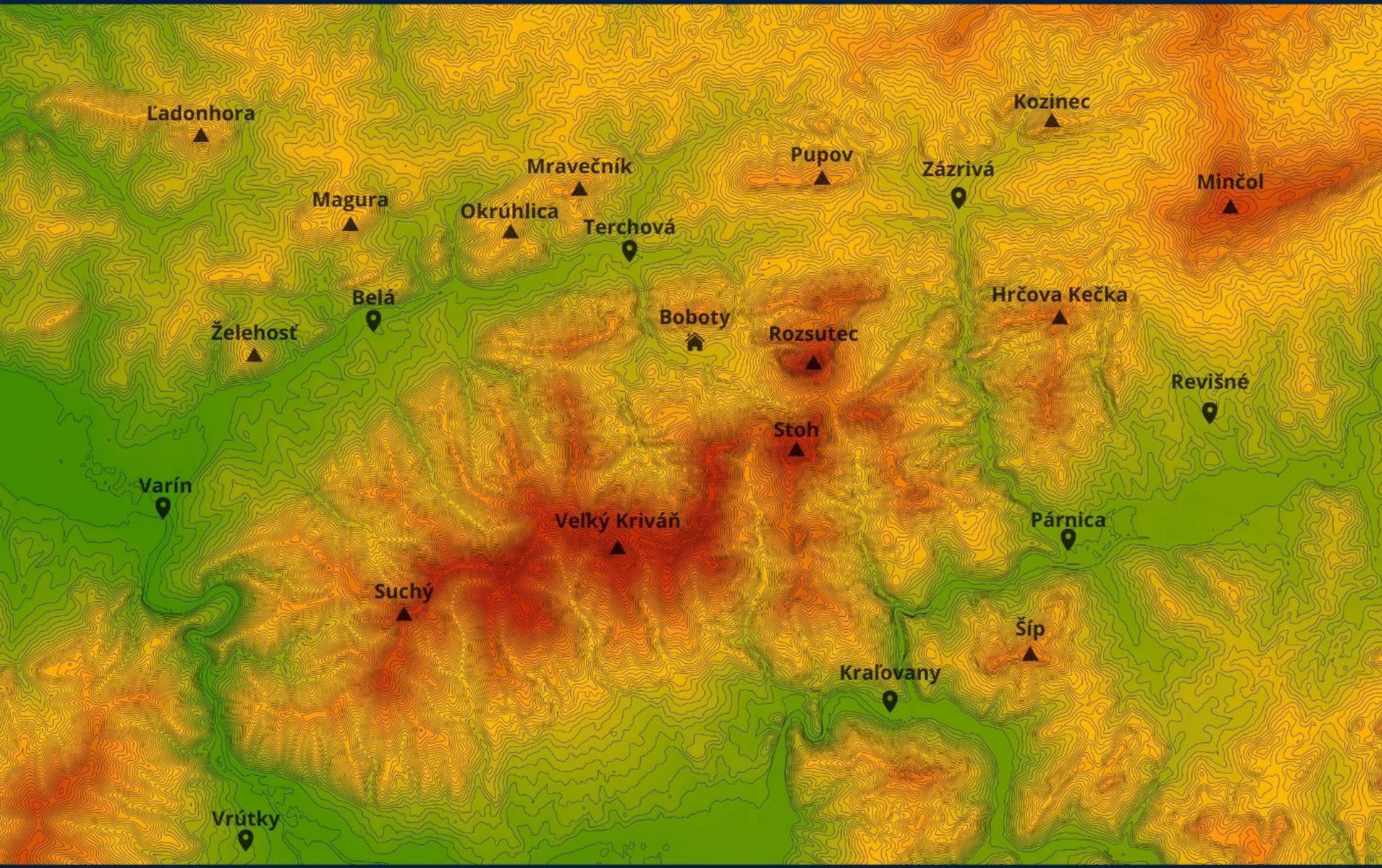
Structure, composition and tectonic evolution of the Pieniny Klippen Belt – Central Western Carpathians contiguous zone (Kysuce and Orava regions, NW Slovakia)

DUŠAN PLAŠIENKA, ROMAN AUBRECHT, VLADIMÍR BEZÁK, MIROSLAV BIELIK, IGOR BROSKA,
JANA BUČOVÁ, KAMIL FEKETE, PAVOL GAŽI, PRZEMYSŁAW GEDL, MARIÁN GOLEJ, EVA HALÁSOVÁ,
JOZEF HÓK, MARTIN HRDLIČKA, MICHAL JAMRICH, ŠTEFAN JÓZSA, RADEK KLANICA, PATRIK KONEČNÝ,
MICHAL KUBIŠ, JÁN MADARÁS, DUŠAN MAJCIN, FRANTIŠEK MARKO, MARÍNA MOLČAN MATEJOVÁ,
TOMÁŠ POTOČNÝ, JÁN SCHLÖGL, JÁN SOTÁK, GUILLAUME SUAN, LENKA ŠAMAJOVÁ, VIERA ŠIMONOVÁ,
FRANTEŠEK TEŤÁK, JÁN VOZÁR



COMENIUS UNIVERSITY BRATISLAVA, 2021

Structure, composition and tectonic evolution of the Pieniny Klippen Belt – Central Western Carpathians contiguous zone (Kysuce and Orava regions, NW Slovakia)

Dušan Plašienka, Roman Aubrecht, Vladimír Bezák, Miroslav Bielik, Igor Broska, Jana Bučová, Kamil Fekete, Pavol Gaži, Przemysław Gedl, Marián Golej, Eva Halásová, Jozef Hók, Martin Hrdlička, Michal Jamrich, Štefan Józsa, Radek Klanica, Patrik Konečný, Michal Kubiš, Ján Madarás, Dušan Majcin, František Marko, Marína Molčan Matejová, Tomáš Potočný, Ján Schlögl, Ján Soták, Guillame Suan, Lenka Šamajová, Viera Šimonová, František Teťák, Ján Vozár

Comenius University Bratislava, 2021

Citation of this work

Plašienka D., Aubrecht R., Bezák V., Bielik M., Broska I., Bučová J., Fekete K., Gaži P., Gedl P., Golej M., Halásová E., Hók J., Hrdlička M., Jamrich M., Józsa Š., Klanica R., Konečný P., Kubiš M., Madarás J., Majcin D., Marko F., Molčan Matejová M., Potočný T., Schlögl J., Soták J., Suan G., Šamajová L., Šimonová V., Teťák F. & Vozár J., 2021: Structure, composition and tectonic evolution of the Pieniny Klippen Belt – Central Western Carpathian contiguous zone (Kysuce and Orava regions, NW Slovakia). Comenius University Bratislava, 148 p.

Peer reviewed by

Michał Krobicki, AGH University of Science and Technology, Kraków, Poland

Jozef Michalík, Earth Science Institute of the Slovak Academy of Sciences, Bratislava, Slovakia

Ondrej Pelech, State Geological Institute of Dionýz Štúr, Bratislava, Slovakia

© The Authors, 2021

Dušan Plašienka[1]
Roman Aubrecht[1, 2]
Vladimír Bezák[2]
Miroslav Bielik[3]
Igor Broska[2]
Jana Bučová[4]
Kamil Fekete[5]
Pavol Gaži[4]
Przemysław Gedl[6]
Marián Golej[2]
Eva Halásová[1]
Jozef Hók[1]
Martin Hrdlička[2, 7]
Michal Jamrich[1]
Štefan Józsa[1]
Radek Klanica[8]
Patrik Konečný[5]
Michal Kubiš[4]
Ján Madarás[2]
Dušan Majcin[2]
František Marko[1]
Marína Molčan Matejová[1]
Tomáš Potočný[1]
Ján Schlögl[1]
Ján Soták[2]
Guillame Suan[9]
Lenka Šamajová[5]
Viera Šimonová[10]
František Teťák[5]
Ján Vozár[2]

Affiliations:

1 – Department of Geology and Palaeontology, Faculty of Natural Sciences, Comenius University Bratislava, Mlynská dolina, Ilkovičova 6, 842 15 Bratislava, Slovakia

2 – Earth Science Institute of the Slovak Academy of Sciences, Dúbravská cesta 9, P.O.BOX 106, 840 05, Bratislava, Slovakia

3 – Department of Engineering Geology, Hydrogeology and Applied Geophysics, Faculty of Natural Sciences, Comenius University Bratislava, Mlynská dolina, Ilkovičova 6, 842 15 Bratislava, Slovakia

4 – DPP Žilina Ltd., Legionárska 8203, 010 01 Žilina, Slovakia

5 – State Geological Institute of Dionýz Štúr, Mlynská dolina 1, 817 04 Bratislava, Slovakia

6 – Institute of Geological Sciences, Polish Academy of Science, Research Centre in Kraków, Senacka 1, 31-002 Kraków, Poland

7 – LAMA Gas & Oil Ltd., Čajkovského 4320/44b, 695 01 Hodonín, Czech Republic

8 – Institute of Geophysics of the Czech Academy of Sciences, Boční II, 141 31 Praha, Czech Republic

9 – UCBL, ENSL, CNRS, LGL-TPE, Université de Lyon, Villeurbanne F-69622, France

10 – Department of Geography and Geology, Faculty of Natural Sciences, Matej Bel University, Tajovského 40, 974 01 Banská Bystrica, Slovakia

This work is licensed under a Creative Commons CC BY-NC-SA 4.0.
Attribution-NonCommercial-ShareAlike 4.0 International License.

Comenius University Bratislava
ISBN: 978-80-223-5237-6 (online PDF version)

Contents

Introduction 1

1 Regional geological frame 2

1.1 Outline of the structure of the Malá Fatra Mountains. 6

1.1.1 Variscan granitic and metamorphic rocks of the Tatric basement 8

1.1.2 Representative localities in the Malá Fatra granitoid massif 12

1.1.3 Mesozoic sedimentary successions of the Tatric, Fatric and Hronic units 17

1.1.4 Central Carpathian Paleogene Basin and "Peri-Klippen Paleogene" 18

1.1.5 Alpidic tectonic evolution. 18

1.1.6 Instructive field sections of Mesozoic units. 22

1.2 Structure and composition of the Pieniny Klippen Belt – an overview 28

1.3 Lithostratigraphy of the Oravic units 32

1.3.1 Czorsztyn (Subpieniny) Unit 32

1.3.2 Kysuca (Pieniny) Unit 33

1.3.3 Grajcarek (Šariš) Unit 35

1.3.4 Other Oravic units. 36

1.4 The Flysch Belt of the Kysuce–Orava region 36

2 Litho-biostratigraphy and structure of the PKB sedimentary successions in the transitional Kysuce – Orava region. 39

2.1 Havrania Zone 41

2.1.1 Kozinec Unit 41

2.1.2 Subpieniny Unit. 42

2.1.3 Pieniny Unit. 43

2.1.4 Rock units with problematic affiliation 43

2.1.5 Important field outcrops and sections 50

2.2 Pupov Zone 68

2.2.1 Pupov Formation 68

2.2.2 Important field outcrops and sections 70

2.3 Plešivá Zone. 72

2.4 Regional field sections 72

2.5 Istebné Zone (Zázrivá–Párnica sigmoid) 97

2.6 Kubín Zone. 98

3 Tectonics of the Pieniny Klippen Belt and adjacent zones in north-western Slovakia 102

3.1 Small-scale structural elements. 103

3.2 On the origin of the Zázrivá sigmoid in the Western Carpathian Pieniny Klippen Belt 108

3.2.1 Models of the Zázrivá sigmoid evolution 110

3.2.2 Magnetotelluric model of crustal architecture in the Zázrivá sigmoid area 113

3.2.3 Discussion and conclusions 115

3.3 Geological structures across the contact between the External and Internal Western Carpathians based on 2D density modelling (northern Slovakia case study) 117

3.3.1 Geological overview 118

3.3.2 Profile PF-1 119

3.3.3 Profile PF-2 122

3.3.4 Conclusions 123

3.4 Tectonic evolution of the Klippen Belt. 123

Summary and conclusions 128

References. 129

Preface and acknowledgements

This publication presents the recent data achieved in frame of scientific projects that were granted to several members of the authors´ team. These projects have been focused on various aspects of geological research in the area concerned, especially to the structure, tectonic evolution, lithology and biostratigraphy of sedimentary formations, and petrology of basement complexes. Our aim is to make the readers acquaint with the new results and actual views on the structure of a piece of the Western Carpathians that connects the internal orogenic zones characterized by the Palaeoalpine nappe structure and the external zones representing the Cenozoic accretionary wedge. In between, the Pieniny Klippen Belt occupies the backstop position and is characterized by a unique composition and complex structure. Nevertheless, many problems remain unsolved, particularly the age and tectonic affiliation of some formations within the Klippen Belt. Hence this work represents the state of the art with a lot of open questions to be resolved by the future research.

There is a range of key field sections and localities, principally in the Klippen Belt, which are presented with the aim to serve also as a field trip stops for the scientific events (e.g. the CETeG meetings, like in the year 2021) or student excursions. At the same time, various specialists are invited to continue investigations in the area and to contribute by novel data from the listed or new localities in the area, because especially the soft rocks, which are by far the most widespread, are subjected to rapid changes in appearance and outcrop conditions.

Elaboration of the presented monograph resulted from a common effort of a comparatively large team of authors. Inevitably, there are some differences in terminology, interpretations and opinions on several topics among the authors. Years-long investigations behind this book were supported by a number of research projects provided by the Slovak Research and Development Agency (projects APVV-16-0146, APVV-16-0482, APVV-17-0170, APVV-18-0107 and APVV-20-0079) and by the Grant Agency for Science, Slovakia (projects VEGA 1/0085/17, VEGA 2/0075/20, VEGA 2/0047/20, VEGA 2/0013/20 and VEGA 1/0435/21). This paper corresponds also to the IGCP-710 Project of UNESCO. We are thankful to the reviewers for their corrections and valuable comments that considerably improved the scientific content of the manuscript. Ladislav Bittó is acknowledged for processing of illustrations in chapter 3.2.

Publication of this monographic work was remunerated by the Slovak Research and Development Agency (project APVV-17-0170) and by the Grant Agency for Science of the Ministry of Education, Science, Research and Sport of the Slovak Republic (project VEGA 1/0435/21), which is gratefully acknowledged. Both projects have been granted to D. Plašienka as the principal investigator.

Introduction

Convergent orogenic systems are characterized by extensive horizontal shortening and large-scale redistribution of crustal material by the tectonic, erosional and sedimentary processes. Shortening is mainly accomplished by stacking of thick- and thin-skinned thrust sheets that resulted from complex orogenic processes. These include subduction of domains composed of the oceanic lithosphere, in rare cases also its obduction, accretion of sedimentary units scraped off the lower plate of a convergent zone, collision of the continental blocks or fragments, post-collision crustal and lithospheric thickening accompanied by subduction of the continental lower crust and subcontinental mantle lithosphere, extensional collapse of overthickened collisional zones, exhumation of previously deeply buried rock complexes, surface uplift and mountain building, deposition of erosional products in a range of syn- and post-orogenic basins etc. These processes leave behind various types of basement-involved and décollement sedimentary nappes, shallow fold-thrust belts and accretionary wedges, ophiolitic sutures or zones of extensive shortening, wrench zones, metamorphic domes and core complexes, sedimentary basins developed in a range of tectonic settings, volcanic edifices and other types of tectonic structures. The collisional orogens may record all these processes and structures in various ways, depending on the amount of shortening and exhumation, composition of rock complexes involved, driving forces, thermal structure, exogenous agents like erosion etc.

Long-term evolving orogens, like the Western Carpathians, usually possess a typical wedge-shape in a cross-section with the outward progression and younging of tectonic processes. However, unlike majority of other collisional orogens (e.g. the Alps), the convergence history of the Western Carpathians was completed by a “soft collision” of the orogenic wedge with the European foreland plate during the Neogene. As a result, the final Western Carpathian structure is characterized by moderate exhumation and surface uplift and widespread presence of virtually non-metamorphic Meso-Cenozoic sedimentary complexes at the present erosional level. Consequently, interpretation of the tectonic evolution of the Western Carpathians is largely based on the sedimentary record. This is particularly the case of the external Carpathian zones, including the Klippen Belt and its neighbouring zones.

The present work aims at description of the composition and structure of the contact zone between the Cretaceous stack of basement and cover nappes of the inner Western Carpathian zones and the Cenozoic accretionary wedge of the outer zones. This boundary is followed by the Pieniny Klippen Belt (PKB), which is a very narrow, but the most distinctive Carpathian suture-like structure differing from the adjacent zones by the unique composition and by the extremely complicated internal structure. We characterize only a short segment of this contact zone in NW Slovakia, which otherwise extends for more than 600 km and forms a backbone of the Western Carpathian orogen. Nevertheless, this segment has many characteristics differing from the other PKB segments that contribute substantially to the knowledge and understanding of the relationships and evolution of this narrow structural zone following the contact between the two principal tectonic systems of the Western Carpathians. In the area concerned, the PKB is closely adjoined by the Malá Fatra mountain range, which is a typical Central Carpathian horst structure – the semi-isolated “core-mountains” composed of the Tatric crystalline basement and its Mesozoic sedimentary cover overlain by the Fatric and Hronic cover nappe systems and surrounded by extensional Cenozoic basins.

1 Regional geological frame

The Western Carpathians represent a northward-convex arcuate collisional mountain belt forming the northernmost segment of the European Alpidic orogenic system. Geographically, the Western Carpathians are linked with the Eastern Alps to the west and with the Eastern Carpathians to the east (Fig. 1.1). These three mountain ranges are united by the outer zones represented by an accretionary wedge shaped during the late Cenozoic (Flysch Belt), while the inner parts were basically formed by the Cretaceous thick- and thin-skinned thrust stacking. However, the inner zones exhibit a very complex evolution with multiple phases of compression, lateral movements and extension throughout the Mesozoic and Cenozoic (e.g., Schmid et al., 2008).

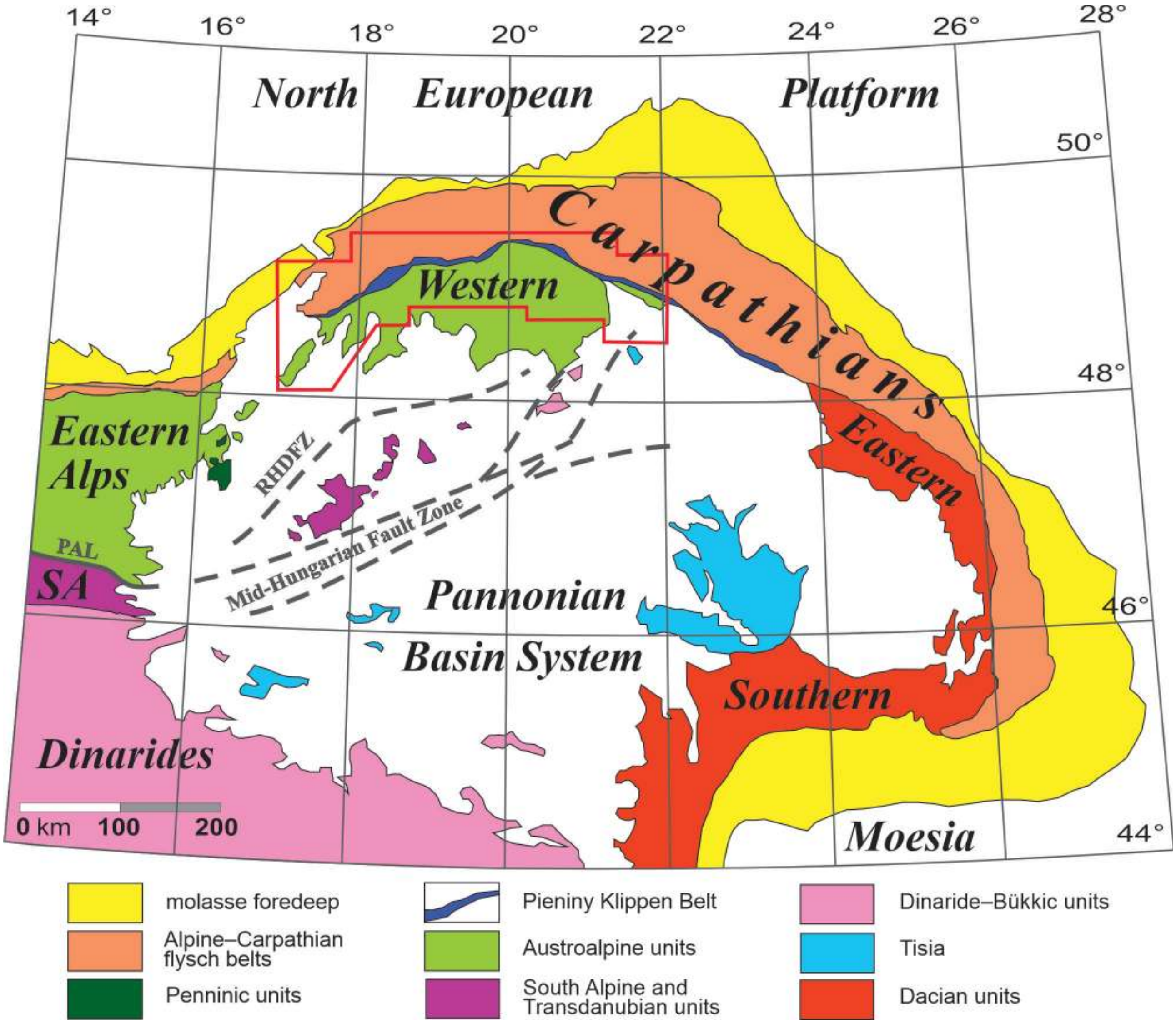


Figure 1.1 Sketch map of the circum-Pannonian mountain ranges, the red-framed polygon indicates the area depicted in Figure 1.2. Abbreviations: SA – Southern Alps; PAL – Peri-Adriatic Line; RHDFZ – Rába–Hurbanovo–Diósjenő Fault Zone (modified after Plašienka, 2018).

In general, the Western Carpathians are characterized by a zoned structure typical for the converging mountain systems. From the evolutionary point of view, three major sections have been discerned (for the recent reviews of the Western Carpathian structure and evolution supplemented by extensive reference lists see e.g. Froitzheim et al., 2008 and Plašienka, 2018a, or in an abridged form by Hók et al. (2014, 2019). Their boundaries are formed by narrow subparallel zones with intricate internal structure. Based on presence of specific, palaeogeographically independent units, which were at least partially deposited on an oceanic crust, these zones are regarded as oceanic sutures and/or ancient plate boundaries. The Meliata suture separates the Internal Western Carpathians (IWC) and the Central Western Carpathians (CWC), and the Pieniny Klippen Belt (PKB) divides the CWC and the External Western Carpathians (EWC – see Fig. 1.2). The southern limit the Western Carpathian orogenic system is formed by the mid-Hungarian fault zone, which is a kinematically complicated Tertiary wrench corridor linked with the Periadriatic "lineament" to the west (Fig. 1.1; e.g. Haas et al., 2000). The outer northern EWC mountain front overrides the autochthonous sediments of the Alpine Molasse Zone and Carpathian foredeep, which cover the southern flanks of the downbended North European Platform (e.g. Picha et al., 2007).

The IWC include two major units – the Transdanubian in the west and Bükkian units in the east, separated from the CWC by the Rába–Hurbanovo–Diósjenő Fault Zone (Fig. 1.1). The IWC units exhibit the southern vergence of the Late Jurassic and Early Cretaceous fold-thrust structures and represent the Carpathian orogenic retro-wedge (Plašienka, 2018a). They mostly include the passive margin Triassic to Jurassic (Bükk) or to Lower Cretaceous (Transdanubian) successions, while obducted Jurassic ophiolite-bearing nappes occur in the east (Bükk Mts). During the Cretaceous, shortening relocated to the north-vergent CWC pro-wedge, whereby the Meliatic accretionary complexes occupied a position between the retro- and pro-wedge. The existence of the Middle Triassic–Jurassic Meliata Ocean and its Middle–Late Jurassic subduction are witnessed by the Middle–Upper Triassic ophiolites and the Jurassic polygenic mélanges, trench-type deposits and HP-LT metamorphic complexes (see references in Plašienka et al., 2019).

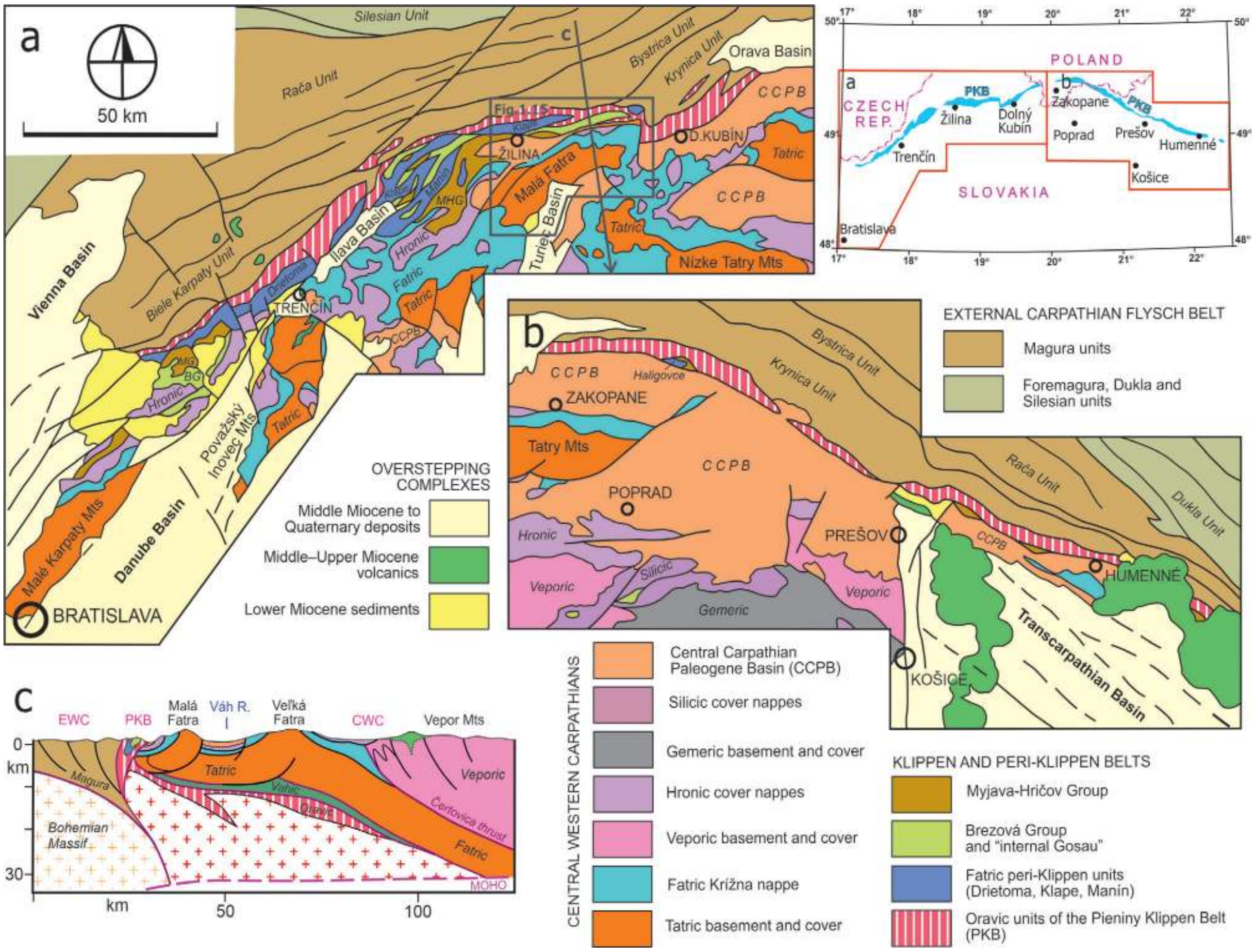


Figure 1.2 Simplified map showing the regional distribution of principal Western Carpathian tectonic units in a wider surroundings of the PKB (Plašienka & Soták, 2015, modified). The rectangle in a outlines the area depicted in Fig. 1.4.

Sequential growth of the CWC pro-wedge in the 130–90 Ma time interval involved both the thick-skinned thrust sheets (Gemeric, Veporic and Tatric from top to bottom) and thin-skinned cover nappe systems (Silicic, Hronic and Fatric). Hence the CWC are characterized as a Cretaceous stack of crustal-scale, southward-dipping thrust sheets reinforced by the pre-Alpine crystalline basement complexes (e.g. Tomek, 1993; Plašienka, 2018a). In general, the CWC thrust stack represents an eastward continuation of the Austroalpine thrust system of the Eastern Alps (cf. Froitzheim et al., 2008; Schmid et al., 2008).

During the Late Cretaceous, the CWC orogenic wedge grew by consumption of the South Pennine Piemont–Váh oceanic lithosphere and accretion of the intra-oceanic Oravic continental ribbon (Czorsztyn Ridge) in the Paleocene. Detached Oravic sedimentary units created an incipient fold-and-thrust belt, which was later transformed into the PKB. Subduction of the outer oceanic branch – the North Pennine Magura Ocean started in the Eocene and was completed during the Early Miocene. Simultaneously, sediments scraped off the subducting oceanic plate and passive European margin formed the EWC accretionary wedge (Flysch Belt). The Cretaceous – Cenozoic frontal accretion was accompanied by several stages of hinterland extensional collapse, such as the Late Cretaceous exhumation of the Veporic metamorphic dome (Janák et al., 2001a; Jeřábek et al., 2012) and subsidence of the Gosau-type basins (Plašienka & Soták, 2015; Kováč et al., 2016 and references therein); formation of the Upper Eocene – Lower Miocene Central Carpathians Paleogene Basin in the fore-arc and the South Slovakian – North Hungarian Basin in the retro-arc position (e.g. Soták et al., 2001; Tari et al., 1993, respectively); and finally by strong back-arc extension of the Pannonian basin system associated with lithospheric thinning and widespread calc-alkaline andesitic to alkaline basaltic volcanism (Kováč et al., 2017 and references therein).

The outer CWC zones are characterized by the presence of the so-called "core-mountains" (Malé Karpaty, Považský Inovec, Strážovské vrchy, Žiar, Tribeč, Veľká Fatra, Ďumbierske Nízke Tatry, Malá Fatra and Tatry Mts, Fig. 1.2), which are late Cenozoic basement highs cored by the pre-Alpine crystalline basement and elevated during the Neogene (Králiková et al., 2016 and references therein). All the core-mountains are built by three superposed large-scale tectonic units – the lowermost Tatric basement-cover sheet overthrust by the Fatric and Hronic cover nappe systems.

According to the surface structure and interpretation of the deep seismic transect 2T (Tomek, 1993), the Tatric Superunit is an internally little disturbed upper crustal thick-skinned thrust sheet, about 10 km thick, which overrides remnants of the South Pennine Piemont–Váh oceanic complexes and possibly also underthrust basement of the Oravic continental ribbon (e.g. Plašienka et al., 2020 and references therein). Tomek (1993) correlated this lower crustal segment with the Briançonnais domain of the Western Alps. The Tatric sheet plunges southward bellow the Veporic crustal wedge for the distance of ca 50 km (Čertovica thrust; Fig. 1.2c). The thrust plane corresponds to the Čertovica fault system on the surface that separates the Tatric and Veporic thick-skinned sheets. This thrust fault is regarded as the root zone of the detached Fatric nappe system, which overthrusts the Tatric substratum for the equal distance of 50 km (Andrusov, 1968; Prokešová et al., 2012).

In most cases, the Tatric crystalline basement retains the original Variscan structures and isotopic ages of metamorphic and magmatic processes (e.g. Putiš 1992; Janák, 1994). It is dominantly composed of high-grade metamorphic rocks – para- and orthogneisses, magmatites and amphibolites, which contain relics of eclogite-facies rocks locally (Janák et al., 2009, 2020). Medium- to low-grade metamorphic rocks are preserved in places only (e.g. in the Malé Karpaty Mts). Large Variscan intrusive bodies include both I- and S-types granitoids (Broska & Uher, 2001; Kohút et al., 2009; Broska et al., 1997, 2013). The Alpine low- to very low-grade overprint is restricted to mylonitic shear zones, particularly in the outer- and lowermost partial Tatric structures that are used to be differentiated as the Infra-Tatric units (e.g. Putiš et al., 2009, 2019).

The Tatric post-Variscan sedimentary cover usually begins with the Lower Triassic deposits. The thick Permian continental red-bed clastics and extrusite volcanic rocks are restricted to the Infra-Tatric units (Považský Inovec and Lúčanská Fatra Mts; Vozárová & Vozár, 1988; Olšavský, 2008; Havrila & Olšavský, 2015), along with the Permian volcanic dykes cutting the basement rocks (Pelech et al., 2017a; Spišiak et al., 2018, 2019). The Triassic sequence complies with the triple division characteristic for the epicontinental Germanic Basin with Lower Triassic clastic sequence of quartzose sandstones and variegated shales, Middle Triassic carbonate complex and Upper Triassic Keuper-type clastics and evaporites. Lower Jurassic wide rifting produced broad subsiding basinal zones separated by the elevated highs (e.g. Plašienka, 2003a), therefore the Jurassic to Lower Cretaceous Tatric successions are subdivided into the ridge-type, comparatively shallow-marine Tatra successions and deep-water pelagic successions presently occupying the northern belt of core-mountains (Šiprúň Basin). All Tatric successions are terminated by the Albian–Cenomanian, in places up to the Turonian synorogenic flysch deposits (Fig. 1.3).

The youngest Tatric formations are overridden by the Fatric décolement nappe system. The classic Krížna Nappe (e.g. Andrusov, 1936, 1968) was detached at the base of the Middle Triassic carbonate complex and thrust northwards as a comparatively thin (some 2–3 km), but areally extensive flat-lying sheet. The Fatric sedimentary successions are rather

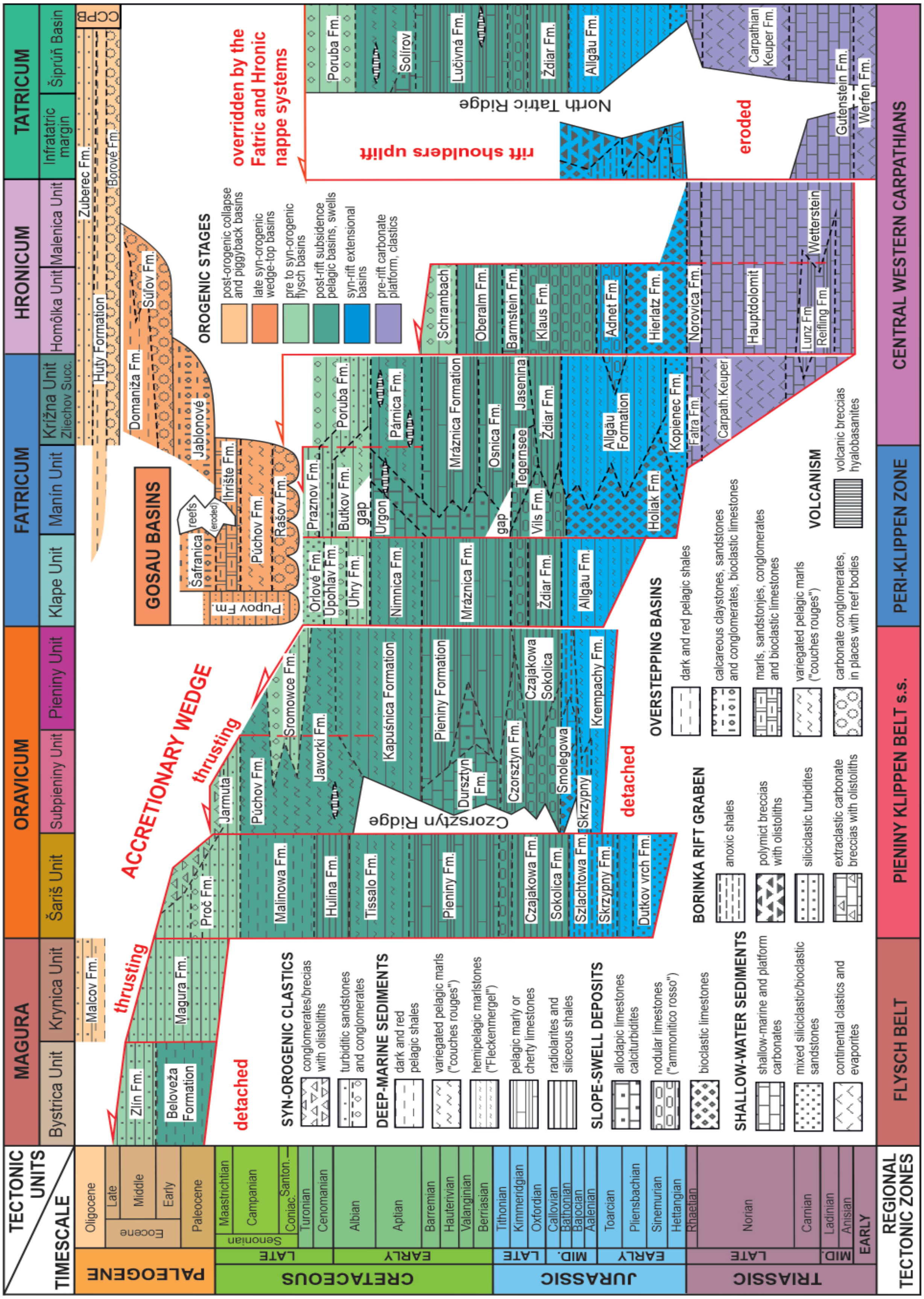


Figure 1.3 Comparative lithostratigraphy of units along the EWC/CWC contiguous zone in NW Slovakia (modified after Plašienka, 2019). Units are arranged according to their present structural position from the north-west (left) to the south-east (right). From the palinspastic point of view, the Fatric and Hronic nappes were derived from more southerly located areas – south of the Tatric domain. The Klape Unit likely originated in the Zliechov Basin, i.e. in the southern Fatric areas. Originally, the Oravic Pieniny Unit and the Infratatric units were located at the northern and southern passive margins of the subducted Vahic oceanic zone, respectively. The Pupov Fm. is restricted to the Varín PKB sector. Note also that not lithostratigraphic units could be shown – for details of e.g. the Oravic successions see Figs 1.20 and 1.21 below.

similar to those of the underlying Tatric cover: Middle Triassic carbonates, Upper Triassic Keuper clastics, Lower Jurassic syn-rift sediments, Middle Jurassic to Lower Cretaceous post-rift either basinal pelagic deposits (most widespread Zliechov Succession; e.g. Michalík, 2007; see Fig. 1.3), or local ridge-type strata (Vysoká Succession), and terminal mid-Cretaceous deep-marine flysch clastics. The Krížna Nappe was emplaced along the weak basal layer of overpressured cataclastic carbonate breccias (Rauhwacke) and evaporites. Internal deformation structures include meso- to macro-scale folds, duplexes, several cleavage sets and syn-emplacement extensional shear zones (Plašienka, 2003b; Prokešová et al., 2012). These structures developed progressively during detachment of the sedimentary sequences from their basement underthrust below the Veporic wedge, their thrust over the frontal Tatric ramp, and the final gravity-driven emplacement over the unconstrained Tatric basinal areas (Šiprúň Basin) some 90 Ma ago.

After a short time lag, the Fatric complexes were ovethrust by the Hronic cover nappe system. This is a widespread thin-skinned thrust sheet composed dominantly of Triassic carbonate complexes. In the southern belt of core-mountains (Malé Karpaty, Nízke Tatry), the Hronic nappes include also the Pennsylvanian to Lower Triassic continental clastic and volcanic formations (Ipoltica Group). The Middle Triassic carbonate series are assigned to several successions differing in the presence and extent of the basinal facies (Havrila, 2011) that were related to the Anisian rifting of the carbonate platform and ramp areas, which ultimately led to breakup of the Meliata Ocean in the southern Carpathian zones (e.g. Kozur, 1991). However, the original depositional Hronic area is not exactly known. Following the Carnian pluvial event (Raibl or Lunz; cf. Aubrecht et al., 2017a) that brought about filling of the intra-shelf basins by terrigenous clastics, the equalized Upper Triassic sedimentary conditions enabled development of extensive Upper Triassic carbonate platforms. Variable Jurassic to Lower Cretaceous formations are thin and, owing to a high structural position exposed to erosion, preserved only locally. The Hauterivian–Barremian deep-marine deposits containing terrigenous sandy material and abundant Cr-spinels in the heavy mineral concentrates represent the youngest known Hronic strata (cf. Jablonský et al., 2001).

1.1 Outline of the structure of the Malá Fatra Mountains

From the geographical point of view, the Malá Fatra Mts consists of two parts – the northern, generally W–E elongated Krivánska Fatra Mts and the southern, SW–NE trending Lúčanská Fatra Mts (Kočický & Ivanič, 2011; Fig. 1.4). Both parts are separated by the deeply incised antecendent gorge of the Váh River. The area described in this work occurs in the borderland of the Kysuca and Orava regions in north-western Slovakia, and covers the Krivánska Fatra Mts of the CWC and adjacent parts of the PKB. The latter include the eastern part of the Varín (Kysuca) sector between villages Lysica, Terchová and Zázrivá, the short N–S trending segment known as the “Zázrivá (or Zázrivá–Párnica) sigmoid” (Andrusov, 1926), and the westernmost part of the Orava sector west of town Dolný Kubín (Figs 1.2 and 1.4).

The W–E trending Krivánska Malá Fatra Mts is about 25 km long and 8–10 km wide asymmetric horst structure bounded by a subvertical fault zone from the south against the Cenozoic sediments of the northern part of the Turiec intramontane basin (Hók et al., 1998; Kováč et al., 2011). Along this fault, the whole mountain range is tilted towards the north, whereby all units on the northern slopes are moderately inclined to the north (Figs 1.2 and 1.4). Thanks to this situation, the sections along the N–S trending valleys and ridges provide instructive, sometimes nearly complete profiles from the Tatric basement core and its Mesozoic sedimentary cover, through the Fatric and Hronic cover nappe units, up to the overstepping Paleogene sediments. The eastern, N–S trending termination of the Krivánska Fatra Mts follows the Central Slovakian fault system that was active during the Neogene (Kováč & Hók, 1993). This fault system is expressed by the single transversal deformation zone in the entire PKB causing its dextral, about 6 km long offset along the so-called Zázrivá sigmoid. The offset resulted also from the eastward axial plunge of the CWC units of the Krivánska Fatra Mts below the Paleogene overstepping deposits and backthrusts of the PKB and EWC Magura units of the Flysch Belt. Thus southern slopes and the main ridge of the mountains with peaks attaining 1,709 m a.s.l. (Mt. Veľký Kriváň) are built by the Tatric basement granitoids and covering Lower Triassic quartzites. Further north-east, the Tatric cover complexes on the main ridge are overlain by the Triassic and Jurassic–Lower Cretaceous Fatric formations (Stoh Hill, 1,607 m). The northern slopes are mainly composed of the cover nappe units – the Fatric Krížna Nappe overlain by a spectacular Hronic nappes outlier on the side ridge (Mt. Rozsutec, 1,610 m a.s.l.), and the Sokolie

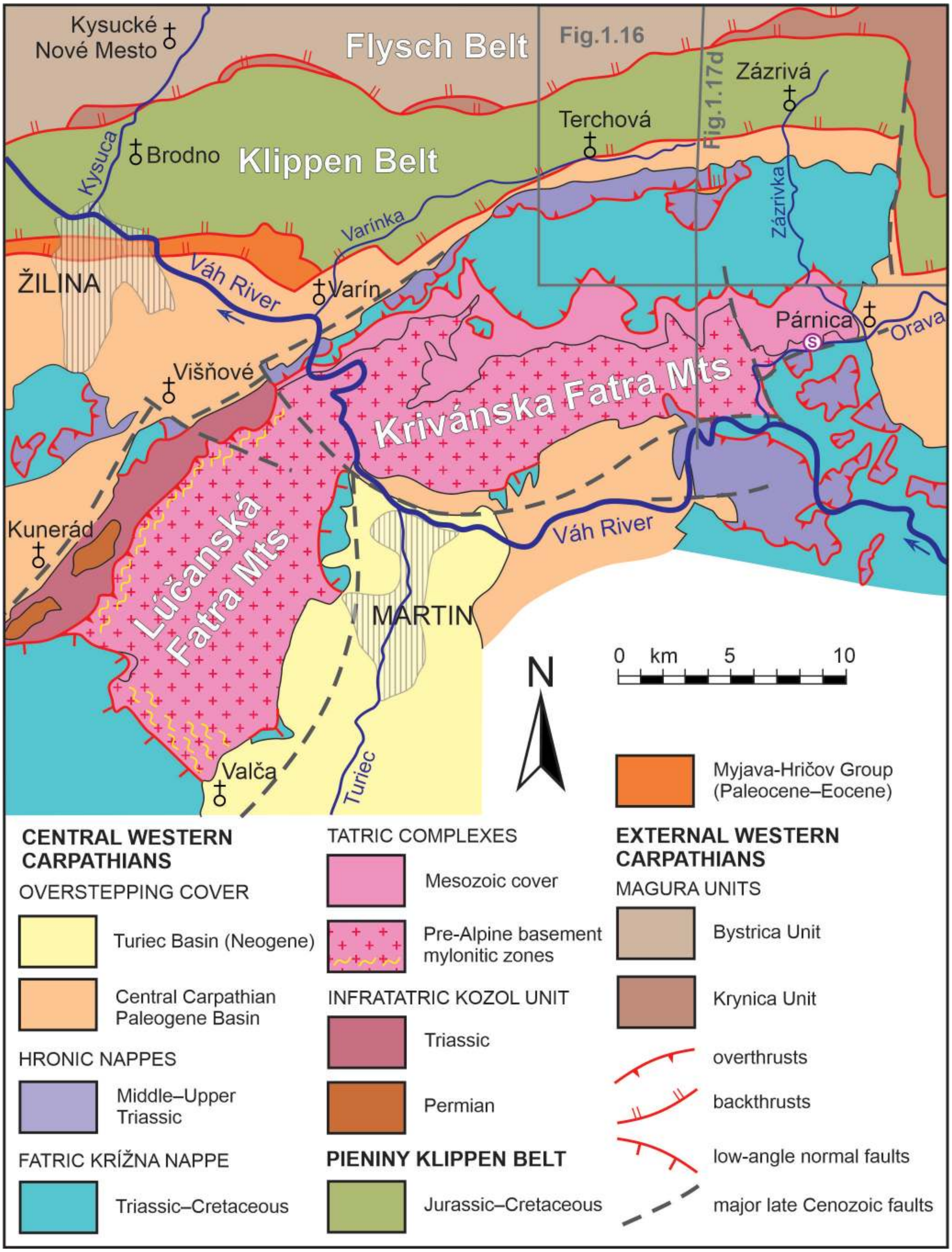


Figure 1.4 Tectonic sketch map of the Malá Fatra Mts and neighbouring areas. Positions of Fig. 1.16 and cross-section "d" in Fig. 1.17 are outlined. S – location of the Smolenová quarry (see Fig. 1.15).

and Boboty ranges (Figs 1.4 and 1.16).

The Tatric crystalline core of the Lúčanská Malá Fatra Mts involves, in addition to the Variscan granitoids, also high-grade metamorphic rocks on the south-eastern slopes of the mountains, and in numerous xenoliths in granitoids. On the other hand, the Tatric sedimentary cover is nearly missing, restricted to Lower Triassic quartzites strongly sheared within the cataclastic-mylonitic zones rimming the crystalline massif from the west and south (see below). In the west, such a broad mylonite-cataclasite zone follows the boundary between the Tatric core and the Kozol Unit in the lower structural position. The Kozol Unit (a.k.a. Kozol anticline; Fig. 1.4) possesses characteristics typical for the Infra-Tatric units. It occupies an external position in front of and partly overridden by the Tatric thick-skinned thrust sheet, it is affected by low-grade metamorphism and, unlike the typical Tatric cover successions, includes several hundreds of metres thick Permian clastic. The Triassic formations are analogous to other Tatric successions, but the Carpathian Keuper Fm. is exceptional by predominance of coarse-grained clastics (Havrila & Olšavský, 2015). Lower Jurassic sequence is composed of poorly preserved dark shales and limestones, younger rocks were not recognized.

1.1.1 Variscan granitic and metamorphic rocks of the Tatric basement

Abundant Variscan granitoid massifs build a substantial part of the pre-Alpine crystalline basement of the CWC, particularly in the Tatric and Veporic units (e.g. Petrík et al., 1994; Kohút et al., 1999; Broska & Uher, 2001; Uher et al., 2019). This chapter presents results of petrological and geochemical investigations of the Malá Fatra granite massif developed during the last two decades by I. Broska together with M. Hrdlička, M. Kubiš and P. Konečný. The characterics of the Malá Fatra granitoids are demonstrated by two large quarries, which are described in detail below.

The Malá Fatra granitoid massif is composed of a relatively wide range of plutonic rocks – from tonalites/diorites to monzogranites. The granitoids are spatially exposed in three distinct zones: (1) tonalite zone predominating in the Lúčanská Fatra and in the southern part of the Krivánska Fatra (Fig. 1.5); (2) granodiorite zone in the northern part of the Krivánska Fatra; (3) zone of granitoids with nebulitic structure (diatexites) in the Lúčanská Fatra Mts. The

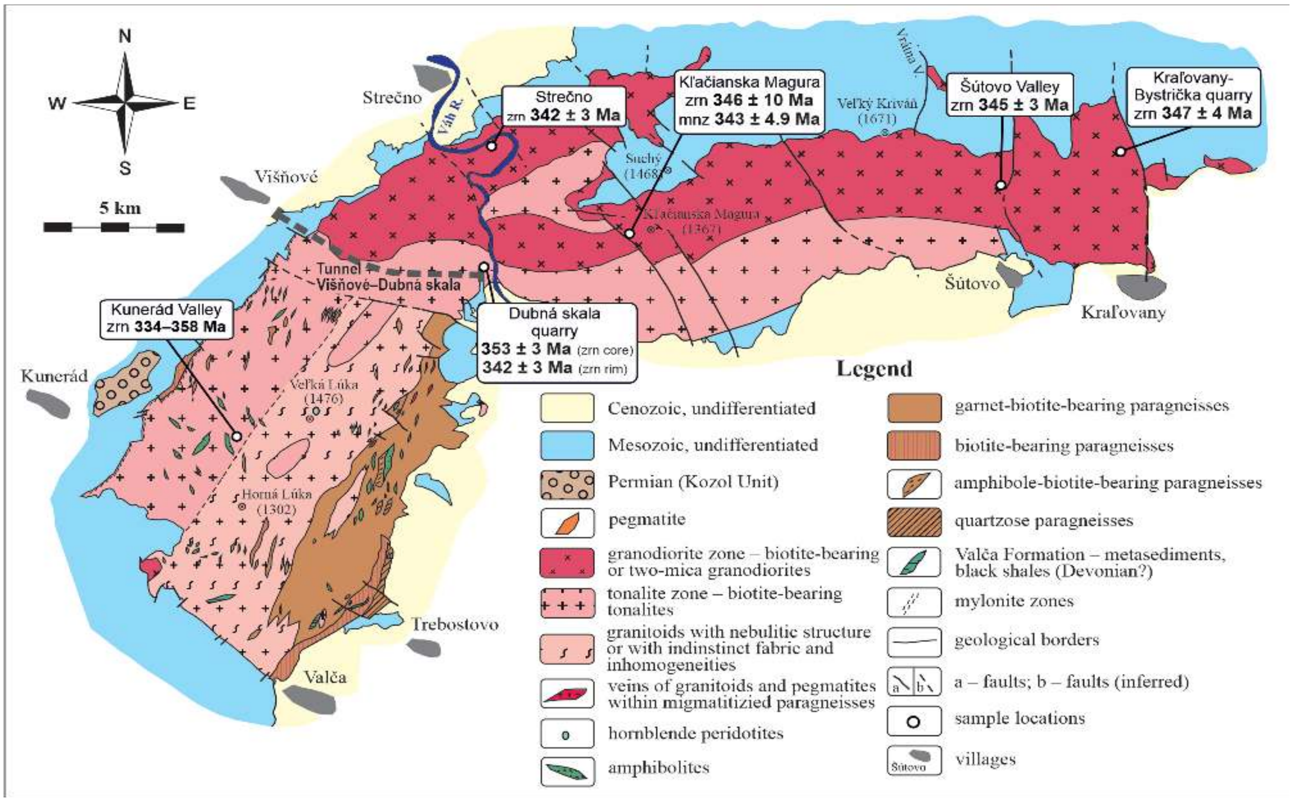


Figure 1.5 Tatric basement map of the Malá Fatra Mts (after Polák et al., 2008; modified by Broska & Svojtka, 2020). The granite bodies are generally inclined to the north in the Krivánska Fatra and to the northwest in the Lúčanská Fatra part. Isotopic age data: Dubná skala and Strečno by Broska and Svojtka (2020); Kľačianska Magura by Hrdlička et al. (2005); Šútovo Valley by Kohút and Larionov (2021); Kraľovany-Bystrička and Kunerád by Broska et al. (in prep.).

nebulitic granitoid migmatites are a partial melting product from the metamorphic complex which includes acid orthogneisses, migmatitized metapelites and metabasites (Janák & Lupták, 1997; Majdán et al., 2004). The nebulite bodies are subvertical and conformable with the metamorphic complexes, with magmatic foliation detectable along the eastern margin of the Lúčanská Fatra Mts (Putiš et al., 2003). Nebulites include also a fragment of spinel-olivine bearing metaultramafite near of the Veľká Lúka summit (Fig. 1.5), which was metamorphosed under the conditions reaching the upper amphibolite facies corresponding to temperatures 700–800°C (Hovorka et al., 1985; Korikovsky et al., 1998). This metaultramafite inclusion represents probably a fragment of metaperidotite or websterite attached to the lower crust by mantle upwelling after delamination or slab detachment of subducted lithosphere (Korikovsky et al., 1998). The thermobarometric data for adjacent metamorphic complex in this zone indicate the attainment of ca 700–750°C and 600 MPa in metapelitic migmatites and 700–750°C at 800–1,000 MPa in garnet-clinopyroxene amphibolite (Janák & Lupták, 1997). Migmatitization took place by partial melting, producing granitic leucosome or diatexite in metagneisses and tonalitic-trondhjemitic layers in metabasites (Janák & Lupták, 1997).

The variability of the granitic rocks in the Malá Fatra Mts was for the first time recognized on the basis of geological mapping and petrographic study by Ivanov and Kamenický (1957). These authors distinguished “hybrid granite to biotite-oligoclase granite” and the relatively younger “Magura type”. In addition, on the northern edge of the Krivánska Fatra, Ivanov and Kamenický (1957) and Kamenický et al. (1987) described the metasomatic alteration of the hybrid, as well as of the Magura granites. Broska et al. (1997) redefined hybrid granite as the I-type and Magura as the S-type. Hrdlička (2006) recognized the granodiorite and tonalite zones in the Malá Fatra massif based on the occurrence of the dominant granite types (Fig. 1.5). The common feature of granitoids is a high degree of postmagmatic and Alpine alteration, chloritization of biotite being the typical feature. In addition to primary mineral paragenesis of the granites, Faryad and Dianiška (2002) described two other mineral associations: (1) Variscan post-magmatic Ca-garnet, prehnite, epidote, titanite and actinolite as a consequence of the pluton cooling and (2) Alpine metamorphic pumpellyite, epidote and chlorite association. The P-T conditions of Alpine metamorphosis have been estimated to 0.3 GPa at temperature of ca 300°C (Faryad & Dianiška, 2002).

The granitoids with nebulitic structures are characterized by indistinct inhomogenities or schlieren of diffuse relics of pre-existing rocks in sense of Menhert (1968), where the paleosome and neosome can no longer be distinguished (Fig. 1.6A). The formerly defined hybrid granites (in sense of Ivanov & Kamenický, 1957) contain a lot of inhomogeneities, but hybrid granites in recent terminology mean the granite development by mixing of magmas derived from mafic rocks with crustal anatectic S-type magmas (hybridisation; H-type granites of Castro et al., 1991). Therefore, it is better to use the term nebulite and nebulite zone for heterogenous granitoids. Nebulites form a large body in contact with the metamorphic complex consisting predominantly of tonalites and less monzo- or syeno-granites. They are medium- to coarse-grained, but locally porphyric due to larger K-feldspar and plagioclase grains (Fig. 1.6A). Distinct foliation and quartz ribbons are the typical features. Plagioclase of albite to andesine composition is mostly subhedral, but locally also coarse-grained with inclusions of accessory minerals such as zircon, apatite, monazite and garnet. Quartz is anhedral and strongly deformed. Biotite is represented by annite with the $MgO/(MgO+FeO_{tot})$ ratio slightly below 0.5.

Description of the Malá Fatra granites follows the lithological (petrographic) zoning shown in Fig. 1.5. The tonalite zone in the southern part of the Krivánska Fatra and on the western side of the Lúčanská Fatra is predominantly composed of medium and fine-grained tonalites, locally of trondhjemitic character (Fig. 1.6B). Plagioclase is mostly subhedral, slightly porphyritic and commonly oscillatory zoned and strongly sericitized. The cores of the plagioclases contain a high An component up to 35 mol. % in comparison with the rims with An up to 25 mol. %. Primary biotite is MgO-rich with 10–12 wt%, TiO_2 concentrations vary between 2.5 and 3.5 wt% and the ratio Mg/(Mg+Fe) = 0.50–0.52. Magmatic K-feldspars are interstitial, not perthitic, and show BaO content up to 2.2 wt%, but also elevated SrO up to 0.16 wt%. On the other hand, secondary K-feldspar is pure orthoclase in composition with negligible concentrations of Na^+, Ba^{2+} and Sr^{2+}. Amphibole is magnesiohastingsite, often altered to actinolite. Accessory minerals apatite, allanite-Ce, epidote, titanite, rutile, “leucoxene”, ilmenite, but also secondary monazite-(Ce) II, allanite-(Ce) II, REE-rich phases, huttonite and hydrogarnet (andradite) are predominantly localized in altered biotite or chlorite.

The hypidiomorphic granodiorites of the granodiorite zone are composed of fine- to medium-grained biotite or two-mica granodiorites and monzogranites with local porphyric texture. They are characteristic for the Krivánska Fatra Mts and are only locally cropping out in the Lúčanská Fatra, especially in its north-western part and at the southern edge (Fig. 1.6C). Granitoids in the northern part of Krivánska Fatra are altered with a different intensity but even to red-coloured granites which are well observable in the canyon close to the Šútovo waterfall. The pink feldspar and albite phenocrysts are locally common, particularly in neighbourhood of tectonic fractures. Late differentiates like pegmatites are rare, but common occurrences of aplite veins are known mainly from the Hoskora valley and from the Kraľovany-Bystrička quarry (Fig. 1.6D). Plagioclase forms mostly subhedral grains up to 1 cm large, locally with oscillatory zoning. Chemical composition of plagioclase is more albitic in comparison to plagioclase from the tonalite zone and the An-component usually reaches up to 30 vol. %, but up to 40% in relic grains from former mixing. Primary K-feldspar forms up to 1.5 cm large perthitic phenocrysts in the interstitial position. Biotite shows a lower MgO component of 8–10 wt%, and consequently lower ratio Mg/(Mg+Fe) = 0.40–0.45 in comparison with the tonalite zone. Biotite is commonly replacement by chlorite, titanite and rutile. Primary muscovites are relatively enriched by Al_{tot}, while the secondary muscovite shows the "phengitic" composition. Most of accessory minerals are enclosed in biotite, or in its alteration products like chlorite. The apatite, zircon, monazite-(Ce) I, garnet, magnetite, ilmenite I are typical primary magmatic phases, while allanite-(Ce), epidote, huttonite, REE-rich phases, titanite, rutile, ilmenite II, carbonate (calcite), hydrogarnet and pumpellyite are secondary phases.

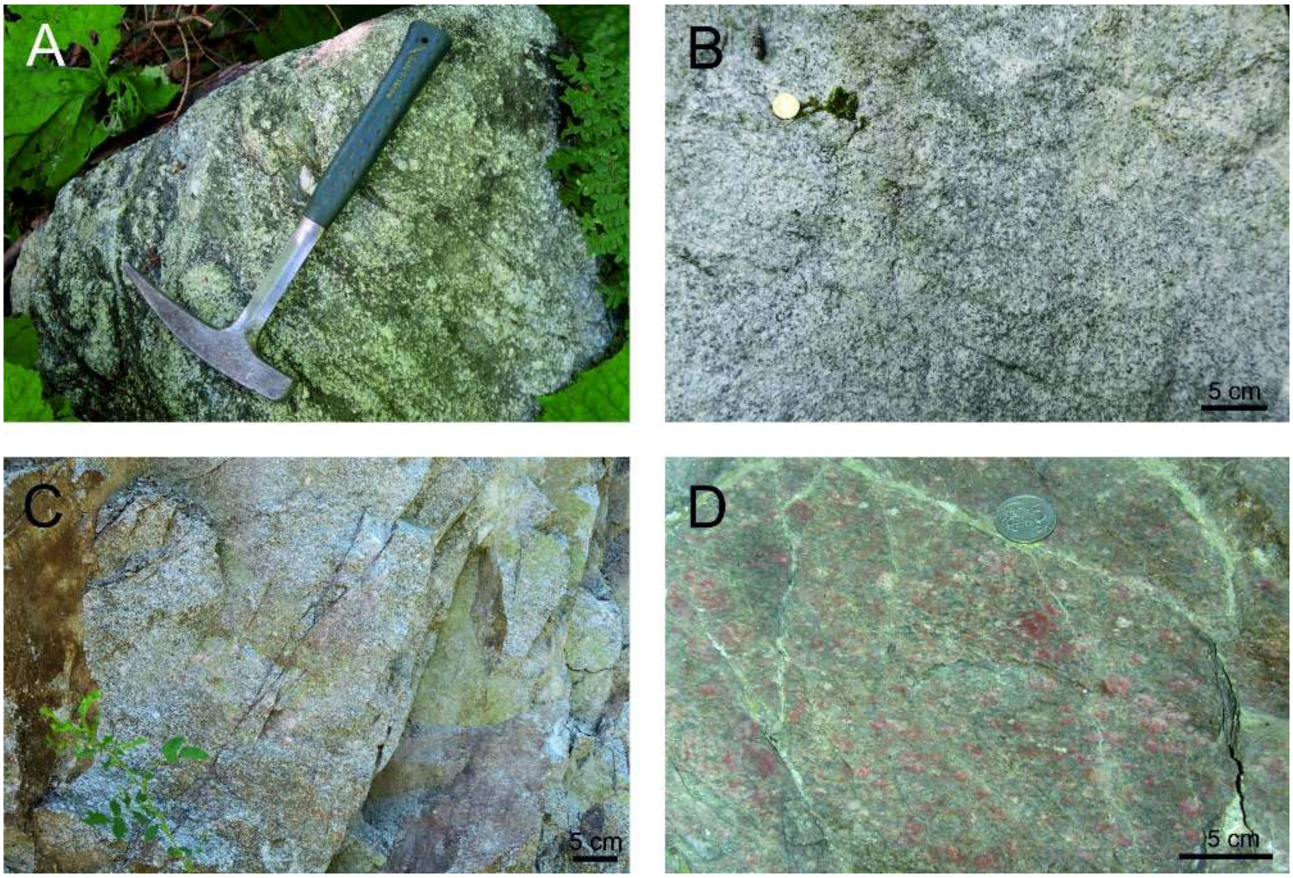


Figure 1.6 Examples of granite types from the Malá Fatra Mts: A – inhomogenous nebulitic granitoid (Lúčanská Fatra); B – medium-grained leucotonalite (Kraľovany-Bystrička quarry); C – Magura S-type granite (cliff on trail to the Starhrad castle ruins); D – metasomatic alteration of the Magura granodiorite (Krivánska Fatra; Šútovo gorge above the waterfall).

According to Shand (1943), the Malá Fatra granitoids show a peraluminous character. The R1-R2 discrimination diagram of Batchelor and Bowden (1985) indicates their orogenic setting and classification diagrams of Frost et al. (2001) characterize them as Mg-rich granites. In sense of Roberts and Clemens (1993), granitoids from both the tonalite and granodiorite zones are middle to high-potassium calc-alkaline rocks. The Harker silica vs. phosphorus diagram indicates different genetic trends and origin for the nebulite and tonalite/granodiorite zones in the Krivánska Fatra Mts (Fig. 1.7A). The diagram of Whalen et al. (1987) classifies the granitic rocks from the Krivánska Fatra as normal I/S-type granites (Fig. 1.7B).

Isotopic study of zircons also clearly separates nebulitic migmatites and granitoids from the rest of granitoids occurring in the tonalite/granodiorite zones. The zircon δ^{18}O revealed the mostly crustal character of zircons from the nebulite zone, but mantle influence for zircons from the granodiorite and tonalite zones. The δ^{18}O in zircons from less fractionated granodiorite zone yield the values of 6.8‰ using SMOW standard, but the most fractionated oxygen in zircons from nebulites gives values above 7.4‰ up to 8.56‰ (Hrdlička, 2006).

The bulk rock composition and mineral assemblage of the Malá Fatra granitic rocks was modified during several events and mainly by: (1) Variscan post-magmatic alteration; (2) Variscan extensional cooling; (3) Permian thermal imprint and (4) Alpine low-grade metamorphism. Therefore, several petrochemical nomenclatures calculated from the whole-rock analyses (e.g. Streickeisen & Le Maitre, 1979) are incompatible with modal classifications.

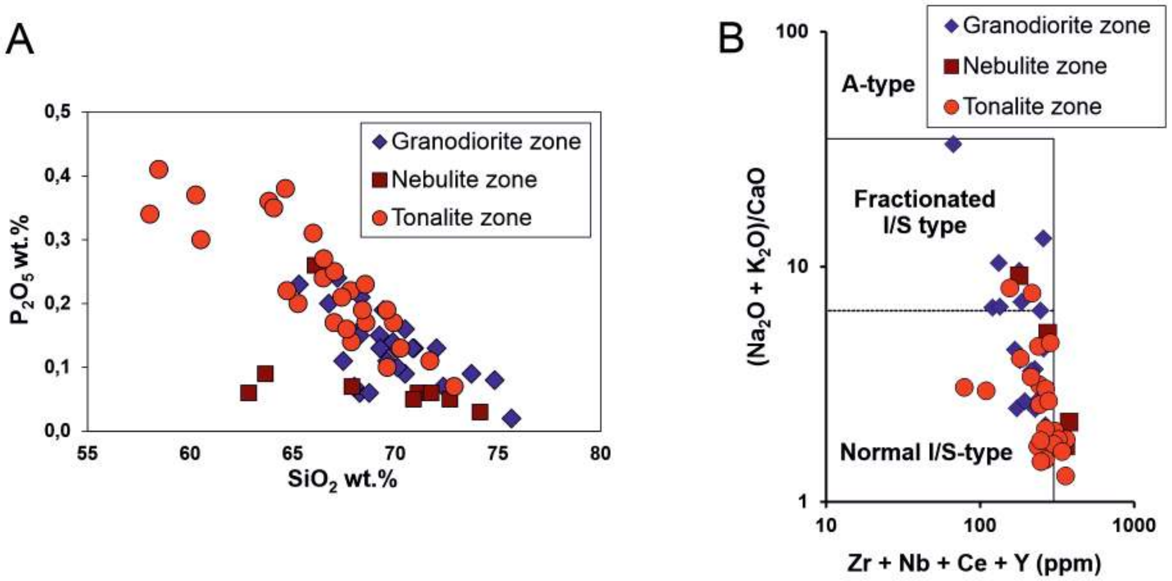


Figure 1.7 Discrimination diagrams of the Malá Fatra granitoids: A – the Harker diagram indicates different genetic trends for granitoids from the nebulite and from the granodiorite/tonalite zone in the Kriványska Fatra Mts; B – diagram of Whalen et al. (1987) classifies Kriványska Fatra granitoids as the normal I/S-type.

The Variscan evolution of granites is documented by isotopic zircon and monazite dating. Granodiorites from the Dubná skala quarry were dated to 353+5 (-11) Ma by the U-Pb method from several large zircon concentrates (Shcherbak et al., 1990). Current ICP MS point dating of the zircons from the Dubná skala quarry revealed their age zoning: (1) the cores yielded concordia age of 353±3 Ma, while (2) rims show the age 342±3 Ma. ICP MS dating of zircons from the Magura granite close to Strečno village yielded the weighted mean peak of ca. 342±3 Ma (Broska & Svojtka, 2020). This age is close to ICP MS dating of Magura granite from the Kľačianska Magura Hill (346±10 Ma; Hrdlička et al., 2005) and is supported also by monazite dating. The Variscan post-intrusive cooling of the Lúčanská Fatra granitic pluton is documented by the muscovite Ar-Ar dating with the plateau age of 344.8±2.2 Ma (Hók et al., 2000). The Tournaisian ages of zircons from I-type granitoids are relatively young in comparison to known ages from the I-type granitoids in the Western Carpathians (Petrík & Kohút, 1997; Kohút et al., 1999; Broska et al., 2013) and could be related to terminal stages of subduction arc-related magmatism followed by the collisional stage. The titanite formation ages from similar environments (Uher et al., 2019) confirm the late Visean imprint of I-type granites. The vast calc-alkaline Visean granite magmatism of 350–341 Ma form main granite body north and west of the Malá Fatra massif and probably resulted from melting of lower crust induced by heat flow from rising asthenosphere after the slab breakoff. In this sense, the Malá Fatra Visean granite massif is syn-tectonic and post-collisional (Broska et al., in prep.).

Bagdasaryan et al. (1992) reported commonly low initial Sr isotopes (^{87}Sr/^{86}Sr)$_i$ = 0.70627±0.00022 or ^{87}Sr/^{86}Sr ratios in the range 0.70876 and 0.70848 for granitoids from the Malá and Veľká Fatra Mts. The low Sr ratios imply Rb-poor crustal source (Kráľ, 1992, 1994). Kohút et al. (1999) described ^{87}Sr/^{86}Sr = 0.7063 ratio and negative εNd$_{(CHUR)}$ = -2.75 for the granite taken from the Kraľovany-Bystrička quarry at the eastern margin of the Malá Fatra Mts (Fig. 1.5). These data indicate derivation of the Malá Fatra granitoids from metasomatized mantle component mixed with crustal source. The thermodynamic granite data obtained from zircon and REE saturation temperatures and Al-in hornblende geothermometry indicate formation of granites in the temperature range 780–750°C and pressure 500 to 600 MPa (Broska et al., 1997). The data indicate their formation at depths in excess of 15 km, possibly after the subducted slab failure. The early post-Variscan tectonic history of the Malá Fatra granitoid massif included probably also the Permian thermal overprint documented by the U-Th total Pb monazite dating of newly formed monazite in apatite from samples taken from tonalite close to the Permian lamprophyre dyke in the Dubná skala quarry (Hrdlička, 2006).

Alpine thermal overprint of granites was determined by the zircon and apatite fission tracks (Danišík et al., 2010). The zircon FT ages from granitoids in the Malá Fatra indicate the Jurassic/Cretaceous thermal event associated with extensional tectonics (143.7±9.6, 143.7±8.3, 135.3±6.9 Ma) and some influence of the Eocene orogeny by the age 45.2±2.1 Ma. Thermal modelling of the apatite FT (13.8±1.4 to 9.6±0.6 Ma) revealed fast cooling in terms of exhumation of the basement and creation of the topographic relief, as corroborated by the sedimentary record in the surrounding Neogene depressions. AFT results significantly refine a general exhumation pattern of basement complexes in the Central Western Carpathians and lowering of AFT ages towards the orogenic front is evident, where all the external core-mountains located closest to the orogenic front (including the Malá Fatra Mts.) were exhumed after some 13 Ma from temperatures of about 120 °C (Danišík et al., 2010; Králiková et al., 2016).

Due to a deep erosion level, the granite massif in the Krivánska Fatra Mts is almost without metamorphic roof rocks. In the Lúčanská Fatra Mts, the north-east thrusting has been documented in the highway tunnel Višňové–Dubná skala, where 100 m of granitic cataclastites accompany the top-northwest thrust plane of granites over the Mesozoic cover rocks (Hók et al., 2002, 2020). Owing to the northward tilting of the Krivánska Fatra massif, the tonalite zone with I-type affinity represents a deeper part of the massif, while granodiorites form the upper parts with a more intense metasomatic overprint (Fig. 1.5).

In summary, the Krivánska Fatra granite body is recently exposed in the length of ca 20 km in the W–E direction. According to zircon LA ICP-MS dating, the hybrid magma chamber was formed in the lower crustal conditions influenced by mantle during the Tournaisian (353 Ma). The Visean granite emplacement occurred probably as a response to the slab breakoff in a transpressional regime, as it is indicated by the elongated shape of the magmatic body and deformation of rock-forming minerals. Locally, primary magmatic lineation is also visible. The monazite age of ca. 348 Ma could indicate the intensive alteration of granitoids by post-magmatic fluids after the emplacement of the Visean granite masses. Such circumstances are indicated by the character of xenolithic paragneisses with simple composition. The granodiorite/tonalite body exposed in the Kraľovany-Bystrička quarry was followed by postcollisional granodiorite intrusions of the age 343 Ma known from other places in the Krivánska Fatra massif, which likely resulted from the slab breakoff event (Broska et al., in prep.).

Data from the Malá Fatra crystalline massif record several Variscan and Alpine evolutionary stages: (1) Tournaisian magmatism dated to ca 353 Ma; (2) Visean post- collisional magmatism; (3) late Variscan extensional reworking in the time span 360–342 and cooling during exhumation at ca 330 Ma; (4) Permian thermal overprint at 270 Ma; (5) early Alpine Jurassic/Cretaceous thermal overprint in 143 Ma; and finally (6) late Alpine Eocene overprint at ca 45 Ma connected with development of the N–S oriented mineralized veins. Data from Variscan granites of the Malá Fatra basement contribute not only to understanding of episodic generation of granite intrusions in the Variscan segments of the Western Carpathians, but shed light also on their superimposed Alpine tectonic evolution.

1.1.2 Representative localities in the Malá Fatra granitoid massif

There are two large, but presently inactive quarries in the Malá Fatra Mountains, where the granitic rocks were studied in detail by I. Broska, M. Hrdlička, J. Madarás, M. Kubiš and P. Konečný. These are quarries in the Bystrička Valley close to Kraľovany village in the Krivánska Fatra Mts and on Dubná skala at the boundary of the Lúčanská and Krivánska Fatra Mts in the Váh Valley (Fig. 1.5).

I. The Kraľovany-Bystrička quarry

The Kraľovany-Bystrička quarry (GPS N49.180222°, E19.124923°; 520 m a.s.l.) exposes Variscan equigranular granodiorite/tonalite rocks of the Krivánska Malá Fatra crystalline core with abundant aplites and xenoliths. The presence of large biotite gneissic xenolith is rare in the Kriváň granite massif, but here it is an indication of the upper position within the granite body, which is supported also by abundant aplitic dykes (Fig. 1.8A, B). The granitic rocks in the quarry are pervasively altered by post-magmatic fluids and heavily penetrated by young Alpine carbonate veinlets.

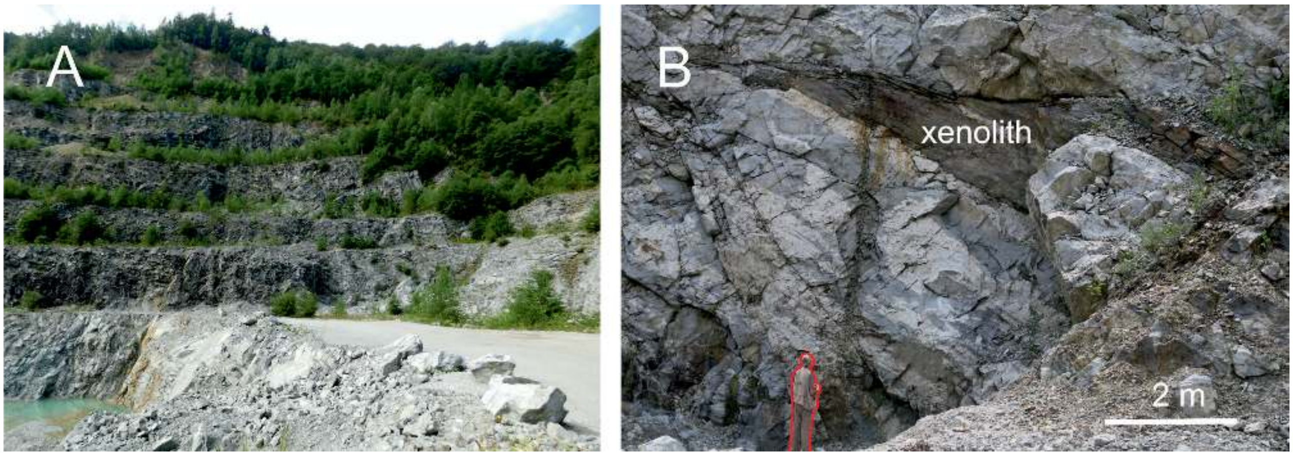


Figure 1.8 The Kraľovany-Bystrička granite quarry. A – general view, xenolith is located to the left on the first floor of the quarry; B – the gneiss xenolith forming ca 5 m long body. Note the bright pegmatite/aplite dykes in granitoids.

The granodiorite is equigranular, medium-grained, light grey and relatively poor in Kfs, therefore some parts of quarry with lower content of alkali feldspar are classified as a tonalite ("granotonalite" sensu Castro, 2013; Fig. 1.9A, B). Cores of hypidiomorphic plagioclases are andesine in composition and locally make up a cumulate-like texture. Quartz is allotriomorphic and dark grey. Biotite is totally disintegrated to chlorite with titanite, epidote and rutile exsolutions. As can be seen elsewhere in the Kriváň granite massif, former biotite was represented mainly by phlogopite. Chlorite derived from the biotite is rich in inclusions of accessory apatite and zircon. K-feldspar is interstitial with low Ba in comparison to porphyritic phenocrysts known from the other parts of granite massif in the Krivánska Fatra (ca. 0.2 vs 2.0 wt%). Early magmatic zircon is oscillatory zoned, Zr/Hf_{wt} is ca. 30, late zircon from rims shows HfO_2 up to 2.5 wt% and lower Zr/Hf_{wt} ratio.

The syn-tectonic granodiorite is slightly peraluminous (A/CNK = 1.17), SiO_2 = 68.70 wt%, P_2O_5 = 0.06 wt% $Na_2O/K_2O \approx 3$, Sr content = 518 ppm, Ba 322. Chondrite normalized REEs shows steep patterns (La_N/Yb_N = 29) and slightly negative Eu-anomaly with Eu/Eu* value of 0.74. Total Th-U-Pb microprobe monazite dating shows age of 348±5.6 Ma (Fig. 1.10A). The monazite is probably younger than zircon because it replaces early apatite. This newly-formed monazite is often accompanied by secondary allanite-(Ce) (Fig. 1.10B). Similar ages around 350 Ma were obtained by Sentpetery et al. (2020) using CHIME dating of monazites in the Vrátna dolina Valley a few km westwards. Altered granites with pink feldspar parts are located along the late Alpine, N–S trending mineralized fractures in the quarry. The galena and sphalerite, which form quite large 0.X cm grains within the carbonate and quartz matrix, have been detected in clusters in several cm wide dykes which cut the granites in the N–S direction (Fig. 1.11A, B). The granites themselves contain scattered accessory

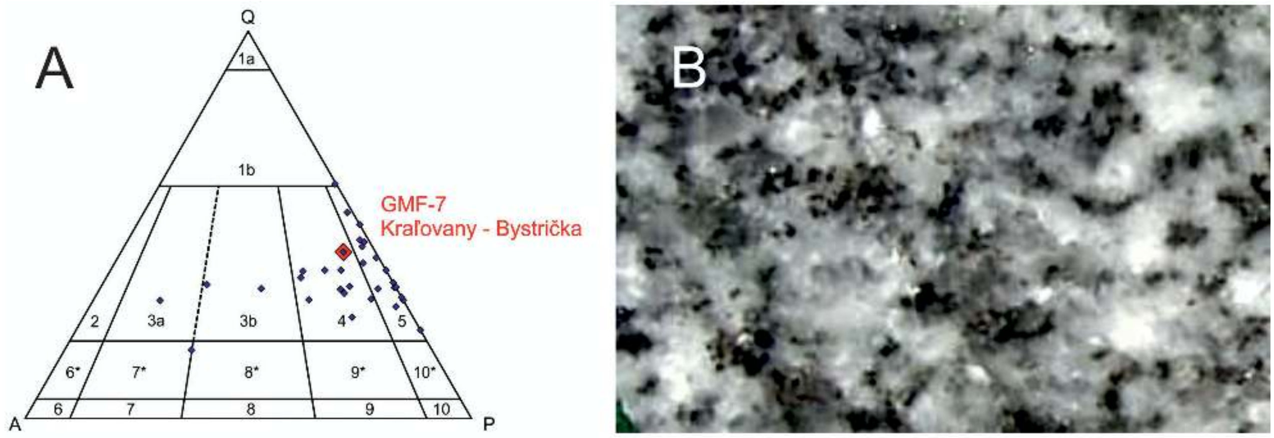


Figure 1.9 A – Modal analysis of granites from the Kraľovany-Bystrička quarry in comparison with other granitoids from the Krivánska Fatra Mts (field 4 represents granodiorite, field 5 is tonalite); B – equigranular structure of granodiorite (sample MF 7a; width 4 cm; photo by Hrdlička, 2006).

galena and sphalerite as well.

Variously oriented fracture sets in the Kraľovany-Bystrička quarry indicate three Alpine tectonic processes: (1) the oldest extensional joints in the NW–SE direction might have developed during the early Alpine NW–SE compression connected with NW-vergent thrusting of the Tatric basement sheet; (2) the NNW–SSE directed extensional fractures; (3) the youngest mineralized fissures oriented in the N–S direction (ca. 100/40), connected with a strong fluid activity, resulted in formation of the quartz-carbonate veins and pink granite parts. In general, this development of steeply inclined extensional fractures is in line with the gradual clockwise rotation of the main compression axis of the regional stress field from the NW–SE to N–S during the Cenozoic (see chapter 3 below).

II. The Dubná skala quarry

Dubná skala (GPS N49.138333°, E18.886111°; 425 m a.s.l.) is a large quarry in the Variscan tonalites and granodiorites of the Tatric basement, which are inter-

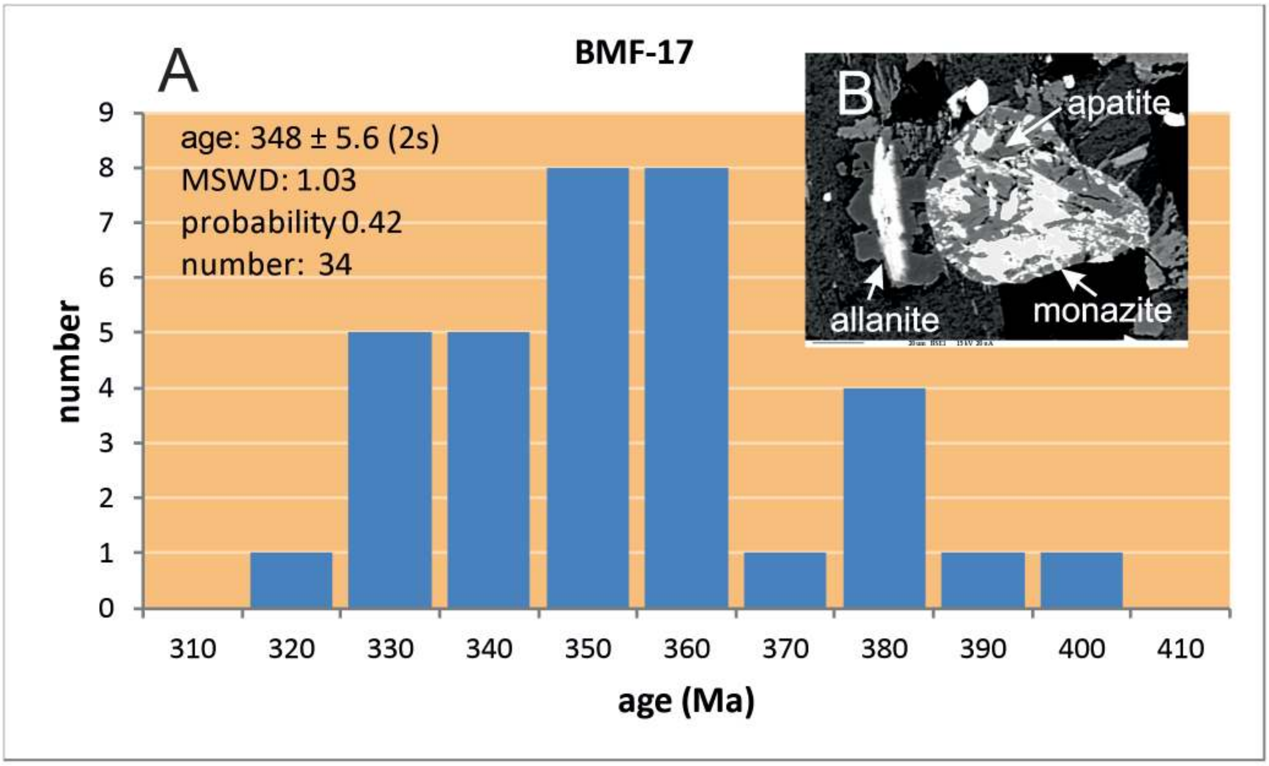


Figure 1.10 A – microprobe monazite dating of granitoid from the Kraľovany-Bystrička quarry; B – monazite BSE image (bright part) in early magmatic apatite along with secondary allanite-(Ce) on the left side (bright rod).

Figure 1.11 A – the N–S oriented fissures and quartz veins (red dashed line) containing carbonate, galena and sphalerite (ankerite) mineralization; B – detail of a quartz vein.

sected by the Permian lamprophyres here. The granitoids are exposed about 700 m north of the contact with migmatitized crystalline schists of the Lúčanská Fatra massif (Fig. 1.12A, B).

Both the biotite tonalite and granodiorite were described from the quarry, the tonalite being located mostly in its central part (Macek et al., 1982). The tonalite is hypidiomorphic granular, light grey to grey, fine- to medium-grained. Plagioclase is hypidiomorphic and greenish due to secondary epidote (saussuritisation) with anorthite component up to An40. K-feldspars form spots of antiperthite within plagioclase, interstitial K-feldspar is non-perthitic. Quartz shows undulose extinction and locally resorbs plagioclase or biotite. There are also Mg-rich biotite and epidote, the average modal composition is Qtz 25, Kfs 5, P 59, Bt 10, Acc 1.

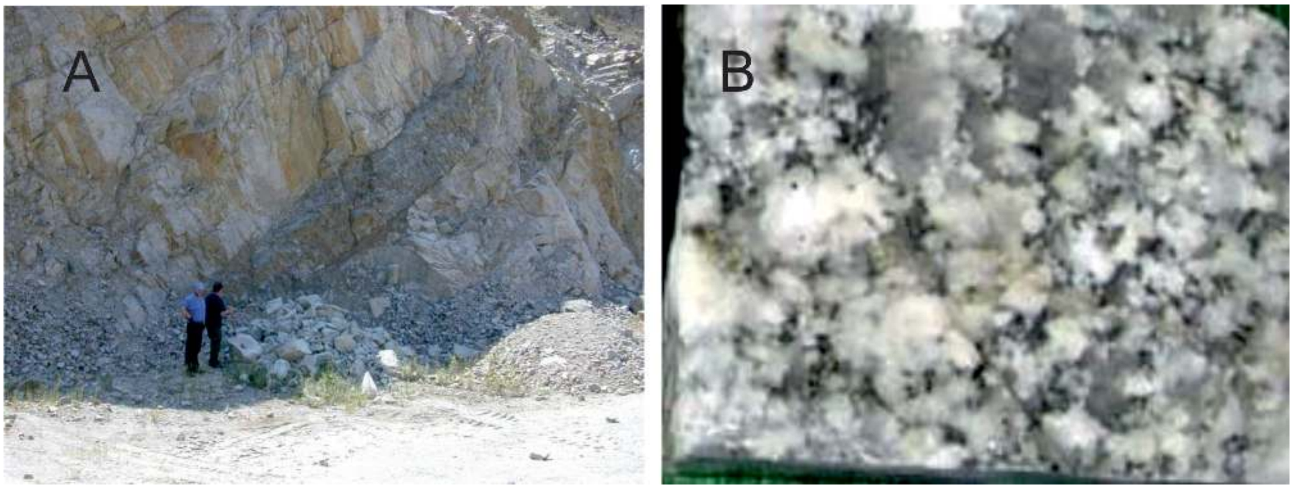


Figure 1.12 Dubná skala quarry: A – Permian lamprophyre intruded into Variscan tonalite/granodiorite (recently covered by a dump pile); B – granodiorite structure from the quarry.

Granodiorite is medium-grained and porphyritic with K-feldspar phenocrysts which form hypidiomorphic to allotriomorphic individuals of light pink colouring. K-feldspar is presented as orthoclase ($Or_{93}Ab_7$) with triclinity to 0.2. Plagioclases are hypidiomorphic, white to grey, quartz is allotriomorphic and dark grey. Granodiorite contains allanite-(Ce), hornblende, apatite and zircon with morphological mean I.T. index above 350. SiO_2 concentrations vary from 64 up to 72 wt%. Modal composition (in %): Qtz 29. Kfs 13, P 45, Bt 11, Ms 1, Ac 1. The granitoids are altered by the late magmatic fluids; microfolded biotite indicates superimposed deformation (Fig. 1.13A). Typical subsolidous alterations of plagioclase are sericitization, albitization and particularly sausseritization. Biotite breaks down into chlorite, sphene, epidote and rutile. Degradation of titanite is

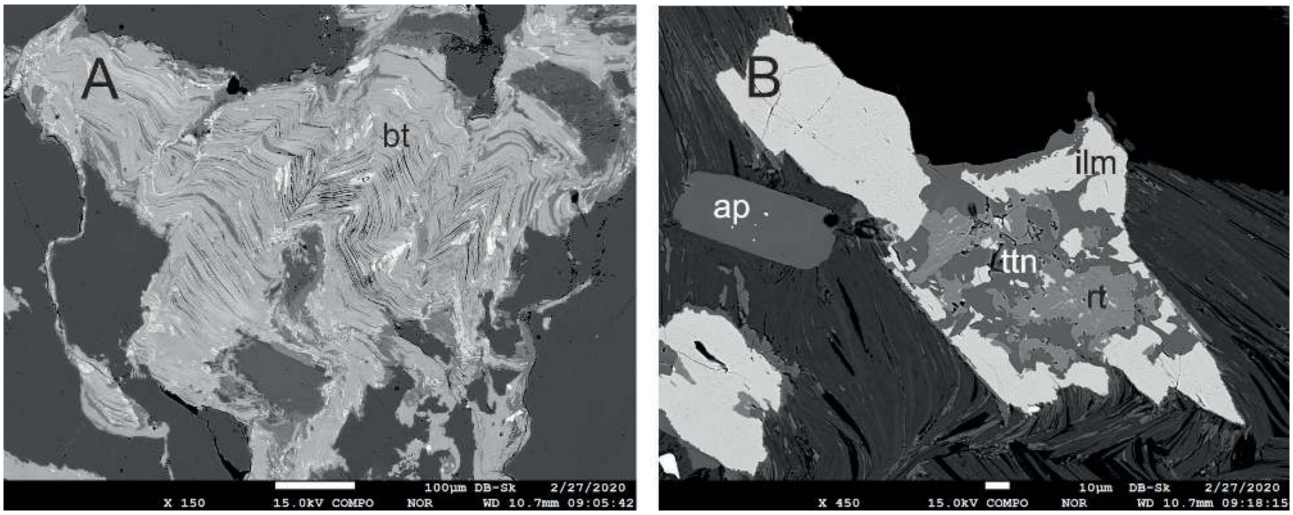


Figure 1.13 BSE images of tonalite from the Dubná Skala quarry: A – deformed biotite in a local shear zone; B – disintegrated titanite and newly-formed ilmenite and rutile (from Broska & Svojtka, 2020).

an example of alteration by the fluidal overprint (Fig. 1.13B).

The tonalite is slightly metaluminous (A/CNK = 0.97) with SiO_2 = 67.70 wt%, P_2O_5 ≈ 0.33 wt%, Na/K ≈ 1.5, Sr content 660 ppm, Ba 1680. The biotite is Mg rich Fe/(Fe+Mg) ≈ 0.4, allanite-(Ce) shows a low Al content (Al_2O_3 15 wt%) typical for the I-type granitoids. Low zircon Zr/Hf_{wt} ratio around 31 is in coincidence with the I-type affinity. REE normalized patterns characterise negative Eu-anomaly, the average La/Sm ratio in the I-type is 3.9. Normalized REE-pattern shows enrichment of LREE above HREE with a negligible positive Eu- and Yb-anomaly similar to the REE-patterns of Malá Fatra granites (Broska et al., 1997; Hrdlička, 2006). The REE chemical features of a specimen are: Eu/Eu* = 1.2; $(Ce/Yb)_N$ = 28.4 $(Ce/Sm)_N$ = 4.3; $(Tb/Yb)_N$ = 1.9.

Accessory mineral parageneses for both granite types are similar and the heavy mineral concentrations indicate I-type character of granitoids: apatite (>700 g/t), allanite-(Ce) (348 g/t), epidote-zoisite (684 g/t), magnetite (80 g/t), titanite (35 g/t), and pyrite (80 g/t). Zircons display the morphological parameters IT above 400 and IA 298. Early magmatic zircon shows oscillatory zoning, Zr/Hf_{wt} is 31, but later zircon precipitation displays HfO_2 up to 3 wt% and lowering of Zr/Hf_{wt} ratio. Zircon population of the tonalite contains clear or rarely pale brown, mostly euhedral, both short- and long-prismatic, about 150–350 µm long grains or their fragments. Internal zircon structures exhibit symmetrical, oscillatory growth zoning preserved in nearly all imaged grains, but all grains show uniform overgrowth rims ca. 10–30 µm wide (Fig. 1.14A).

Granodiorites from Dubná skala were dated to 353±6 (-11) Ma by the U-Pb method from the large zircon concentrates (Shcherbak et al., 1990). LA ICP MS zircon point dating show the concordia age peak of ca. 353±3 Ma, while dating of rims provided 342 ±3 Ma (Fig. 1.14 B). Th/U zircon ratio from the cores shows median 1.01 typical for the magmatic origin, but the rims show only 0.2 in average. The overgrowth rims were interpreted as thermally induced zircon precipitation by fluids derived from a body emplaced in the granodiorite zone (Broska & Svojtka, 2020).

Granitoids in the Dubná Skala quarry are in places cut by Permian calc-alkaline lamprophyre dykes 0.5–3 m wide. They reveal similar characteristics like in the Nízke Tatry Mts (Spišiak et al., 2019) and in some nearby localities in the Malá Fatra Mts, as well as from the highway tunnel just below the quarry (Spišiak & Hovorka, 1998; Spišiak et al., 2018). In the northern part of the Považský Inovec Mts, dykes of Permian alkaline basalts were described by Pelech et al. (2017a). Clinopyroxenes (diopside to augite), amphiboles (kaersutitic), biotites (annite) and plagioclases are major primary minerals of the dykes; accessory minerals include apatite, ilmenite, rutile, pyrite, chalcopyrite, and pyrrhotite. Apatite has a relatively low F, but increased Cl content compared to typical apatite from Variscan granitic rocks of the Western Carpathians. The chemical composition of the lamprophyres indicates their calc–alkaline character, but affinity to alkaline lamprophyres is suggested by the Ti enrichment in clinopyroxene, amphibole and biotite. According to modal classification of the minerals, the studied rocks correspond to spessartite lamprophyre (Spišiak et al. 2018, 2019).

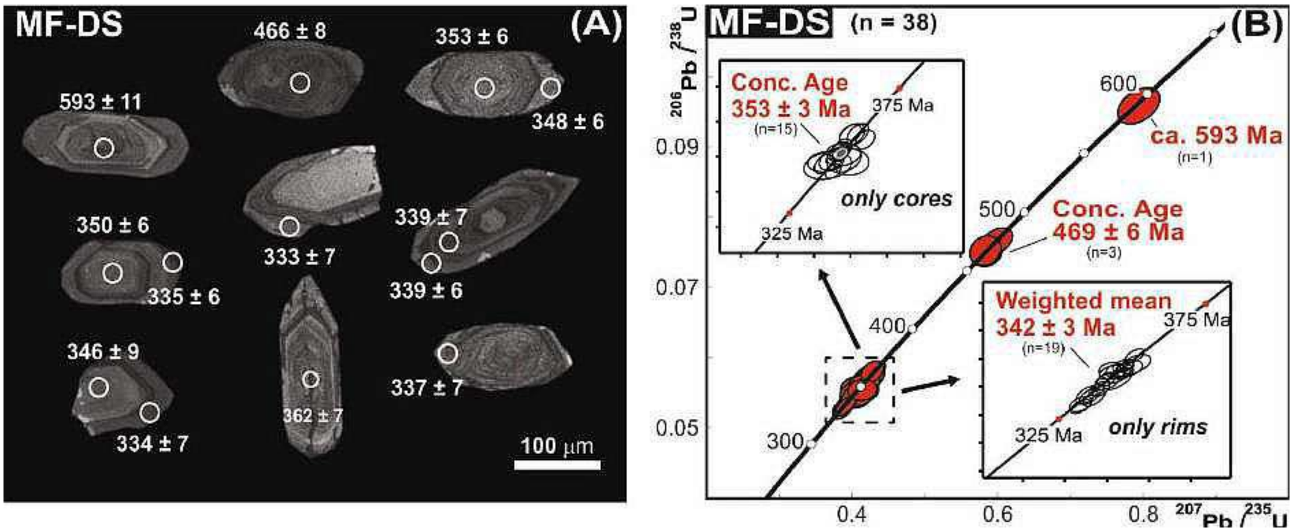


Figure 1.14 A – CL images of zircons from the Dubná Skala tonalite show their oscilatory zoning and rim overgrowth; B – concordia diagram of zircons from the Dubná skala tonalite with Tournaisian cores and Visean overgrowths documents their age zoning (adopted from Broska & Svojtka, 2020).

The differences in the chemical composition of the rocks (including Sr and Nd isotopes) probably resulted from the contamination of primary magma by crustal material during magma ascent. At contacts of mafic veins with the surrounding tonalities, ca 2 cm thick zones of intense chloritization of the host rock occurs. Within thicker veins, the transitions from porphyric and amygdaloidal types into the holocrystalline, evenly granular types in the central parts of veins can be observed. The dykes contain numerous xenoliths, or disintegrated parts of the tonalite host rock. U/Pb dating of apatite revealed the 263.4±2.6 Ma age of lamprophyres (Spišiak et al., 2018). The probably Permian overprint of the host granitoids was identified by Hrdlička (2006), who described precipitation of oriented Permian monazite in the apatite from surrounding granitoids and monazite age ca 260 Ma indicating a simultaneous origin with lamprophyres.

1.1.3 Mesozoic sedimentary successions of the Tatric, Fatric and Hronic units

The Tatric sedimentary cover consists of nearly complete Triassic to mid-Cretaceous succession. The lower transgressive base is formed by the Lower Triassic clastic sequence of continental quartzitic sandstones (Lúžna Formation; Fejdiová, 1980; Mišík & Jablonský, 2000) and variegated shales (Werfen Fm. or "Werfenian beds" – Lexa et al., 2000; Fejdiová, 1977, respectively). The Anisian to Carnian shallow-marine carbonatic complex includes dark massive to thick-bedded limestones (Gutenstein Fm.) and dolomites (Ramsau Fm.) deposited in extensive shelf areas affected by hypersaline conditions and synsedimentary seismicity (e.g. Mišík, 1968; Polák, 1976). The Upper Triassic continental red-beds are represented by quartzitic conglomerates, sandstones, siltstones, variegated shales and evaporites in places (Carpathian Keuper Fm.; cf. Havrila & Olšavský, 2015).

In majority of the Tatric successions, the Rhaetian deposits and sometimes also older Triassic strata are missing due to their erosion during the Early Jurassic rifting that brought about destruction of the Triassic shelf and ensuing differential subsidence of broad Jurassic extensional basins and relative elevation of narrow intra-basinal highs (e.g. Plašienka, 2003a). The belt of north-western core-mountains, including the Malá Fatra (Fig. 1.2), is characterized by prevailing basinal Jurassic – Lower Cretaceous successions deposited in the so-called Šiprúň Basin (Fig. 1.3; cf. Polák, 1978). The Lower Jurassic syn-rift strata consist of dark-grey sandstones, sandy-crinoidal limestones and calcareous shales passing to hemipelagic spotted marlstones and spiculitic marly limestones of the "Fleckenmergel-Fleckenkalk" facies (Algäu Fm.). During the Middle Jurassic, the basin gradually subsided near the CCD level with deposition of the "siliceous Fleckenmergel" and black spongolites followed by only a few metres thick radiolarian limestones and calcareous radiolarites (Callovian–Oxfordian Ždiar Fm.; Polák & Ondrejičková, 1995). Kimmeridgian grey marly and nodular limestones are overlain by the Tithonian to Barremian, more than 100 m thick, well-bedded pelagic limestones of the Biancone-Maiolica facies with black chert nodules (Lučivná Fm.; Polák & Bujnovský, 1979). During the Aptian, limestones became more marly and siliceous and contain layers of allodapic bioclastic cherty limestones and in places also small bodies of submarine hyalobasanitic lava flows. The terminal synorogenic Albian–Cenomanian sequence is, due to the increasing input of terrigenous sandy material, formed by turbiditic flysch deposits and occasionally also conglomerates containing "exotic" pebbles of disputable provenance (Poruba Fm.; Mišík et al., 1981).

In the Malá Fatra Mts, the Fatric Krížna Nappe is represented by a continuous sedimentary succession from the Middle Triassic up to the Cenomanian (Fig. 1.3). The lower rigid part of the nappe body is composed of the Middle Triassic massive or thick-bedded limestones and dolomites. These are overlain by the continental and lagoonal clastic and evaporitic deposits of the Keuper facies, which is thicker and more fine-grained compared to Tatric Keuper, with prevalence of variegated shales and evaporitic dolomites. Presence of thin discontinuous layers and lenses of Carnian clastics (Lunz Fm.) in the upper part of the dolomite complex and Rhaetian fossiliferous limestones are other differences in comparison to the Tatric cover, but the overall character still matches the epicontinental Germanic Triassic facies realm.

The Lower Jurassic syn-rift deposits include dark grey calcareous sandstones, sandy-crinoidal limestones and shales (Kopienec Fm.) passing to cherty limestones, grey spotted limestones and marlstones (Allgäu Fm., a.k.a. Janovky Fm. in Slovakia; Fig. 1.3). Discontinuous bodies of upper Toarcian ammonitico rosso facies limestones (Adnet Fm.) occur in places only. The deepening Middle–Upper Jurassic post-rift sequence consists of siliceous limestones and spongolitic cherts, variegated radiolarian limestones and radiolarites (Ždiar Fm., mainly Oxfordian), variably coloured marly and siliceous limestones (Jasenina Fm., Kimmeridgian), light platy maiolica-type limestones (Osnica Fm., Tithonian–Berriasian), thick complex of grey marly limestones and marlstones

(Mráznica Fm., Valanginian–Hauterivian) and blackish marls and calcareous shales with intrabasinal olistostrome bodies (Párnica Fm. with Vlkolínec Breccia, Barremian–Aptian – cf. Jablonský & Marschalko, 1992) and submarine basanitic lava flows (Spišiak & Hovorka, 1997). This typical deep-marine Zliechov Succession is terminated by the Albian–Cenomanian, coarsening-upward synorogenic flysch sequence of dark calcareous shales, turbiditic sandstones and sandy limestones with bodies of exotic conglomerates in places (Poruba Fm.; cf. Jablonský, 1978).

The overlying Hronic nappes form the northernmost strip of the CWC allochthonous units in the Krivánska Fatra Mts, including the spectacular outlier of cliffy Mt. Rozsutec. Similarly like the Fatric nappes, the Hronic nappes are detached at the base of the Middle Triassic carbonate complex, but the sedimentary successions of both nappe systems differ substantially. Following the Anisian carbonate ramp, the Ladinian Hronic sedimentary area was differentiated into basinal successions with pelagic nodular and cherty limestones (Reifling Fm.) that were neighbouring prograding Wetterstein carbonate platforms. The Carnian clastic Lunz Formation is present just in places, being overlain by the upper Carnian–Norian Hauptdolomite complex (Fig. 1.3). The Middle Triassic sedimentary sequence is characteristic for transitional successions between the Dobrá Voda Basin and the Mojtín-Harmanec carbonate platform and has been affiliated with the Ostrá Malenica partial nappe by Havrila (2011). No Jurassic strata of the Hronicum are preserved in the Malá Fatra Mts.

1.1.4 Central Carpathian Paleogene Basin and "Peri-Klippen Paleogene"

The link between the northern marginal zones of the CWC and the PKB is provided by the Paleogene sediments that are assigned to two, in part independent and in part closely related depositional settings and structural zones. In the area concerned, they compose an about 1–3 km wide belt that separates the Hronic complexes of the Krivánska Fatra Mts from units of the PKB (Fig. 1.4). Near Terchová village, the Senonian and Paleogene deposits analogous to the Myjava–Hričov Group form a narrow strip rimming the PKB from the south. They are composed of variegated Upper Cretaceous marls, Paleocene claystones, sandstones and conglomerates with patch reef bodies (Kambühel limestone) occurring as loose blocks in secondary positions (Scheibner & Scheibnerová, 1961; Scheibner, 1968a; Samuel & Haško, 1978; Buček & Köhler, 2017), or as pebbles in Oligocene conglomerates of the CCPB in the Orava territory (Köhler & Gross, 1994). These are overlain by the Middle Eocene flysch deposits and create an imbricated, steeply north-dipping, about 500 metres wide belt, which is rapidly wedging-out eastwards.

In large CWC areas, sediments of the Central Carpathian Paleogene Basin (CCPB) are usually flatly lying and little disturbed (e.g. Soták et al., 2001). However, the typical CCPB formations are missing in the belt of Paleogene sediments west of Terchová. The basal transgressive formation of carbonatic breccias is older than in typical CCPB and shows a heterochronous development from the middle Lutetian in the west to the Bartonian–Priabonian towards the east. The basal clastics are overlain by the Terchová Beds (Gross, 2008 and references therein) composed of alternating carbonatic breccias and sandstones with thick intervals of hemipelagic, locally variegated claystones. The following flysch sequence is also different from the Oligocene Zuberec Formation of the CCPB – it contains variegated claystones and is older (Middle Eocene), thus it shows an affinity to the Žilina and/or Domaniža formations (Soták et al., 2017, 2019). By these features, the Paleogene successions near Terchová are closer to the southerly located Peri-Klippen Hričov–Žilina zone and Súľov–Domaniža Basin (see also Samuel & Haško, 1978) than to the CCPB proper.

In the Zázrivá region, characteristic formations of the CCPB Podtatranská Group (Gross et al., 1984; Gross, 2008) are appearing. The basal Borové Formation consists of chaotic accumulations of breccias composed of material derived from the underlying Triassic carbonates of the Hronic units, which are overlain by a thick sequence of carbonate conglomerates and nummulitic sandstones (Bartonian – early Priabonian). The basal complex is eroded by deep channels filled with polymict conglomerates (Pucov Member) and overlain by the Huty Formation of dark claystones, Globigerina marls and menilitic shales (earliest Oligocene). Overlying Oligocene Zuberec and Biely potok formations are composed of sedimentary cycles of turbidites, amalgamated sandstone megabeds (hyperpycnalites) and sandstone lithosomes.

1.1.5 Alpidic tectonic evolution

Development of the CWC nappe structure during the Cretaceous was largely controlled by basin inversion and reactivation of the pre-existing Jurassic rift-related extensional structures. As indicated by the sedimentary record in particular, the Early Jurassic rifting seized wide areas of former Triassic epicontinental shelf areas in the present Western Carpathians. It was inferred that rifing took place in several phases (Plašienka, 2003a, 2018a and references therein). The most widespread was the early Early Jurassic rifting event (ca 200–190 Ma) that produced wide basinal areas like the Fatric Zliechov (cf. Michalík, 2007) and Tatric Šiprúň basins, which then subsided thermally during the Middle Jurassic to Early Cretaceous times. Late Early and early Middle Jurassic (ca 180–170 Ma) rifting pulses affected preferably the northern Tatric zones and culminated by the breakup of the South Pennine Piemont–Váh oceanic domain (Plašienka, 2003a). However, the extensional tectonic regime persisted also during the post-rift stage until the mid-Cretaceous times, as revealed for instance by small portions of submarine alkaline basaltic flows and dykes cutting the Tatric crystalline basement, aged approximately 120–100 Ma (Spišiak & Hovorka, 1997; Spišiak et al., 2001 and references therein). In the High Tatra cover succession, the earliest manifestations of alkaline basaltic volcanism appeared already in the earliest Cretaceous (Madzin et al., 2014), similarly as in the eastern part of the Czorsztyn Ridge (Oszczypko et al., 2012a; Krobicki, 2018; Krobicki et al., 2019).

In addition, processes of Late Jurassic to Early Cretaceous crustal thinning are corroborated by the zircon fission track (ZFT) data from the basement granitoids of the Malá Fatra Mts. Danišík et al. (2010) reported ZFT ages between ca 145 and 135 Ma, which were alternatively interpreted as a very low-grade metamorphic event related to extensional tectonics and elevated heath flow. As a result of long-term extensional regime, the continental crust of the Tatric–Fatric basinal areas was strongly attenuated and became predisposed to compressional deformation.

Cretaceous shortening of the CWC regions propagated from the inner towards the outer zones, being most likely triggered by the slab pull force exerted by the sinking Meliatic oceanic slab (Plašienka, 1991, 2003a, 2018a; cf. Handy et al., 2010). Stacking of the upper-crustal thick-skinned and detached cover thrust sheets prograded from the Late Jurassic Meliata suture northward by Early Cretaceous shortening of the former passive margin (Gemeric over Veporic basement sheets). In mid-Cretaceous times, inversion affected the southern margin of the Fatric Zliechov Basin adjoining the elevated Veporic domain (Plašienka, 2003b). Subsequently, the thinned Fatric crust was thrust under the Veporic basement wedge along a crustal-scale shear zone (Čertovica thrust zone, Fig. 1.2c), which is still well visible on the deep seismic profile 2T (Tomek, 1993). Simultaneously, the Fatric sedimentary cover complexes were detached and, after the northern Veporic margin collided with thicker crust of the southern Tatric ridge, they lost contact with their former basement and were emplaced over the Tatric foreland as the Krížna Nappe (Prokešová et al., 2012). This short final overthrusting episode took place most probably during the late Turonian (ca 90 Ma ago), but might have lasted until the Santonian along the outer Tatric edge (Pelech et al., 2017b). The far-travelled Fatric diverticulations, such as the Manín and Klape units of the present Peri-Klippen Zone, glided beyond the outer Tatric edge to overly the Vahic oceanic complexes. In this position, they were subsequently incorporated into the developing Upper Penninic accretionary wedge. Within the wedge, these units were affected by repeated out-of-sequence thrusting along with their post-emplacement Gosau cover (e.g. Plašienka, 2020 and references therein).

After the nappe structure of the vast CWC areas was completed by about 90–85 Ma, shortening relocated to the northern Tatric margin, i.e. at the Pennine vs. Austroalpine boundary in terms of the Alpine tectonics (e.g. Handy et al., 2010). Subduction of the South Pennine Piemont-Váh Ocean commenced at the same time, as it is indicated by the Coniacian age of the oldest synorogenic trench-type flysch deposits in the Vahic Belice Unit (Považský Inovec Mts; Kullmanová & Gašpariková, 1982). The Campanian to possibly Maastrichtian variegated pelagic marlstones with olistostrome bodies supplied by the clastic material derived from the upper Tatric plate are the youngest documented Vahic sediments involved in thrusting along the northern Tatric margin (Plašienka et al., 1994). It evokes that the northern Tatric edge was transformed from the passive to active margin and experienced compressional deformation with basement-involved thrusting and imbrication during the latest Cretaceous (Plašienka, 1995a, b, 2018a; Putiš et al., 2019 and references therein). The structurally lower- and outernmost Tatric elements affected by the post-Turonian shortening low-grade and metamorphism were designated as the Infra-Tatric units. In particular, these include the Borinka Unit in the Malé Karpaty Mts, the Inovec Nappe in the Považský Inovec Mts and the Kozol Unit in the Lúčanská Fatra Mts – cf. Putiš (1991, 1992), Putiš et al. (2008, 2009, 2019), Plašienka (1990, 1995c, 2012a, 2018a), Plašienka & Marko (1993), Plašienka et al. (1991, 1993, 1994).

In the Malá Fatra Mts, the Late Cretaceous tectonic events were documented in its south-western part

(Lúčanská Fatra Mts). The NW boundary of the Tatric crystalline massif (mainly granitoids) is rimmed by a conspicuous mylonitic to cataclastic zone providing a contact with the underlying Infra-Tatric Kozol Unit. The mylonitic thrust zone includes also scarcely preserved, but ductilely strongly sheared Mesozoic carbonates. According to Ondrášik et al. (2009), gently SE-dipping blastomylonites represent a top-to-NW overthrust shear zone of the main body of the Tatric thick-skinned thrust sheet overriding the Kozol Unit. Mylonites were dated by the ^{40}Ar/^{39}Ar age spectra to approximately 90–70 Ma. This mylonitic shear zone is westward replaced by steeply dipping cataclastic zones (Hók et al., 2002, 2020). Similar mylonites occur also at the southern margin of the Lúčanská Fatra crystalline core near its contact with the overlying, considerably reduced Tatric Mesozoic cover, but directly with the Krížna Nappe in most cases (Valčianska dolina Valley NW of Valča village; Fig. 1.4). Here, the gently west-dipping shear zone was dated to ca 72 Ma (^{40}Ar/^{39}Ar plateau age on a sericite concentrate; Hók et al., 2000). Gentle dip and large omission of Mesozoic complexes would imply its connection with a low-angle normal fault, although Hók et al. (2000) did not find relevant shear-sense criteria. Supposedly, the extensional shear zones developed on top of the Tatric basement sheet due to coeval compression-related crustal stacking and thickening.

Timing and emplacement mechanism of the Hronic nappes is a complicated problem. Hronic units are typical superficial cover nappes floating above the underlying units with a pronounced structural and metamorphic discordance. Besides a weak burial-induced static metamorphic recrystallization of the Upper Paleozoic formations (pumpellyite-prehnite-quartz facies; Vrána & Vozár, 1969), the Triassic carbonates are thermally almost not affected, as indicated by the conodont colour alteration indices typically below 2 (Gawlick et al., 2002; Havrila, 2011). The sole of the Hronic nappes is formed by carbonate cataclatic breccias (Rauhwacke) without recognized shear-sense criteria. Internal nappe structures are exclusively brittle with ramp-flat thrusts, duplexes or partial nappes and scarce macrofolds in well-bedded sequences (Kováč & Havrila, 1998; Havrila, 2011). The youngest synorogenic sediments are of the Hauterivian to possibly Barremian age, thus this is likely also the time of commencement of shortening of the original Hronic area. This is not exactly known, however, since the Hronic are rootless nappes not connected to any basement substratum. With a considerable time delay, after the internal deformation, the Hronic nappes were finally emplaced in post-Turonian times. Whereas in the frontal CWC zones the Hronic thrusting might have been partially simultaneous with the underlying Fatric nappes, the structural and metamorphic gap with respect to Fatric units increases southwards and reaches omission of three penetrative deformation stages and the contrast between the anchimetamorphic record (250–300°C) in the underlying Northern Veporic Veľký Bok cover succession versus virtually non-metamorphic Hronic nappes (Plašienka, 1995d). The low-grade metamorphism in the Northern Veporic basement was dated by ^{40}Ar/^{39}Ar method on white micas to ca 90–85 Ma (Putiš et al., 2009 and references therein), hence emplacement of Hronic nappes should have been at least a bit younger.

On the other hand, the Hronic complexes are transgressively overlapped by the Gosau deposits along the outer CWC margin. These start with the upper Turonian freshwater limestones (Hók & Littva, 2018 and references therein) followed by the Coniacian–Santonian carbonate conglomerates and sandstones (e.g. Wagreich & Marschalko, 1995). While these continental and shallow-water sediments still might have been deposited in piggyback basins during overthrusting of the Hronic nappes, the younger Campanian red pelagic marlstones were deposited in open-marine conditions that seized vast Carpathian areas. Accordingly, the Hronic nappes should have been already emplaced at that time.

To summarize, the available data indicate that the Hronic nappes were emplaced in the time interval between 90 and 80 Ma, more precisely perhaps between 85 and 80 Ma, i.e. during the late Santonian to early Campanian – evidently out-of-sequence with respect to the progradational shortening and thrusting of the underlying CWC units. The Cretaceous nappe structure of the broad CWC areas was then overlapped by deposits of the Central Carpathian Paleogene Basin (CCPB). Their transgressive base is formed by the Middle–Upper Eocene carbonate breccias and nummulitic limestones, which are succeeded by the Upper Eocene to Oligocene hemipelagic shales and turbiditic sandstones. Near the contact with the adjacent Klippen Belt, these sediments are strongly disturbed by south-verging fold and thrust structures (Marko et al., 2005). Southward backthrusting affected also more inner CWC zones, for instance the prominent N-dipping reverse fault on the ridge of Mt. Rozsutec (see the Rozsutec tour below), as well as in other areas of the Malá Fatra Mts (Sentpetery, 2011; Sentpetery & Hók 2012). The post-Paleogene south- or southeast-vergent reverse faults and backthrust commonly occur along the outer CWC margin south of the PKB, for instance in the Strážovské vrchy (Maheľ, 1985; Pečeňa & Vojtko, 2011; Pelech & Olšavský, 2018) and

Považský Inovec Mts (Plašienka, 1995c).

Low-temperature thermochronologic data about the Miocene to Pliocene exhumation of the Malá Fatra Mts are provided by the apatite fission track ages (AFT) from the Tatric basement rocks. Together with the other core-mountains along the outer Tatric margin (northern part of the Považský Inovec and High Tatra Mts), they show the youngest cooling ages in the Western Carpathians, which are generally ranging between 20 and 10 Ma, but mostly 15–10 Ma (Danišík et al., 2010; Králiková et al., 2016). These ages are interpreted as resulting from the Middle Miocene erosional and partly also extensional tectonic removal of overlying CCPB sediments and Mesozoic nappe units.

The late Cenozoic exhumation was connected also with the surface uplift. The assymetric Malá Fatra horst is marked by an important vertical throw along the faults that rim the horst from the south and south-east against the Neogene deposits of the Turiec Basin. These deposits contain detrital zircons with the Late Cretaceous ZFT ages (Králiková et al., 2014) that might record an intermediate stage of denudation. During the uplift, a mountainous relief with incised antecedent valleys like the Váh River dividing the Lúčanská and Krivánska Fatra Mts and the Zázrivka Valley in the eastern Krivánska Fatra were formed.

An important, but controversially interpreted issue concerns the nature of the fault that separates the Krivánska Fatra horst from the Cenozoic filling of the Turiec Basin tu the south (Fig. 1.4). This generally W–E trending fault, named the Turany fault (Bezák et al., 2004), is commonly interpreted as a steeply south-dipping normal fault (see e.g. chapter 3.3 below). However, this interpretation meets problems with balancing at the crustal level, because it would need an extraordinary northward tilting of the Krivánska Fatra core by some 40° along a horizontal axis, which is hardly achievable in a simple regime with N–S extension. Therefore, we infer that the fault is steeply south-dipping or subvertical and originated in a compressional regime along with other post-Paleogene south-verging thrust structures in the Krivánska Fatra Mts (Fig. 1.17d). However, this interpretation has not been documented by the structural research yet, partly because of poor outcrop conditions. An indirect hint comes from the quarry Smolenová near Párnica village, which is located directly at the Turany Fault (Fig. 1.4). Polák (1979) described an older situation in this quarry with a slice of granitoids and Lower Triassic clastics squeezed within Middle Triassic carbones of the Tatric cover (Fig. 1.15a), which he interpreted as a recumbent fold. We infer that it would be rather a tectonic sliver emplaced along the compressional or oblique dextral Turany fault. Presently this slice is difficult to recognize in this active quarry (Fig. 1.15b), it was probably largely mined-out.

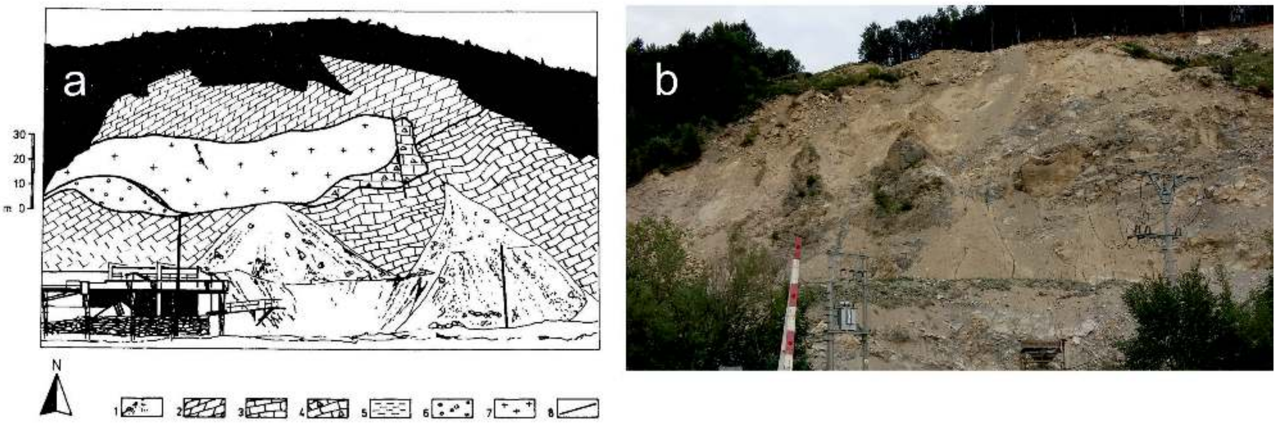


Figure 1.15 The Smolenová quarry near Párnica. a – situation in 1970-ties (Polák, 1979): 1 – scree; 2 – Middle Triassic dolomites; 3 – Middle Triassic limestones (Gutenstein Fm.); 4 – carbonate crush breccia of Triassic carbonates; 5 – Lower Triassic shales; 6 – Lower Triassic quartzites; 7 – granodiorites; 8 – faults. b – present state (2019).

This situation is similar like in the case of the Sub-Tatra fault system at the southern foots of the asymmetric horst of the Tatry Mountains (Fig. 1.2). There, kinematics of this fault has been also interpreted as either extensional or compressional, the latter case e.g. by Janák et al. (2001b), who applied the model of Narr and Suppe (1994) as in this situation south-vergent basement-involved duplex structure with a subvertical frontal fault. Peripheries of uplifting compressional horsts were affected by low-angle normal faulting that obliterated the master thrust faults, like for instance extensional allochthons of Fatric formation overlapping directly the Tatric crystalline basement along the Turany fault and also westward near the town of Martin (Fig. 1.4; see also Pivko, 1990).

1.1.6 Instructive field sections of Mesozoic units

The Fatric and Hronic nappe units build up a substantial part of the Krivánska Fatra Mts, where good informative outcrops are scattered over a wide area. Therefore, to see as much as possible needs longer walking tours. Since the area occurs in the National Park Malá Fatra, it is only possible along the touristic trails or forest roads. There are two such well accessible, moderately difficult walking trips – (1) the Rozsutec round-tour and (2) the Lučivná–Biela section (Figs 1.16 and 1.17).

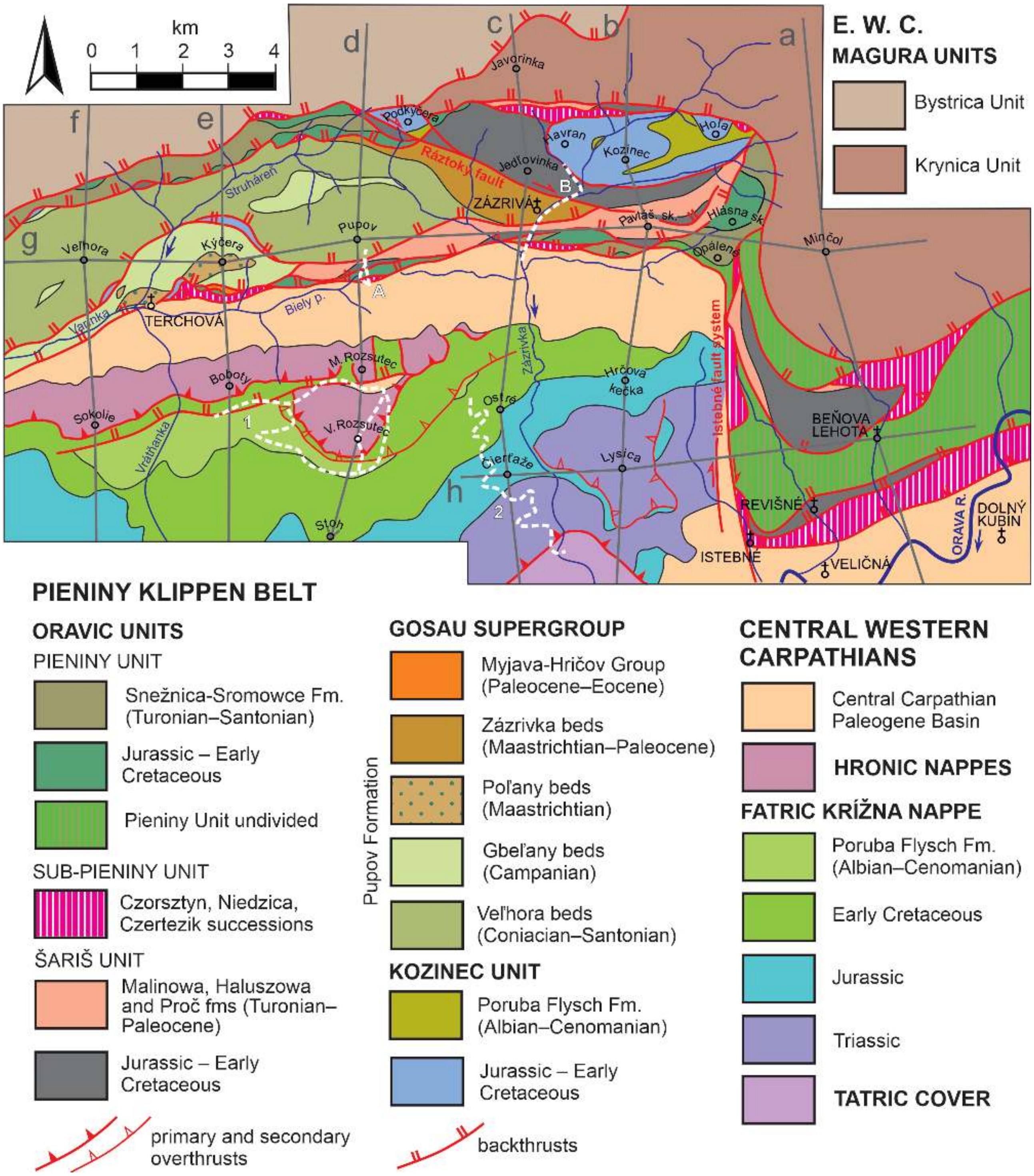


Figure 1.16 Tectonic map of adjoining parts of the Kysuca and Orava sectors of the PKB and neighbouring units (for the location see Fig. 1.4). Cross-sections a–h are interpreted in Fig. 1.17. White dashed lines mark the excursion routes (1), (2), (A), (B) and (C) described in the text (see also Fig. 2.1).

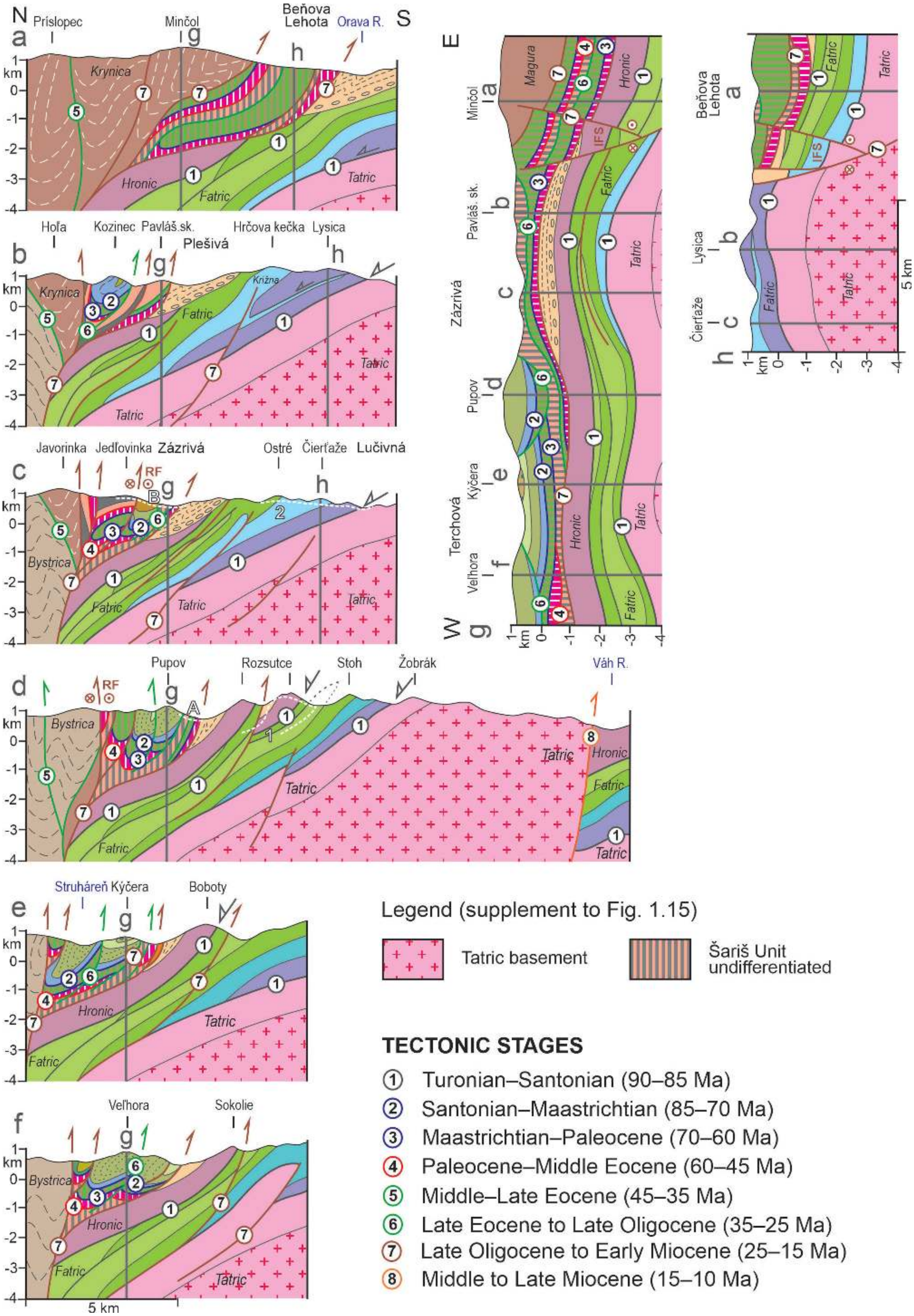


Figure 1.17 Tectonic cross-sections of the PKB and adjacent zones in NW Slovakia. For their positions and legend see Fig. 1.16. IFS – Istebné fault system. Partially according to Plašienka et al. (2020).

(1) The Rozsutec tours

This trip has several possible routes and starts in the Vrchpodžiar saddle (GPS N49.24075° E19.07293°; 750 m a.s.l.) reachable by the yellow touristic path from the parking place in Štefanová settlement, or by the bike trail from the hotel Boboty. Alternatively, it can be reached also from hotel Diery in Terchová-Biely Potok by following the blue path along the deep incised Jánošíkove diery gorge. This gorge is modelled in Middle Triassic carbonates of the Hronicum. The trip (1) follows wider surroundings of the cross-section labelled "d" in Figures 1.16 and 1.17.

The tour continues along the green touristic trail towards the east. The grey, schistous marly limestones occurring in the scree belong to the Lower Cretaceous Mráznica Formation of the Fatric Krížna Nappe. After climbing some 60 altitude metres in the wood, a flat meadow indicates soft rocks – dark calcareous shales and turbiditic sandstones of the mid-Cretaceous (Albian–Cenomanian) synorogenic Poruba Fm., which is the youngest member of all Fatric successions. However, a nice outcrop can be found only some 4.7 km to the south in an old abandoned road (Fig. 1.18b, GPS ca N49.23475° E19.07554°).

Walking further along the green trail, it enters the wood where Lower Cretaceous marly limestones occur again. This is an important and typical feature – the sole of the overlyin Hronic nappes seldom overthrusts the youngest Fatric rocks, i.e. the Poruba Flysch Fm., but usually lies directly on the Mráznica or even older formations (see also Sentpetery et al., 2020). It indicates that emplacement of the Hronic nappes postdated thrusting, internal deformation and partial erosion of the underlying Fatric units with some time delay (cf. Fig. 1.19).

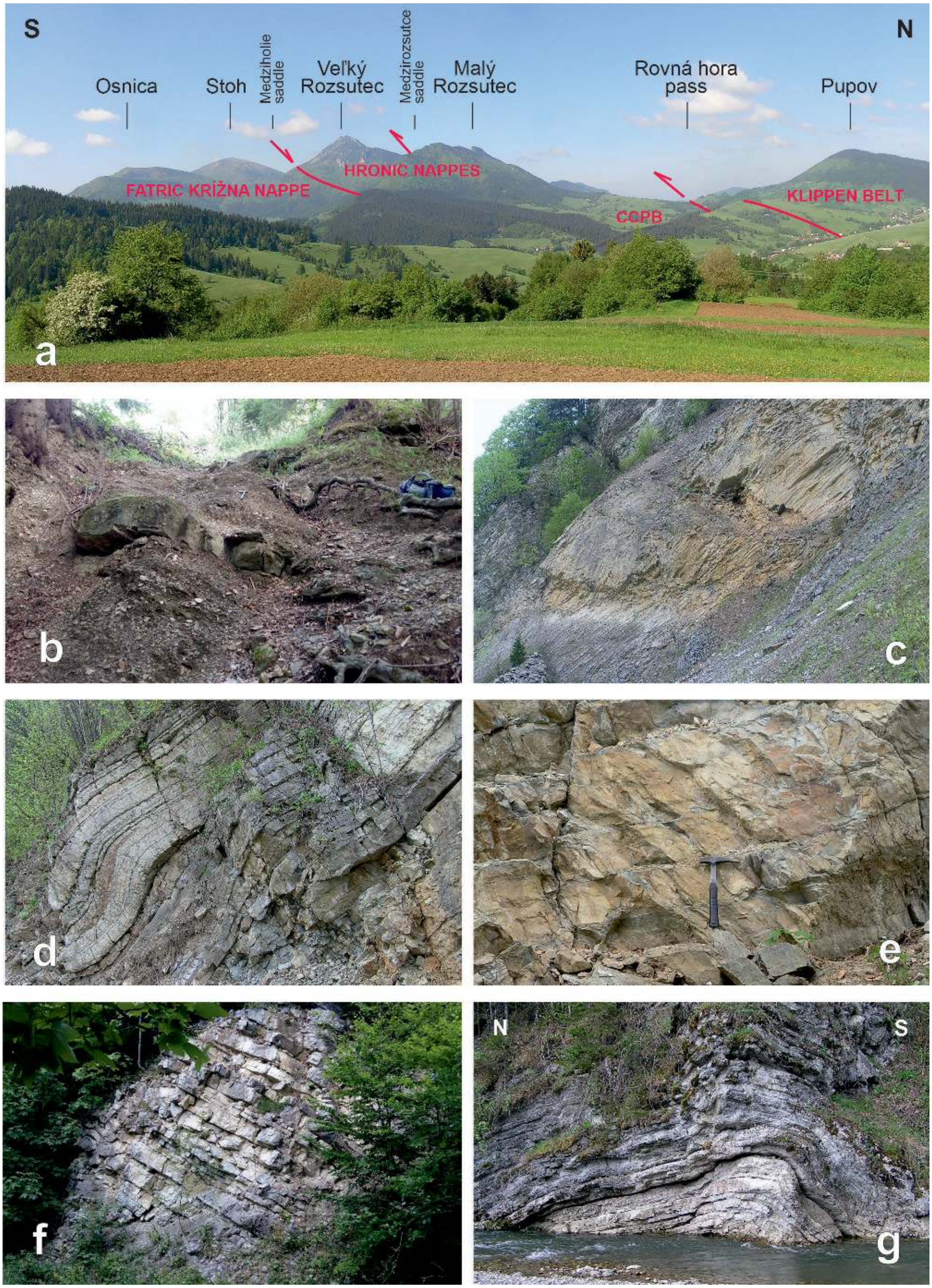
About 200 m east of the meadow, fallen blocks of massive Triassic limestones indicate approaching to the overthrust plane of the Hronicum. However, the contact is not directly exposed. Then the green path follows rock cliffs composed of Middle Triassic platform limestones (Wetterstein Fm.) until entering the main valley where it merges with blue path for about 250 metres where both trails split again. It is recommended to follow the green trail, which is more instructive from the geological point of view, although the blue one may be more attractive for climbing-lovers.

The green path follows, for about 1 km up to the Medzirozsutce saddle, an important tectonic feature known as the Medzirozsutce reverse fault. "Medzirozsutce" means that it is located between Malý (Small) and Veľký (Great) Rozsutec hills (Figs 1.16, 1.17d and 1.18a). It is a large-scale, post-nappe, steeply N-dipping reverse fault that originated during extensive post-Paleogene backthrusting along the northern Tatric edge, whereby the adjacent part of the PKB was thrust southwards for a distance of at least 5 km (Figs 1.17d and 18a). This fault was known already to Uhlig (1902), but correctly interpreted only later by Matějka (1931), and repeatedly illustrated since (e.g. Andrusov, 1968; Polák, 1975, 1979; Marko et al., 2005; Plašienka et al., 2020). Walking up the valley, the slopes on the western side are formed by Lower Cretaceous limestones of the Krížna Nappe with overlying Hronic Triassic carbonates on the ridge of Malý Rozsutec Hill. On the eastern slopes, there are numerous blocks and clasts of carbonate breccias, which represent the basal member of the Central Carpathian Paleogene Basin that transgressively overlies Triassic carbonates of the Hronic outlier of Mount Veľký Rozsutec. This structure continues to the saddle Medzirozsutce (GPS N49.24302° E19.10704°; 1,200 m a.s.l.) and a few hundreds metres further east. Occassionally, also some Paleogene marls can be found in meadows at the Medzirozsutce saddle.

There are two possible ways how to pass Veľký Rozsutec from the Medzirozsutce saddle. From both the geological and touristic point of view, the red trail crossing directly Mount Veľký Rozsutec (1.610 m a.s.l.) is more attractive, but not permitted during the spring season from March to mid-June. In the underlier of Paleogene breccias, the trail provides a nice profile through various Middle Triassic carbonates of the Hronicum – Ladinian basinal nodular and cherty limestones of the Reifling Formation are in part overlain by slope facies of the Raming Formation that contain bioclastic debris from the prograding upper Ladinian – lower Carnian Wetterstein carbonate platform. The steep southern slope of Veľký Rozsutec is built by Anisian Ramsau dolomites and Guttenstein limestones. The latter are underlain by Lower Cretaceous limestones of the Fatric Mráznica Formation.

During the springtime closure of the red trail, the blue path passing by Veľký Rozsutec along its eastern slopes may be used. Below the Paleogene dolomitic breccias, there are nice outcrops in the bedded cherty limestones of the Ladinian basinal Reifling Formation, but the slopes are mostly covered by debris. Approaching the Medziholie saddle south of

Figure 1.18 Field photographs from the Krivánska Malá Fatra Mts (D. Plašienka): a – panoramic view from the east on the CWC–PKB contiguous zone west of Zázrivá; b – mid-Cretaceous flysch (Poruba Fm.) of the Krížna Nappe, Štefanová (Rozsutec tour); c–g Lučivná–Biela section: c – Lower Cretaceous limestones of the Tatric cover, type locality of the Lučivná



Fm.; d – gentle fold in upper Middle Jurassic radiolarian limestones (Ždiar Fm.), Krížna Nappe; e – axial-plane cleavage, the same outcrop as d; f – Tithonian–Berriasian calpionella limestones (Osnica Fm.); g – S-vergent post-Paleogene fold in the Lower Cretaceous marly limestones (Mráznica Fm.) Krížna Nappe, left bank of the Zázrivka Brook east of Biela settlement.

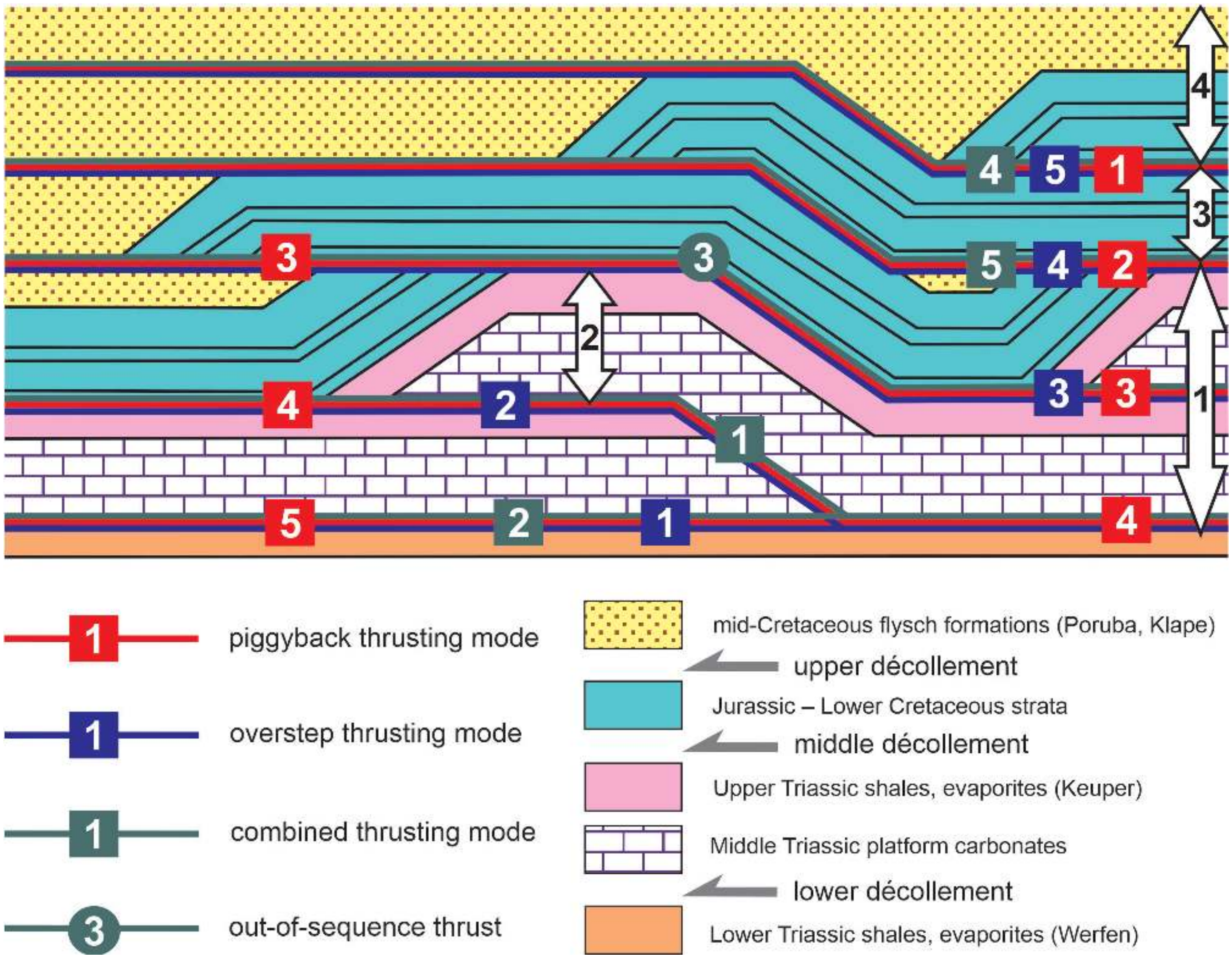


Figure 1.19 Geometrical model of internal thrust structures of the Fatric units that developed during their detachment from the underthrust basement substratum. Vertical double arrows mark the principal partial Fatric units: 1 – the Krížna Nappe with 2 – the Lysica duplex; 3 – the Manín Unit; 4 – the Klape Unit. After stacking, these partial units were gravitationally emplaced in the present position by the diverticulation manner – i.e. the unit 4 (Klape) glided farthest north, being in part overridden by unit 3 (Manín) followed by the main body of the Krížna Nappe (1-2).

Mount Veľký Rozsutec, the scree is formed by Lower Cretaceous limestones (Mráznica Fm.) of the Fatric Krížna Nappe. At the crossing of the blue and red touristic trails closely below the Medziholie saddle (GPS N49.24302° E19.10704°), dark marly shales and sandstones of the mid-Cretaceous Poruba Flysch Formation are cropping out. Here again they do not appear directly below the Hronic overthrust plane, but are sandwitched between two slices of the Lower Cretaceous limestones. Heavy mineral (HM) analyses from this locality and from two other sites further west (Vrátna and Štefanová valleys crossing and Pod Sokolím; Aubrecht et al., 2020) revealed dominance of Cr-spinels (7–40%) and ultrastable ZRT assemblage (11–50%). However, the Medziholie locality is exceptional by a high content of garnet (73.5%), which is otherwise quite rare. The variability in the HM content and the general low compositional maturity of turbiditic sandstones indicate short transport ways and relatively rapid emergence-erosion-deposition processes (Aubrecht et al., 2020).

(2) The Lučivná–Biela section

This walking trip begins in the abandoned quarry Bralo near the ski resort Lučivná, above the sharp curve of the road from Zázrivá to Párnica (GPS N49.20913° E19.16592°; Fig. 1.16). This is the type locality of the Lučivná Formation (Polák & Bujnovský, 1979), the Lower Cretaceous sequence of the Tatric sedimentary cover (Figs 1.3, 18c). Pale grey, micritic pelagic limestones are well-bedded with thin intercalations of grey claystones and contain nodules, lenses or discontinuous layers of black cherts. Presence of aptychi and absence of ammonite shells indicates deposition between the ACD and CCD levels. Corroded belemnites and crinoid ossicles, as well as pyrite framboids are also present. The lower part contains Tithonian calpionellids, but the main part of about 100 metres thick formation shows the radiolarian microfacies. The Barremian to Aptian sequence contains distal bioclastic calciturbidite beds revealing nearness of the Urgonian carbonate platform (Michalík et al., 1990).

The tour continues northward along the western slopes of the Zázrivka Valley, approximately along the cross-section “c” depicted in Figures 1.16 and 1.17. Behind the metal bridge above the Zázrivka River, debris of the youngest member of the Tatric cover succession – the mid-Cretaceous Poruba Flysch Formation can be found at the foots of the Lučivná ski slope. After having passed the ski resort, the Veľká Lučivná side valley is already modelled in the Middle Triassic carbonate complex of the Fatric Krížna Nappe. Following the forest road uphill and continuing generally northward, numerous outcrops of bedded dolomites (Ramsau Fm.) appear along the road cut. However, a look eastward on slopes of the Lysica Hill on the other side of the Zázrivka Valley is more interesting from the point of view of structure of the Krížna Nappe. As can be seen from the geological map and cross-section (Fig. 1.16 and 1.17c), the stratigraphic succession of Triassic formations of the Krížna Nappe is doubled there. This structure was described as the “digitation de Lysica” by Matějka (1931), i.e. a recumbent macrofold with a reduced overturned limb. A modified, duplex interpretation is offered here. The duplex is bounded by the floor thrust, which is the main thrust plane of the nappe, while the roof thrust follows the secondary internal detachment plane developed within the soft Keuper shales and evaporites (Fig. 1.19). In between, the duplex is formed by fault-bend folding and thrusting along an inclined ramp cutting the thick Middle Triassic dolomite complex. The detached Jurassic and Cretaceous strata above the roof thrust are well-bedded and thus prone to folding, therefore they were shortened by mesoscopic folding in front of the duplex as it will be seen later in the section. It is supposed that this deformation occurred during detachment of the sedimentary succession of the Krížna Unit from its basement substratum already in the original homeland area, and then the duplex structure was passively transported into the present allochthonous position during the final nappe emplacement (Prokešová et al., 2012).

Before the sharp road curve tracing the side ridge, there are small outcrops in layers of dark shales alternating with dolomite beds. This sequence was described as the Tržinovo Formation (Sýkora et al., 2011). Dark claystones and dolomites alternate in several decimetres thick beds in altogether about 10 m thick formation, which is correlated with the Carnian Pluvial Event (a.k.a. Reingraben, Raibl or Lunz event; cf. Havrila et al., 2019) marked by siliciclastic input during a short-term humid period in overall arid Triassic climate. Where present, these shale intercalations (and sandstones of the typical Lunz Fm. in other places) separate the lower Ramsau dolomite complex from the overlying Hauptdolomit Formation.

Behind the sharp curve, the road runs along-strike of dolomite bedding for several hundred metres. Then the debris and outcrops of the overlying Carpathian Keuper Formation of Norian age emerge. This is a continental clastic-lagoonal formation of variegated shales, siltstones, sandstones and evaporitic dolomites. The uppermost Triassic – Rhaetain black fossiliferous limestones with shale intercalations (Kössen Fm.; a.k.a. Fatra Fm.) are cropping out at the timber depository place (GPS N49.22248° E19.14335°).

The rest of the section along the timber roadcut exhibits a nearly complete Jurassic to Lower Cretaceous succession of the Krížna Nappe. This is a typical deep-water Zliechov Succession which is the most widespread among the Fatric units (see Fig. 1.3). It shows development from the Lower Jurassic syn-rift deposition, through gradual post-rift subsidence with hemipelagic and later eupelagic sediments up to terminal mid-Cretaceous syn-orogenic clastics heralding the onset of inversion and shortening of the Zliechov Basin that preceded detachment of the Fatric sedimentary complexes and their nappe emplacement over the foreland Tatric areas.

The Rhaetian limestones are overlain by the Hettangian–Sinemurian grey sandy shales, sandy-crinoidal limestones to calcareous sandstones in places, which are designated as the Kopieniec Formation (formerly known as the Gresten Beds). Besides crinoids, the formation is rich in bivalves and brachiopods, intraclasts, oolits, fragments of phosphorites and occasionally also ammonites (e.g. Polák & Rakús, 1973). During the Early Jurassic, the terrigenous clastic input gradually decreased and the Pliensbachian–Toarcian sequence is composed of hemipelagic dysoxic dark-grey spotted marlstones and spiculitic limestones of the Fleckenmergel-Fleckenkalk facies (Allgäu Formation) reaching a considerable thickness of several hundred metres. These rocks pass upwards into the so-called “siliceous Fleckenkalk” of possibly Aalenian age. As the sea bottom deepened due to the post-rift thermal subsidence, the calcite content in the sediments decreased on the expense of silica derived from sponge spicules.

During the Middle Jurassic, the Zliechov Basin became a sort of a starved basin with very thin and feebly dated eupelagic sediments. At the same time, the colour of sediments changed from dark-grey indicating poorly aerated environs in semiisolated basins to variegated, chiefly reddish sediments. This change may indicate opening of marine connections to the World Ocean during breakup and commencement of spreading of the Pennine oceanic domains linked with the Central Atlantic.

A few tens of metres thick siliceous sediments are composed of variegated radiolarian limestones (Fig. 1.18d) and red ribbon radiolarites that were deposited below the local CCD level. In the Krížna Unit, these abyssal sediments were dated to late Bathonian–Oxfordian with possible extension into early Kimmeridgian and designated as the Ždiar Formation (Polák & Onrejičková, 1993; Polák et al., 1998). This formation is cropping out in the next part of the section. Well-bedded siliceous limestones and radiolarites are contorted by irregular, in part typical chevron folds especially in radiolarites. Folds in limestones are associated with a weak axial-plane cleavage (Fig. 1.18e).

The section continues with the Upper Jurassic strata. Radiolarites are overlain by variegated siliceous and marly limestones of the upper Kimmeridgian to lower Tithonian Jasenina Formation. This is in turn overlain by the upper Tithonian–Berriasian Osnica Formation (Fig. 1.18f), which is composed of white calpionella-bearing limestones of the typical maiolica or Biancone facies (GPS N49.23278° E19.1433°). The next is the Valanginian–Barremian Mráznica Formation, which is the thickest and areally most extensive member of the post-rift Zliechov Succession. It is composed of a monotonous, at least 500 metres thick complex of schistous dark-grey argilaceous limestones and marlstones. In the footwall of the Medzirozsutce backthrust, the Mráznica limestones are deformed by metric S-vergent asymmetric folds in places (Fig. 1.18g).

The content of terrigenous clay minerals increases upwards, whereby the Mráznica Fm. passes into the Aptian Párnica Formation composed of dark grey to black marlstones and marls. These are exposed at the last point of the section down in the Biela Valley near the bus stop in Biela village (GPS N49.24292° E19.13922°). There the Párnica marls are deformed by synsedimentary slumping. In some localities nearby, the Aptian marly sequence contains intraformational olistostrome bodies known as the Vlkolínec Breccia (Jablonský & Marschalko, 1992). The youngest member of the Zliechov Succession – the Albian–Cenomanian Poruba Flysch Formation is not exposed along the examined Lučivná–Biela section.

1.2 Structure and composition of the Pieniny Klippen Belt – an overview

The intricacy of the tectonic structure of the Klippen Belt due to Laramide and post-Paleogene folding is so great that it could seem useless to look for some regularities or clear-cut types of tectonics. (Andrusov, 1974, p. 154)

The Pieniny Klippen Belt (PKB; pieninische Klippenzug – Neumayr, 1871; Uhlig, 1890) got its name according to its characteristic structure, where hard rocky blocks – the klippen – composed of Middle Jurassic to Lower Cretaceous limestones are embedded in a soft matrix formed by the Lower Jurassic and Upper Cretaceous to Middle Eocene marls, shales and flysch deposits – the "klippen mantle". Thus the competent klippen successions were originally inserted within incompetent strata prone to folding, shearing and formation of décollement horizons. Owing to this rheological stratification and polystage deformation processes, the competent sequences were largely fragmented and often form isolated blocks floating in soft strata. Nevertheless, the "block-in-matrix" structure is not a general rule for the PKB; there are segments with well preserved original nappe structure, or with quite long, continuous and less disturbed stratigraphic successions. The recent ideas about the composition of individual units or successions distinguished in the PKB come from such more-or-less continuous sections, while there are many uncertainties with assignment of the soft matrix strata elsewhere.

It is remarkable that, considering the area extent in the map view, the klippen blocks form a minor portion of individual PKB segments – commonly less than 50%, which diminishes to zero in places. On the other hand, distinguishing of the PKB units or successions has been chiefly based on the lithostratigraphy of the hard klippen sequences, which are usually well exposed in comparison to their surroundings. Consequently, the poorly or temporarily exposed marly, shaley and deep-water clastic flysch formations may still provide significant new information about the structure of a particular PKB segment. The current work may serve as an evidence – the novel results presented below were chiefly gathered from the klippen matrix formations that helped to reconcile some, although not all, puzzling aspects of the PKB structure.

In general, two principal groups of units can be distinguished in the structure of the Pieniny Klippen

Belt. The **Oravic units** (Maheľ, 1983) may be seen as intrinsic for the PKB, they have special lithostratigraphic successions different from the CWC units and thus must have been derived from an independent palaeogeographic zone. This zone has been interpreted as an intra-oceanic continental ribbon rimmed from both sides by oceanic domains – the South Pennine Piemont–Váh and the North Pennine Valais–Rhenodanubian–Magura oceanic realms (Plašienka, 2003a, 2012a, 2018a and references therein). From the point of view of tectonic position, the PKB Oravic units correspond to the Middle Penninic units of the Western Alps, which view is supported also by some similarities in lithostratigraphy and overall age range of sedimentary units involved. However, unlike majority of the Alpine Middle Penninic units, the Oravic units are entirely detached from their basement and were deformed in a high structural position, without any signs of metamorphic transformations. These differences resulted from diversities in the Cenozoic tectonic evolution of both mountain ranges – strong collisional processes and crustal thickening in the Alps versus extension and basin formation in the Western Carpathians.

The other group of PKB units are sometimes referred to as "non-Oravic", which indicates their different composition and structural position, despite incorporated in the PKB edifice. These units mainly occur in the Middle Váh River Valley in western Slovakia, where they form a variously wide belt adjacent to the Oravic units from the south. The belt was named as the "**Peri-Klippen Zone**" by Maheľ (1980). Based on lithostratigraphic criteria, these units have been mostly affiliated with the CWC elements, namely with the Fatric nappe system (see discussion in Plašienka, 1995a, 2012a, 2019 and references therein). Hence the Manín, Klape, Drietoma and Haligovce units are regarded as frontal Fatric elements emplaced in the superposition over or juxtaposition next to the Oravic domain and then jointly deformed during the latest Cretaceous and Paleogene. The post-thrusting overstepping, but still syn-deformation, late syn-orogenic formations (Senonian–Eocene Gosau Supergroup) were deposited in dynamic wedge-top piggyback basins above the developing External Carpathian accretionary wedge (Plašienka & Soták, 2015; Kováč et al., 2016 and references therein).

During the more than hundred years of intense research, a number of tectonic units and/or sedimentary successions have been distinguished within the PKB. Owing to various criteria applied, their terminology changes from author to author (e.g. Uhlig, 1890, 1904, 1907; Andrusov, 1938, 1968, 1974; Horwitz, 1963; Stráník, 1965; Scheibner, 1968b; Sikora, 1974; Birkenmajer, 1977, 1986; Haško, 1978a, b; Nemčok, 1980; Maheľ, 1981, 1989; Marschalko, 1986; Salaj, 1994a, b, 1995, 2006; Mišík et al., 1996; Jurewicz, 2005, 2018; Aubrecht et al., 2017b; Golonka et al., 2015, 2019; Marzec et al., 2019). In the descriptions below, we are relying mainly on the eastern Slovakian PKB branch, where the tectonic relationships and lithostratigraphic content of individual units are well recognizable (Plašienka & Mikuš, 2010; Plašienka, 2012a, b; Plašienka et al., 2012). There, three principal Oravic nappe units were distinguished. From bottom to top, these are the Šariš, Subpieniny and Pieniny thrust sheets. We suppose that these units are present also in the Kysuca and Orava PKB sectors, although their stratigraphic continuity and structural relationships are by far less clear.

The lower- and outermost **Šariš Unit** (including the Kopanice, Fodorka, Brvnište, Hulina, Grajcarek, Lackovec, Kyjov and Inovce units or successions distinguished in different PKB parts by various authors) overrides or juxtaposes the most internal elements of the EWC Flysch Belt (Biele Karpaty and Magura units). It consists of diverse, mostly deep-water pelagic Jurassic to Upper Cretaceous, and clastic uppermost Cretaceous to Middle Eocene sediments (Figs 1.3, 1.20 and 2.6). In the eastern PKB branch (lithostratigraphy mainly according to description of the Grajcarek Unit by Birkenmajer, 1977; see also chapter 1.3 below), the oldest recognized member is represented by the upper Toarcian to Bajocian Szlachtowa Formation (e.g. Birkenmajer & Gedl, 2017 and references therein) – black dysoxic shales and siliciclastic turbiditic sandstones, which are typical by the various, often high content of clastic white mica flakes. The upper, probably late Bajocian part contains also layers of dark allodapic crinoidal-sandy limestones and kalkarenites, which were likely derived from the then elevated Czorsztyn Ridge. Szlachtowa Fm. is overlain and partly laterally replaced by the green-grey marly shales of the Bajocian–Bathonian Opaleniec Fm., which pass upward into dark-grey Bathonian–Callovian, Mn-bearing siliceous shales (Sokolica Fm.). Younger eupelagic formations are strongly condensed and usually only a few metres thick – red ribbon radiolarites (Czajakowa F., Oxfordian to Kimmeridgian), red nodular and cherty limestones (Czorsztyn Fm., Kimmeridgian), red marlstones and siliceous shales (lower Tithonian Palenica Member – cf. Józsa, 2019), pale-grey marly spotted limestones (Tithonian to Barremian Pieniny Limestone Formation) passing into dark-grey spotted „Fleckenmergel“ marlstones and siliceous shales (Aptian–Albian Kapuśnica or Tissalo and Wronine fms), and blackish siliceous shales and radiolarian silicites (upper Albian to Cenomanian Hulina Fm.). The Upper Cretaceous sequence is composed of the CORB-type (Cretaceous Oceanic Red Beds) non-calcareous variegated, mostly cherry-red shales with thin beds of grey-green siliciclastic sandy turbidites (Turonian–Campanian Malinowa Fm.). The terminal syn-orogenic sequence is formed by the Maastrichtian–Lower Eocene deep marine clastic deposits of the Jarmuta-Proč Fm. – calcareous sandy turbidites with mass-flow olistostrome bodies (Milpoš Breccia) containing clasts derived predominantly from the overriding Subpieniny Unit. A large part of the Czorsztyn-type klippen in Eastern Slovakia are in fact olistoliths embedded in calcareous flysch of the Proč Fm. (Plašienka & Mikuš, 2010; Plašienka et al., 2012; Plašienka, 2012a, 2018b). In places, these are overlain by the Lutetian deep-marine variegated shales with manganese nodules.

The **Subpieniny Unit** (a.k.a. Czorsztyn Unit, but we use the original terminology introduced by Uhlig, 1907 hereafter) is, due to the competence contrast between stiff blocky klippen and their soft marly matrix, a rather incoherent nappe sheet composed of numerous thrust stacks, duplexes, and imbrications. Its various lithostratigraphic successions were derived from an intra-oceanic Czorsztyn Ridge and its slopes. The most widespread Czorsztyn Succession represents a submarine, but temporarily emergent swell known as the Czorsztyn Ridge. The transitional successions, such as the Niedzica-Pruské and Czertezik, originated on edges of tilted halfgrabens and faulted slopes facing towards the adjacent Kysuca-Pieniny Basin. Lithology and stratigraphy of these successions were described in detail in numerous papers (e.g. Birkenmajer, 1977, 1986; Mišík, 1979, 1994). The Czorsztyn-type successions are characterized by Lower Jurassic to Aalenian hemipelagic spotted marls and black shales, Middle Jurassic (upper Bajocian) syn-rift, sandy-crinoidal limestones and scarp breccias (Smolegowa and Krupianka fms, Krasin Breccia – Aubrecht & Szulc, 2006), Middle–Upper Jurassic red nodular limestones of the "ammonitico rosso" facies (Czorsztyn Fm.), and various uppermost Jurassic to Lower Cretaceous shallow-marine fossiliferous limestones (e.g. the Dursztyn Fm.). The transitional Niedzica and/or Czertezik successions include also a package of Callovian–Oxfordian radiolarites amidst the nodular Czorsztyn limestones, and the Lower Cretaceous "maiolica" limestones (Pieniny Fm.). The ridge emerged during the Barremian–Aptian, which is recorded by widespread karstification and fissure filled with younger sediments (Aubrecht et al., 2006). The uneven rugged surface was then covered by variegated hemipelagic marls of the "couches rouges" facies ranging from the Albian up to the Campanian. The Subpieniny successions are terminated by the uppermost Cretaceous coarsening-upward calcareous flysch deposits (Maastrichtian–Danian? Jarmuta Fm.; Figs 1.3 and 1.20). They contain also bodies of unsorted chaotic breccias (Gregorianka Breccia – cf. Nemčok et al. 1989; Plašienka & Mikuš 2010) and Záskalie Breccia in the Orava sector – Marschalko et al., 1979) composed of material derived from the overriding Pieniny Unit (Jurassic radiolarites, Lower Cretaceous limestones, mid-Cretaceous marlstones).

The structurally highest Oravic tectonic unit of the PKB – the **Pieniny Nappe** – includes several, slightly differing lithostratigraphic successions as well (Pieniny s.s., Kysuca, Branisko, and possibly also the Podbiel-Orava and Nižná successions). It was derived from the southern foots of the Czorsztyn Ridge at the transition to the South Pennine (Piemont-Váh) oceanic domain. The Pieniny-type successions are typically composed of Lower–Middle Jurassic spotted marlstones of the "Fleckenmergel" facies and black shales, Middle–Upper Jurassic radiolarites (Czajakowa Fm.), Upper Jurassic red nodular limestones (Czorsztyn Fm.), Tithonian–Barremian maiolica-type cherty limestones (Pieniny Fm., e.g. Michalík et al., 2009), mid-Cretaceous dysoxic shales and bioturbated marlstones, Cenomanian–Turonian variegated pelagic marls, and Coniacian–Santonian deep-marine turbiditic clastics, including polymict "exotic" conglomerates (Snežnica and Sromowce fms). The Pieniny Nappe is folded and imbricated, but generally continuous. In the western PKB part, it is dominated by the basinal Kysuca Succession (Figs 1.3 and 1.20).

All Oravic successions have never been buried to considerable depths; they were affected only by diagenetic transformations at temperatures below ca 150–200°C, and distorted only by brittle deformation processes – faulting, shearing, fracturing, veining and pressure solution producing a weak cleavage in marly rocks (Plašienka, 2012b). Fossils like ammonites and bivalves, and microfossils in particular, are often very well preserved, so the stratigraphic age of the majority of sedimentary formations has been known for a long time.

In the Late Cretaceous times, the southern Oravic zones were reached and partly overridden by "non-Oravic" units of the supposed Fatric affiliation (Manín, Klape and Drietoma units in the western and the Haligovce Unit in the eastern PKB branches). The largest exposure of the Manín Unit occurs in the Middle Váh River Valley in western Slovakia (e.g. Plašienka, 2019 and references therein), the Haligovce Unit in the Pieniny Mts is considered as its analogue. The **Manín Unit** is composed of relatively shallow-water formations including Lower Jurassic cherty sandy-crinoidal limestones to sandstones, and Middle–Upper Jurassic red nodular limestones. The Lower Cretaceous strata are represented by maiolica-type pelagic limestones, marly and cherty limestones and the most conspicuous member of the Manín Unit – the Aptian to lower Albian Urgonian platform limestones (Borza et al., 1987; Michalík & Vašíček, 1987; Michalík & Soták, 1990; Rakús & Hók, 2005; Michalík et al., 2012; Fekete et al., 2017). These are overlain by a drowning-related hardground and then followed by Albian dark pelagic marls (Butkov Fm.) passing gradually into a coarsening-upward Cenomanian–Turonian turbiditic sequence with boulder beds and olistoliths (Praznov Fm., olistoliths of the Kostolec klippen; e.g. Marschalko, 1986; Plašienka et al., 2017; Plašienka, 2019 and references therein). The surface structure of the Manín Unit is dominated by the mid-Cretaceous hemipelagic and flysch formations, whereas older stiff limestones build several large "klippen", which are in fact brachyanticlines (Manín and Butkov Hills; Plašienka et al., 2018). Contrary to earlier views, the Senonian sediments in the Klape and Manín Zone have recently been interpreted as representing a post-nappe, Gosau-type cover deposited in piggyback basins (cf. Salaj, 2006; Plašienka & Soták, 2015). Presently the occur in brachysynclinal zones in the Middle Váh Valley area (Plašienka et al., 2018). The mid-Cretaceous formations of the Manín Unit are overridden by the frontal elements of the typical Fatric Krížna Nappe from the SE and are juxtaposed to the Klape Unit in the NW.

The **Klape Unit** was considered either as a part of the Vahic accretionary complex (Maheľ, 1981), marginal wildflysch complex of a laterally moving transform plate margin (Marschalko, 1986; Rakús & Marschalko, 1997), or as a diverticulation of the Fatric nappe system (Krížna Unit) of the CWC origin (Plašienka, 1995a, 2018a, 2019; Kissová et al., 2005; Prokešová et al., 2012). First of all, the Klape Unit consists of thick mid-Cretaceous (Albian–Cenomanian) wildflysch complexes with exotic conglomerates (Upohlav conglomerates, e.g. Marschalko, 1986) and klippen (olistoliths in this case – cf. Plašienka et al., 2017) of Triassic and Jurassic carbonates. The flysch complex is overlain by a shallowing-upward sequence of neritic oyster-bearing sandstones and tempestites of the late Cenomanian–Turonian age (Orlové Fm; e.g. Marschalko & Rakús, 1997). Upohlav conglomerates contain an extraordinary variety of sedimentary and magmatic pebbles derived from the inner Carpathian zones (Mišík & Sýkora, 1981; Mišík & Marschalko, 1988; Marschalko & Rakús, 1997); their sources were often placed in the completely vanished "Ultrapieninic Cordillera", later renamed as the exotic "Andrusov Ridge" (Birkenmajer, 1988). However, recently this concept was doubted by several authors (e.g. Kissová et al., 2005; Plašienka, 2012a, 2018a; Krobicki et al., 2018).

The pre-Turonian members of the **Drietoma Unit** represent probably also original parts of Fatricum. Drietoma Unit crops out in the western sectors of the PKB in the Middle Váh River Valley and in its westernmost exposures prior to being submerged below the Miocene filling of the Vienna Basin (Hók et al., 2009). It includes also Upper Triassic rocks, the Carpathian Keuper and Kössen (Fatra) fms, which are nowhere present in the PKB Oravic units. Overlying strata, such as thick Lower Jurassic Kopieniec and Allgäu fms, Upper Jurassic radiolarites and nodular limestones, as well as Lower Cretaceous cherty and biodetritic limestones are akin to the Fatric Zliechov Unit. Terrigenous turbiditic sequence, resembling the Klape or Poruba flysch deposits, is the youngest, Albian–Cenomanian member of the Drietoma Unit (Began, 1969).

Senonian to Middle Eocene sediments occurring within the Peri-Klippen zone of western Slovakia were affiliated with the **Gosau Supergroup** (Plašienka & Soták, 2015 and references therein). They are composed of alternating shallow- and deep-water, dominantly carbonate clastic formations (Fig. 1.3). Transgressive Coniacian–Santonian conglomerates containing recycled exotic pebbles in places (Rašov Fm.) are passing upwards into deep-marine "couches rouges" marlstones of the Campanian age, which are in turn succeeded by the shallowing Maastrichtian–Paleocene succession of turbiditic sandstones, marlstones, sandy bioclastic limestones and conglomerates with reef bodies. Early Eocene extensional collapse gave way to deposition of marginal clastic carbonate aprons (Súľov Fm.) replaced basin-ward by a deepening succession of the Lutetian variegated pelagic shales (Soták et al., 2017, 2019). According to the interpretation by Plašienka and Soták (2015), the Gosau strata were depositetd in the piggyback, wedge-top basins above the developing PKB accretionary wedge, and their sedimentary environments with alternating deepening and shallowing sequences were chiefly controlled by the subcritical vs. supercritical wedge taper geometry, respectively. During the late Eocene, the Gosau sediments were folded and are in part unconformably overlapped by the Upper Eocene to Lower Miocene deposits of the extensive Central Carpathian Paleogene Basin (e.g. Soták et al., 2001; Kováč et al., 2016 and references therein).

1.3 Lithostratigraphy of the Oravic units

1.3 Lithostratigraphy of the Oravic units

This chapter, compiled by R. Aubrecht, provides a review and some details about the Mesozoic litho-biostratigraphy and sedimentary environments of the PKB Oravic units. The division applied follows the traditional views, in which a tectonic independence is ascribed to each unit with a characteristic succession of sedimentary formations. Also the names of lithostratigraphic units are used in the original forms introduced by Birkenmajer (1977; e.g. the Czorsztyn limestone Formation), while in the rest of the text we use abridged forms (Czorsztyn Fm.).

1.3.1 Czorsztyn (Subpieniny) Unit

The Czorsztyn Unit (Fig. 1.20) was the shallowest one of all the PKB units and its sedimentary record is spatially and temporally most variable (Aubrecht et al., 1997, 2017b). In a majority of klippen, the Middle Jurassic to Lower Cretaceous part of Czorsztyn Unit is preserved. Lower Jurassic sediments were often detached and are preserved only at several localities, e.g. Dolný Mlyn, Beňatina, Novoselitsya and Priborzhavskoe (Rakús, 1995; Krobicki et al., 2003; Schlögl et al., 2004; Wierzbowski et al., 2012). The lithostratigraphic record of the Czorsztyn Succession starts with black to dark-grey clayey limestones to shales with fauna of ammonites, oysters, and spiriferinid brachiopods of the Sinemurian age (Dolný Mlyn Formation). It is followed by spotted limestones to marlstones (typical "Fleckenkalk/Fleckenmergel" facies) of the Allgäu Formation (late Sinemurian – late Pliensbachian). Toarcian to Aalenian stages are mostly represented by black-shale facies of the Skrzypny Shale Formation (lithostratigraphic terminology mainly after Birkenmajer, 1977), but locally also red varieties may occur (e.g. the Hŕbok Formation at the Beňatina locality – Schlögl et al., 2004), or by condensed sandy limestones with ferruginous stromatolites and rich ammonite fauna (uppermost Pliensbachian–Aalenian deposits in the Priborzhavskoe quarry in Transcarpathian Ukraine – Wierzbowski et al., 2012). From the Bajocian (or latest Aalenian) onward, the lithostratigraphic units are much better preserved, occurring at many places all along the Pieniny Klippen Belt. Bajocian stage was characterized by rising of the Czorsztyn Ridge (Krobicki & Wierzbowski, 2004; Krobicki, 2009; Barski et al., 2012; Segit et al., 2015) due to Mid-Jurassic rifting and block tilting. Shallowing of the sedimentary area was indicated by local coral bioherms (Vršatec Limestone – Ivanova et al., 2019) that occur solely in the western part of the Pieniny Klippen Belt (Middle Váh Valley), but at most places it is manifested by presence of crinoidal limestones of white to reddish colours (Smolegowa and Krupianka limestone formations, respectively). The crinoidal limestones locally bear signs of synsedimentary tectonics related to rifting, such as cliff breccias (Krasín Breccia – Mišík et al., 1994a; Aubrecht, 1997a, 2001a; Aubrecht & Szulc, 2006) and neptunian dykes (Aubrecht & Túnyi, 2001). Since the latest Bajocian, deepening due to the global sea-level rise and post-rift thermal subsidence occurred in the Oravic sedimentary area. This was manifested in the Czorsztyn Succession by the Ammonitico Rosso-type sediments (red nodular limestones – Czorsztyn Limestone Formation), deposition of which lasted until the Early Tithonian. In the Middle Váh Valley, but also at some localities in the east, micritic, non-nodular variety of these limestones occurs (Bohunice Limestone Formation – Mišík et al., 1994b). Lack of nodularity in these limestones was partly caused by the fact that they represent mud-mound deposits, often with stromatactis structures (Aubrecht et al., 2002, 2009).

In the Tithonian and in places up to Berriasian, the condensed, nodular facies all along the Czorsztyn Ridge gave way to completely non-nodular facies represented by the Dursztyn Limestone Formation, comprising biomicritic Calpionella limestones (Sobótka Limestone Member), ammonite coquinas, or bivalvian-brachiopod coquinas (Rogoźnik and Rogoża coquinas, respectively). The Lower Cretaceous deposition (Berriasian to Valanginian) is characterized by bioclastic Calpionella-bearing limestones of the Łysa Limestone Formation, overlain by the Valanginian crinoidal limestones of the Spisz Limestone Formation (Krobicki, 1996; Krobicki & Wierzbowski, 1996). Locally, intraclastic limestone breccias with fragments of Tithonian–Berriasian Calpionella limestones (Walentowa Breccia Member; Birkenmajer, 1977) occur in the Valanginian. Along with the rift-related alkaline basaltic volcanism (Ukrainian Velykyi Kamianets section; cf. Oszczypko et al., 2012a), they indicate an important rifting event, possibly connected with opening of the Valais–Rhenodanubian–Magura branch of the Alpine Atlantic (North Penninic) Ocean (Plašienka, 2003a). After the Valanginian, the limestone deposition terminated, followed by a hiatus encompassing the entire Hauterivian, Barremian and almost entire Aptian. The hiatus was caused by a large-scale emersion of most of the Oravic domain, reaching up to the margins of the Kysuca-Pieniny Basin (Aubrecht et al., 2006; Józsa & Aubrecht, 2008). After hiatus, deposition of red marls (Couches Rouges or Scaglia Rosa-type sediment) of the Chmielowa Formation (latest Aptian–Albian) started. In the Cenomanian, siliceous deposition temporarily occurred in form of the Pomiedznik Formation with radiolarite intercalations. Then, the deposition in form of variegated Globotruncana marls ("Púchov marls", Jaworki Fm.) followed by flysch-type deposits of the Sromowce Formation lasted until the very end of Mesozoic, when the Laramian collision of the Oravic domain with the CWC occurred, terminated by synorogenic to early post-orogenic coarse clastics of the Jarmuta Formation (Fig. 1.20).

Occurrences of the Czorsztyn Unit in the Kysuce and Orava parts of the PKB are relatively rare. Some even do not appear in recent maps, e.g. a nice klippe with Czorsztyn Limestone rich in ammonites at the northwestern end of the Dlžniansky Cickov Valley at the contact with the Flysch Belt. Very interesting is a klippe north of Zázrivá, which also was not registered in earlier maps. It contains a perfectly preserved paleokarst surface that originated during the Hauterivian-Albian emersion (Jamrichová et al., 2012). Some klippen mapped by Haško and Polák (1978) as belonging to the Czertezik Unit (Haško, 1976) are in fact Czorsztyn Unit klippen, e.g. a klippe at the northern end of the Istebné Valley. There is also an interesting occurrence of the Czorsztyn Unit in Revišné village, where it is in a tectonic contact with the succession which was interpreted as belonging to the Grajcarek (Šariš) Unit. The Middle Jurassic crinoidal limestones here contain also the Krasín Breccia, which is its first-found occurrence outside the Middle Váh Valley (Molčan Matejová et al., 2019). This klippe also does not occur in the older map of Gross et al. (1993).

1.3.2 Kysuca (Pieniny) Unit

The most deep-water Oravic units, Kysuce and Pieniny units, have very similar development and, therefore, they use to be presented under the common name Kysuca-Pieniny Unit (Kysuca Unit is named Branisko Unit in Poland). Sediments of this unit represent filling of a basin situated originally south of the Czorsztyn Ridge. It was still underlain by a continental crust, although considerably attenuated.

Lower Jurassic formations of the Kysuca-Pieniny Unit are always detached from the rest of the Jurassic sediments. Therefore, attribution of the Lower Jurassic sediments is often problematic. Moreover, it is also biased by the earlier redefinitions of this unit, because formerly also the Drietoma, or Orava units were considered to be just special developments of the Kysuca-Pieniny Unit. There is no continuous section with an untectonized contact between the Lower and Middle Jurassic sediments of this unit.

The Sinemurian, so-called Gresten Beds (sandstones, arkosic sandstones to quartzites) have been considered as the oldest Jurassic sediments of the Kysuca-Pieniny Unit (e.g. Andrusov, 1931a). They can be found in the Orava territory, e.g. in the Jedľovinka klippe near Zázrivá (see chapter 2.1.4 below), or Krásna Hôrka klippe near Tvrdošín. The Gresten Beds are followed by spotted marly limestones (Allgäu Formation) which reach up to the Aalenian.

The Middle and Upper Jurassic part of the Kysuca-Pieniny Unit (Fig. 1.20) starts with Aalenian–Bajocian grey to black shales of the Harcygrund Formation (former "Posidonia" beds), with common presence of thin-shelled bivalves *Bositra buchi*. So-called Zázrivá beds, which were originally defined as being of Sinemurian age (Haško & Planderová, 1977) most likely belong also to the Harcygrund Formation, or to similar Skrzypny Formation, as evidenced by findings of Bositra shells and an ammonite *Grammoceras* sp. (Aubrecht et al., 2004). Black-shale sedimentation was still identical in all the Oravic units, because the sedimentary area was still not dissected by the Czorsztyn Ridge. However, unlike in the Czorsztyn Unit, deep-sea spotted limestones and spongolites (Podzamcze Limestone – formerly known as "Supra-Posidonia" Beds) were sedimented in the Bajocian and Bathonian. Crinoidal limestones, which are typical for the Czorsztyn sedimentary area, can be found in the Kysuca-Pieniny Unit only in form of distal calciturbidites (Flaki Limestone). Callovian and Oxfordian is represented by the Czajakowa Radiolarite Formation, which is the deepest marine sediment of the Oravic domain. The lower part is usually greenish, whereas the upper part is red. Their origin is related to the global sea-level rise, accompanied by elevated CCD all over the Tethys. Similar radiolarite formations occur in all the basin areas of the Western Carpathians, but they are best developed in the Kysuca-Pieniny Unit. The Kimmeridgian time was then characterized by a sea-level drop and the CCD level decreased also. While in the Pieniny Unit, there was still a radiolarite deposition, in the Kysuca Unit it has turned to deposition of the Ammonitico Rosso facies (Czorsztyn Limestone), which is thinner

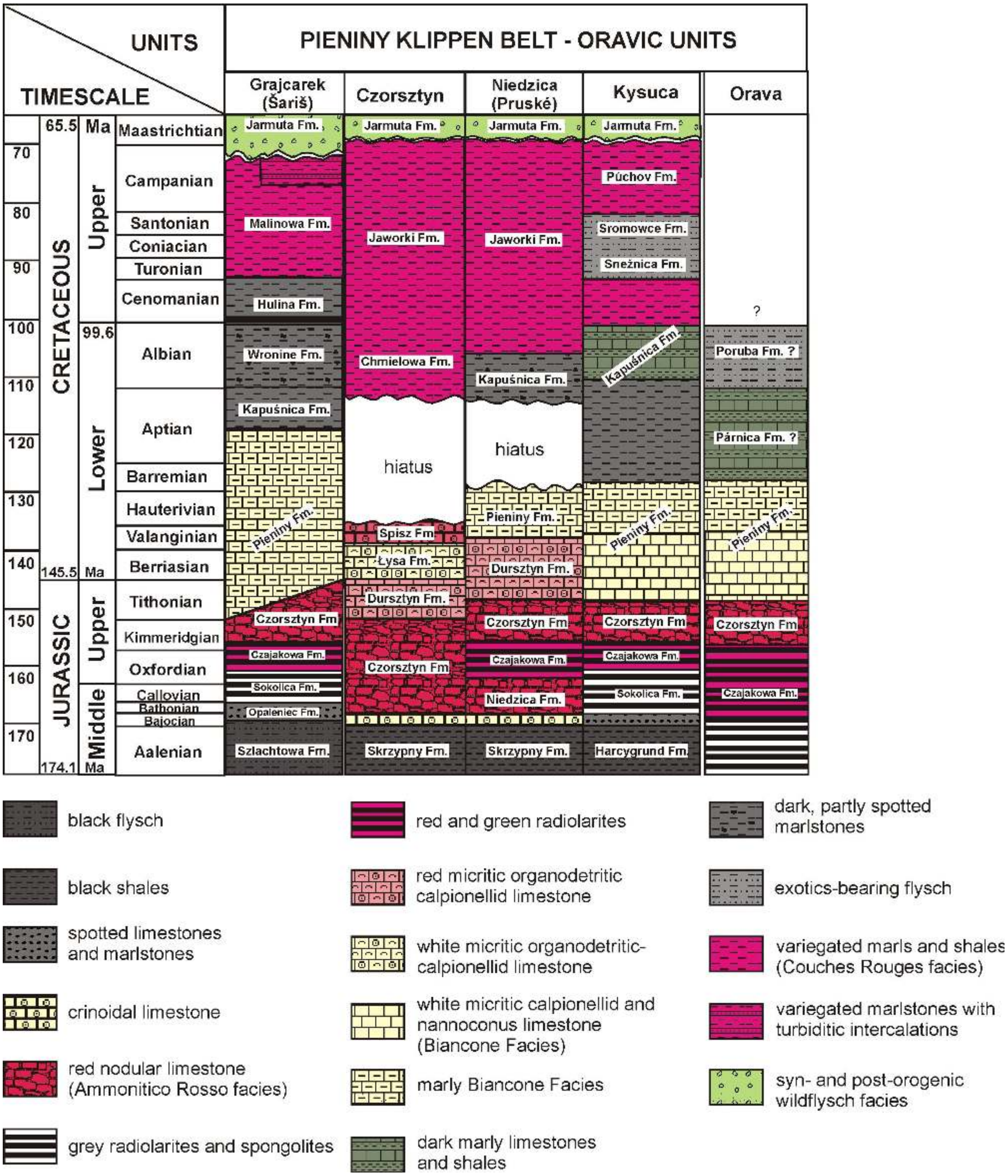


Figure 1.20 Outline of the lithostratigraphy of the Oravic units (R. Aubrecht).

than in the Czorsztyn Unit, where it covers the whole period from the uppermost Bajocian to Tithonian. From the Tithonian to Early Barremian onward, white, cherty Calpionella and Nannoconus limestones were deposited (Biancone, or Maiolica facies). This lithostratigraphic unit is called Pieniny Formation. Since the Barremian, the carbonate sedimentation gradually turns to marly and clayey ones. The Barremian–Aptian is represented by black shales of the Koňhora Formation and Albian to early Cenomanian by the Tissalo Formation. These are bluish-grey to greenish, often spotted marlstones with beds of greenish limestones. Red-coloured marls and marlstones are typical for Middle and Upper Cenomanian (Lalinok Formation). Early to Middle Turonian is represented by the Kysuca Formation consisting of red shaly marlstones intercalated by fine-grained sandstones. During the Turonian, the first massive input of sandy siliciclastics occurred, in form of turbidites (Snežnica Fm.). During the Coniacian and Santonian, the detritus became coarser, represented by exotic conglomerates (Sromowce Formation). They are very similar to the Albian Upohlav Conglomerates of the Klape Unit. It is obvious that in this time the Kysuca and Klape units were close to each other. The Sromowce Formation is overlain by red Púchov Marls. Then a hiatus occurred due to tectonic collision with the Carpathian internides. The Kysuca Unit, which was the innermost Oravic unit, was the first one which was affected by this collision. The largest klippen of the Pieniny Unit occur in the Pieniny Mts. (Trzy Korony, Dunajec Gorge). The Kysuca Unit is best outcropped in the Rudina and Brodno klippen north of Žilina.

Jurassic development of the Kysuca-Pieniny Unit is very similar to the Nižná Unit defined in the Orava territory. Therefore, the Nižná unit is considered to be a subunit of the Kysuca-Pieniny Unit (Scheibner, 1967). It differs only by presence of the Barremian–Aptian shallow-water, Urgonian-type limestones (Nižná Formation; cf. Józsa & Aubrecht, 2008).

The Kysuca-Pieniny Unit is one of the most widespread Oravic units in the Kysuce and Orava territories. However, the succession of the unit is strongly dissected. Therefore, it is formed by separated Lower Jurassic klippen, detached from the Middle Jurassic along the Toarcian–Aalenian black shales, as well as Middle Jurassic to Lower Cretaceous silicites and limestones are often detached from the Senonian flysch successions along the Barremian to Albian marlstones. For instance, along the Orava River, there is almost continuous belt of exotics-bearing Senonian flysches, but their attribution to the Kysuca-Pieniny Unit is unclear. Only in the well-exposed section near Zemianska Dedina it was able to attribute the exotics to the Nižná Unit (Starek et al., 2010). Equally problematic is attribution of the zone with exotic flysch occurring in the overturned position from the Pupov Hill as far as Pálenica near Zázrivá. This zone was interpreted as belonging to the Manín Unit by Haško & Polák (1979). However, this was before the redefinition of the unit. Nowadays, this flysch could be attributed either to the Klape Unit, or to the Kysuca Unit. The latter is more likely, because the Santonian flysch is in stratigraphic contact with Campanian variegated marls, which is the situation which appears also at the Kysuca Unit type locality (for an alternative view see chapter 2.2).

1.3.3 Grajcarek (Šariš) Unit

The northern analog of the Kysuca-Pieniny Unit, originally deposited north of the Czorsztyn Ridge, has been defined by under the name Grajcarek Unit (Birkenmajer, 1977; Birkenmajer & Gedl, 2017). Later on, its lithostratigraphy was augmented up to Paleogene and the unit was renamed as the Šariš Unit (Plašienka & Mikuš, 2010). The unit has a similar Jurassic–Lower Cretaceous facies succession with some small differences, e.g. flysch development in the Aalenian (Szlachtowa Formation) and very condensed Maiolica facies (Pieniny Limestone). Presence of the Albian radiolarites (Groń Radiolarites – Birkenmajer, 1977) was not confirmed later and cannot be considered as a difference with respect to the Kysuca-Pieniny Unit. The Šariš Unit was presumably situated north of the Czorsztyn Ridge, in the area of the future Magura Basin of the Flysch Belt (Fig. 1.20). Distinguishing of this unit is logical, however the small differences still do not enable to prove, whether it was deposited south or north of the Czorsztyn elevation. A klippe in the stratigraphic range from Kimmeridgian to Albian, interpreted as belonging to the Grajcarek (Šariš) Unit, was recently reported from Revišné village (Molčan Matejová et al., 2019). Some flysch deposits dated by dinoflagellates to Aalenian were found below the Jedľovinka Hill near Zázrivá. They can represent the Szlachtowa Formation and as such attributed to the Grajcarek (Šariš) unit (see chapter 2.1.4 below).

According to Birkenmajer (1977, 1986), the folded PKB units were unconformably overlain by the Maastrichtian Jarmuta Formation consisting of hemipelagic marls and mudstones with turbiditic sandstone beds (Orbitoids-bearing in places), conglomerates and breccias. However, this interpretation has been questioned recently since the Jarmuta and/or the Proč formations appear to be in a normal stratigraphic succession of the Pieniny and/or the Šariš units, respectively (Jurewicz, 2005, 2018; Plašienka & Mikuš, 2010; Plašienka, 2012a, b; Plašienka et al., 2012; Plašienka et al., 2020 – supplement). According to these authors, coarse-grained sandstones and breccias containing the klippen material do not represent transgressive sediments, but olistostrome bodies emplaced within the Maastrichtian (Jarmuta Fm. in the Subpieniny Unit) and Maastrichtian–Eocene (Jarmuta-Proč Fm. in the Šariš Unit) deep-marine calcareous flysch deposits.

1.3.4 Other Oravic units

Between the Czorsztyn Ridge and the Kysuca-Pieniny Basin, a sedimentary area of so-called transitional units (Czertezik, Niedzica and Pruské) occurred. These units include formations deposited in both the shallow- and deep-water, especially Middle Jurassic environments. According to the first description of Birkenmajer (1959), the Czajakowa radiolarites should rest directly on the crinoidal limestones of the Smolegowa and Krupianka formations in the Czertezik Unit. Later it was presented that at all localities, at least a thin layer of red nodular limestones and claystones is present (Wierzbowski et al., 2004), which puts distinguishing of the Czertezik Unit in doubt. It can then be ranked either to the Niedzica, or to the Pruské Unit. In the Niedzica Unit, the crinoidal limestones are thick and massive, like in the Czorsztyn Unit. On the other hand, they occur in form of crinoidal calciturbidites (Samášky Formation; Aubrecht & Ožvoldová, 1994) in the Pruské Unit. In both successions, the formation of red nodular limestones is divided by the Czajakowa radiolarites to two separate formations: the lower – Niedzica and the upper – Czorsztyn formations (Fig. 1.21).

From the transitional units, only the Czertezik Unit was reported from the Kysuce/Orava territory in the vicinity of Zázrivá (Haško, 1976). However, closer inspection shows that only the occurrence near Zázrivá-Plešivá contains some sort of red silicites, but in unknown position with respect to the crinoidal and nodular limestones. The rest are klippen of the Czorsztyn Unit.

Haško (1977, 1978a) unified the former Podbiel development and Orava Castle development defined by Andrusov (1938), as well as the klippen of Havranský vrch and Kozinec near Zázrivá (characterized as the local Kozinec Unit in chapter 2.1.1) into the single Orava Unit. All these klippen are situated in the Orava territory, but one klippe of the Orava Unit was also found in the Middle Váh Valley (Schlögl et al., 2001). The Orava Unit is characterized by an uninterrupted succession from Lower Jurassic to Lower Cretaceous. The unit belongs to the deep-marine units, but it does not contain Toarcian/Aalenian black shales. Lack of this shaly horizon caused rheological continuity of the klippen, where the Lower Jurassic part is not detached from the Middle Jurassic one. The oldest preserved sediments are Lotharingian spotted limestones and marlstones with ammonites *Echioceras raricostatum* (Allgäu Formation). They are overlain by grey to greenish limestones to siliceous limestones with *Uptonia jamesoni* (Kozinec Formation – Pliensbachian). The Toarcian is represented by red nodular limestone (Adnet Formation). Then follows a relatively thick formation of siliceous limestones to radiolarites (Aalenian?–Oxfordian). In the Kimmeridgian, red nodular limestone appears again (Czorsztyn Formation). Tithonian to Hauterivian are represented by the Biancone (Maiolica) facies, i.e. white Calpionella to Nannoconus limestones without cherts. They pass to the Barremian–Aptian grey marly limestones and marlstones. The stratigraphically highest lithostratigraphic unit is the Albian flysch occurring only in the very bottom of the valley between the Havranský vrch and Kozinec hills (in the tectonically overturned position). This flysch was originally considered by Haško (1978a) as belonging to some other unit which is in tectonic contact with the Orava Unit. However, closer inspection revealed no tectonic contact, but a gradual transition to the stratigraphically underlying marlstones. Presence of the Albian flysch would be atypical for the Oravic units, however. Therefore, Maheľ (1989) considered the Orava Unit as one of the Fatric units incorporated in the PKB structure.

1.4 The Flysch Belt of the Kysuce–Orava region

The outer northern margin of the PKB adjoins the innermost elements of the OWC Flysch Belt formed by the Magura Nappe (a.k.a. Magura Superunit, Magura thrust system). In general, the **Magura Nappe** is subdivided into five tectonic-lithofacial units: the Biele Karpaty, Krynica, Bystrica, Rača and Siary units from the inner to the outer zones. The B**iele Karpaty Unit** is restricted to the south-westernmost part of the Carpathian Flysch Belt, where it continues southwestward into substratum of the Neogene Vienna basin and after that it is linked with the Rhenodanubian Flysch Belt of the Eastern Alps (e.g. Potfaj, 1993). The **Krynica Unit** (a.k.a. Oravská Magura Unit) appears for the first time in the area north of Žilina in fragments that follow the northern PKB margin eastward (Potfaj et al., 2003). From the area north of Zázrivá, approximately from the place where the Ráztoky Fault meets the northern PKB boundary (Fig. 1.16), it considerably widens eastward to form a wide belt that extents to Poland and then up to the Slovakian–Ukrainian border. Between the Biele Karpaty and Krynica units as two innermost Magura

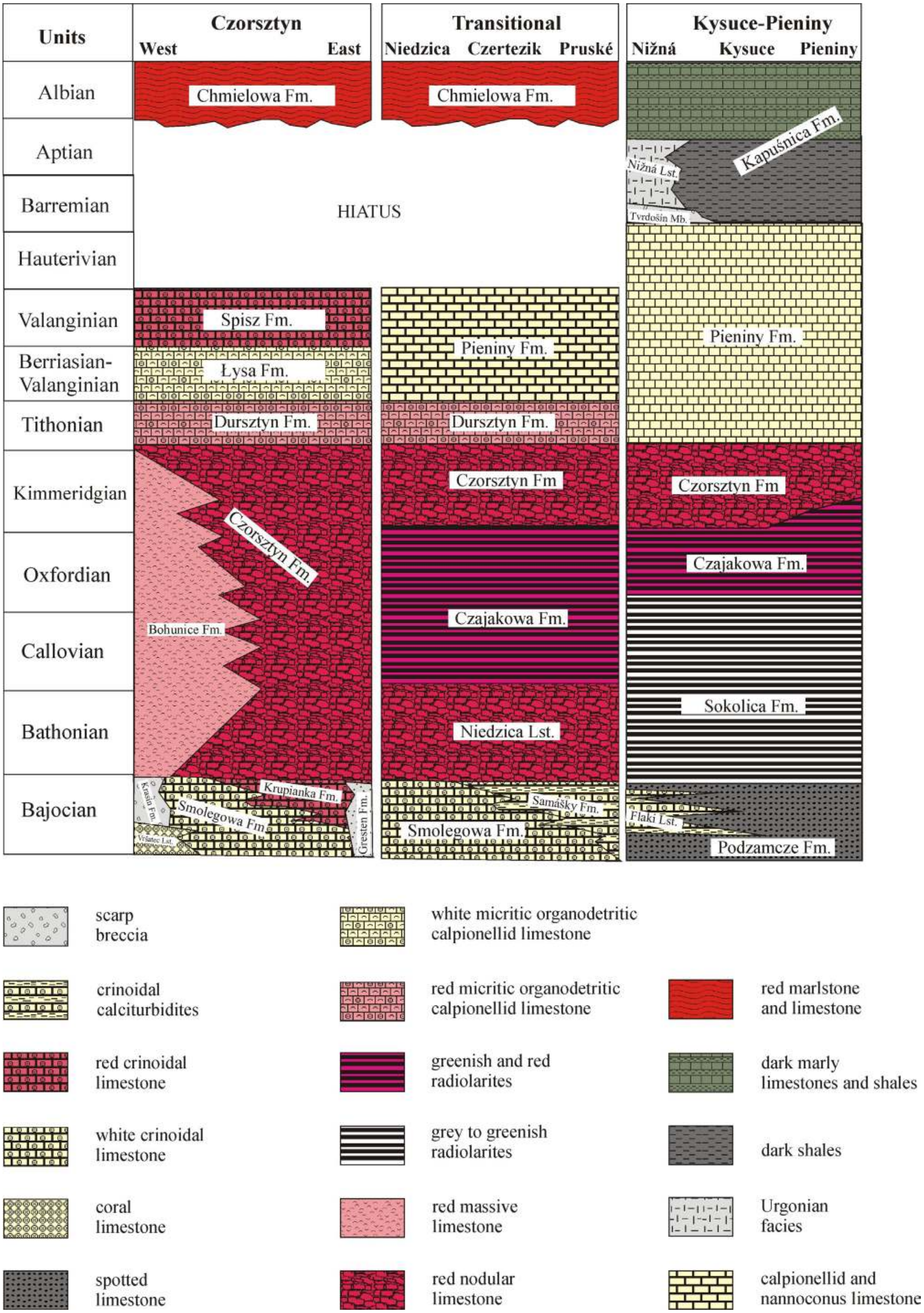


Figure 1.21 Zoomed lithostratigraphy of the Middle Jurassic to Lower Cretaceous formations of the Oravic units – transition from the swell-type Czorsztyn to basinal Kysuca-Pieniny successions.

elements, the more external **Bystrica Unit** is in a direct contact with the Varín PKB segment. Whereas bedding in the Krynica Unit and in the southern part of the Bystrica Unit adjacent to the PKB are steeply north-dipping and indicate their backward tilting and backthrusting together with the PKB units, farther to the north the bedding inclination changes from subvertical to moderately up to flatly south-dipping. Hence it forms an asymmetric fan with the centre located along the contact zone of the Bystrica and Rača units (Potfaj et al., 2003; Pešková et al., 2012).

Recently, the Magura units in the region north and north-east of Zázrivá were thoroughly studied and described by Teťák et al. (2019). For details of their structure, lithology, depositional systems and palaeogeography the reader is advised to this work and references therein.

2 Litho-biostratigraphy and structure of the PKB sedimentary successions in the transitional Kysuce – Orava region

According to the geomorphological division of the Slovak Western Carpathians (Kočický & Ivanič, 2011), the PKB in the eastern part of the area under consideration belongs to the Kysucká vrchovina Mts (district Kysuce klippen) and the eastern part belongs to the Oravská vrchovina Mts. Both areas are allied to the Stredné Beskydy mountainous region. Geological maps were published by Andrusov (1931a, 1938), Haško and Polák (1978) and Gross et al. (1993), online version compiled by various authors is available on the web page http://apl.geology.sk/gm50js.

In addition to literature sources quoted below, this chapter was elaborated on the basis of structural and geological field mapping (D. Plašienka, except of the Istebné and Kubín zones compiled by M. Molčan Matejová, R. Aubrecht and D. Plašienka; see Fig. 2.1), and extensive biostratigraphical and sedimentological data gathered at numerous outcrops and sections (P. Gedl – dinoflagellate cysts; Š. Józsa – foraminifers; J. Soták – foraminifers, sedimentology; J. Schlögl – ammonites; G. Suan – lithology and geochemistry; R. Aubrecht – lithology, biofacies, heavy minerals; E. Halásová and M. Jamrich – nannoplankton). Detailed fieldworks were performed also by M. Sýkora, F. Marko, J. Bučová, P. Gaži, T. Potočný and assisted by numerous students during the field mapping courses having taken place in the Zázrivá area.

The original nappe structure of the PKB in the area concerned is strongly modified up to totally obliterated by the post-nappe out-of-sequence and backward thrusting and transpressional disintegration. As a result, only fragments of sedimentary successions of different units are preserved, often in a strange position. Therefore, we describe the PKB structure in this chapter not in terms of individual nappe units or lithostratigraphic successions characterized above, but following the certain PKB parts or zones distinguished based on some common characteristics concerning the composition and structural pattern.

The PKB of the eastern part of the Varín (Kysuce) sector is about 3 to 5 km wide and is distinctly fault-bounded (Fig. 1.16). The northern W–E trending boundary juxtaposes the PKB against the Magura units of the Flysch Belt – the Bystrica Unit and in the eastern part also the Krynica (Oravská Magura) Unit of the Magura nappe system (Haško & Polák, 1978, 1979; Potfaj et al., 2002, 2003). The southern, WSW–ENE to W–E trending PKB margin is followed by imbricated lenses of the “Peri-Klippen Paleogene” (Gosau-type, Paleocene–Middle Eocene Myjava-Hričov Group). In the Zázrivá area and further eastward, the PKB units are in a direct contact with the deformed Upper Eocene–Oligocene deposits of the CCPB. This PKB part is dominated by the highest mountain of the entire PKB – Pupov Hill (1,096 m a.s.l.) built by Senonian marls and calcareous turbiditic sandstones correlated with the Klape Unit (Pupov Beds – e.g. Haško & Polák, 1979; Potfaj et al., 2003).

The PKB in the Orava and Kysuce region was mapped in detail already in 1930-ies by Andrusov (1931a, 1938) and later by Haško & Polák (1978). While the Andrusov´s map is strictly stratigraphic without any tectonic interpretations, the latter authors distinguished the Klippen Belt units, namely the Kysuca and Orava, which are overlain by the Manín Nappe (nowadays affiliated with the Klape Unit) in the Kysuce sector. The Orava sector of the PKB was for the last time mapped and published in the monograph by Gross et al. (1993).

The area between villages Terchová and Zázrivá belongs to the eastern part of the W–E oriented Varín sector of the PKB, which is through the N–S trending Zázrivá–Párnica “sigmoid” connected with the western part of the SW–NE stretching Orava sector (Scheibner, 1968b). Despite the almost a century lasting geological investigations, the structure of this PKB part is poorly known. The main reason is the extraordinary complicated structure, fragmentarily preserved lithostratigraphic successions, uncertain age and tectonic affiliation of some formations, poor outcrop conditions especially in soft marly and flysch rock complexes, which are moreover affected by slope movements and landslides in many places (as one of the geological Murphy´s laws says, always in the key locations). Hence to attain new data, we have performed detailed geological mapping, structural analysis, sedimentological and biostratigraphic investigations of the PKB formations in this area. In this chapter, we present our new sedimentologic-stratigraphic data according to the regional distribution of the key localities and sections (Fig. 2.1). The biostratigraphic and palaeoenvironmental studies concerned mainly foraminifers and organic-walled dinoflagellates in various, mostly shaley and marly sediments.

We have differentiated three sub-parallel, fault-bounded zones within the eastern Varín sector of the PKB (Fig. 2.1). This area was almost identically subdivided into zones by Andrusov (1931b, 1938, 1968). Each of these zones has a specific composition and structural style: (1) in the N and NE, it is the complexly imbricated Havrania Zone, which is composed of several PKB units juxtaposed to the Magura units of the Flysch Belt; (2) the wide, but eastward wedging-out Pupov Zone composed dominantly of very thick calcareous turbidites of the Pupov Fm.; (3) the southern, comparatively narrow but tightly imbricated Plešivá Zone that juxtaposes deformed Paleogene deposits of the CCPB. Afterwards, we shall briefly characterize the N–S trending zone of the Zázrivá–Párnica sigmoid (4 – Istebné Zone) and the westernmost part of the Orava sector of the PKB (5 – Kubín Zone).

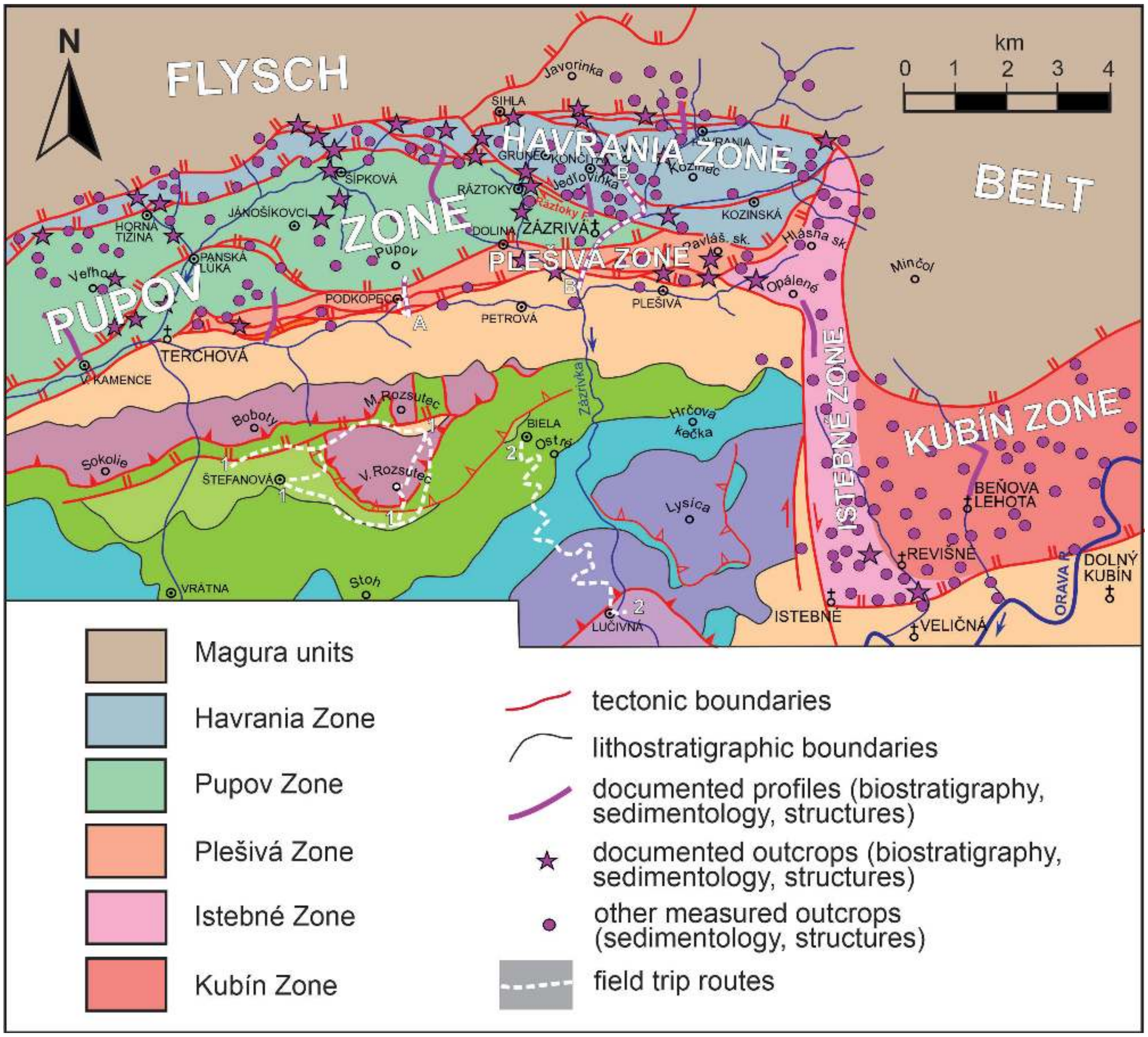


Figure 2.1 Index map of distribution of investigated outcrops and sections with sketched boundaries of the particular PKB zones described in the text.

All these structural zones are bounded by important regional faults. The northern limit of the Havrania Zone against the Magura units is formed by the generally W–E trending discrete boundary named the Rudina Fault by Andrusov (1974). The fault is probably subvertical or steeply N-dipping. Its kinematic character is not known, most probably it is, similarly as in the more western area north of Žilina

(Plašienka et al., 2020), originally thrust fault of Oravic units over the Magura elements, which was later back-tilted up to overturned and reactivated as an oblique-dextral backthrust. The Rudina Fault represents one of the most important and conspicuous structure of the Western Carpathians, since it separates two principal regional tectonic elements – the PKB with its intricate fold-thrust-wrench structure, and the comparatively simpler fold-thrust structure of the Flysch Belt. As such, it represents an interface of rock complexes with contrasting composition, diverse structural record and extensive shortening. Similar, but less pronounced character has also the southern fault of the Havrania Zone boundary against the Pupov Zone, which parallels the Rudina Fault in the western part. In the eastern part of the area, these two zones are separated by a straight, vertical, WNW–ESE trending fault that is clearly a dextral strike-slip, which separates the Havrania zone from both the Pupov and Plešivá zones. We name it as the Ráztoky Fault (Fig. 1.16). The southern PKB (Plešivá Zone) limit is provided by the W–E trending Bytča–Žilina Fault, which brings into contact various PKB units with the Paleogene sediments. Structural studies have documented that the Bytča–Žilina Fault is a steep, N-dipping oblique-slip dextral reverse fault (Marko et al., 2005; Plašienka et al., 2020). The northern boundary of the Plešivá Zone versus the Pupov and Havrania zones is equally north-dipping.

2.1 Havrania Zone

The Havrania Zone is named after settlement Havrania NE of Zázrivá village and Havranský vrch Hill. It occupies a narrow northern strip of PKB, but widens eastward where it embraces almost the whole PKB. The zone is dominated by the Kozinec (996 m a.s.l.) and Havranský vrch (941 m a.s.l.) hills in the eastern part, while the northern zone westward runs across the N–S oriented alternation of ridges and valleys, the highest peak being Podkýčera Hill NW of Zázrivá (1,008 m a.s.l.). Further west, out of the map shown in Figure 1.16, the Havrania Zone can be traced as far as Zlieň Hill north of village Lysica, i.e. the entire zone is about 20 km long, but only some 1 km wide in the northern and up to 3 km in the widened eastern part (Fig. 2.1).

2.1.1 Kozinec Unit

The largest part of the Havrania Zone, especially in its eastern widened part, is formed by a specific Jurassic–Cretaceous sedimentary succession, known as the Orava Series (Haško, 1978a, b). This author correlated the Orava Succession with the klippe Červený kameň near the Podbiel village and with the Orava castle klippe near Oravský Podzámok village, both in the Orava PKB sector. Particularities of these successions were known already to Andrusov (1931a, b), but he did not unite them into a single development or unit. Instead, he correlated the "large Zázrivá klippe" with the Kysuca Series (i.e. Pieniny Unit). The Orava sedimentary succession differs from other PKB Oravic units in several aspects (see above) and shows also some degree of structural independence, therefore it is designated as the local Kozinec Unit in the following text (see also Maheľ, 1989). Comparatively large exposures of the **Kozinec Unit** occur in the eastern part of the Havrania Zone (Podkýčera and Havranský vrch hills, ridge Kozinec–Hoľa; Fig. 1.16).

The overturned sedimentary succession of the Kozinec Unit includes (Haško, 1975, 1977, 1978a): hemipelagic grey spotted marly limestones of the "Fleckenmergel" facies (Sinemurian–Pliensbachian); distinctive greenish-grey marly limestones with Pliensbachian macrofossils (Kozinec beds); "lower" red nodular limestones (Toarcian); siliceous limestones and radiolarites (Middle Jurassic–Oxfordian); "upper" red nodular limestones (Kimmeridgian); Calpionella-bearing limestones (Tithonian–Berriasian); marly spotted limestones (Valanginian–Barremian). Turbiditic sequence occurring in the lowermost structural position in bedrock of the Havranský potok stream has a problematic position. Haško and Polák (1979) interpreted it as the tectonic window of the mid-Cretaceous rocks (Pupov Fm.) of the Klape Unit, but it might belong also to the Kozinec Unit as its youngest member in the overturned succession. Our samples provided only indistinct agglutinated foraminifers of the Albian–Santonian age. Possibly the same flysch sequence (without outcrops) occurs around Hoľa Hill east of Kozinec, where it contains also a body of polymict conglomerates. Similar conglomerates were found in debris on the NE slopes of the Jedľovinka–Končitá ridge and at foots of Podkýčera Hill (Pod Rohom hamlet). They contain pebbles of various limestones of Triassic to Early Cretaceous age, dolomites, sandstones, quartz and rarely also volcanic rocks and bioclasts of red algae.

The tectonic affiliation of the Kozinec Unit is problematic. Its lithostratigraphical content – the

Orava Succession – has been considered as a special, but integral constituent of the PKB in tectonic terms. On the other hand, Maheľ (1989) correlated this unit with the Drietoma Unit of the western PKB branch, which he considered to be an element of the CWC origin incorporated into the PKB as a transpressional coulisse. The large Havranský vrch – Kozinec klippe appears to be an independent structure – a complex nappe outlier in the highest structural position in the Havrania Zone. In contrast to other, fragmentary and strongly imbricated rock complexes of the Havrania Zone, the mostly overturned sedimentary succession of the Kozinec Unit is less disturbed and largely complete. However, the tectonic interpretation of the fold macrostructure of the Kozinec Unit differs from author to author – Andrusov (1938) interpreted an overturned, northward plunging anticline, Haško (1977) and Haško and Polák (1979) described it as a false, south-vergent asymmetric anticline. Accordingly, the window of mid-Cretaceous flysch in the core of the anticline, which should belong to the Manín (Klape) Unit according to Haško (1977), was originally overlying the Kozinec Unit, then both were overtuned together and affected by south-verging macroscopic folding. This is a geometrically perplexing construction, which cannot be restored. In our opinion, the mid-Cretaceous flysch is a stratigraphic constituent of the Kozinec Succession and occurs in the core of a tight syncline with moderately north-dipping axial plane, i.e. the overlying Cretaceous– Jurassic sequence represents the overtuned limb of the syncline which originated during overall backtilting and backthrusting of all PKB units in this area (Figs 1.16 and 1.17b).

Besides the Kozinec Unit, the other sedimentary formations of the Havrania Zone most probably belong to the three principal Oravic units of the PKB. However, their assignment to a particular unit or succession is sometimes ambiguous, especially in the case of the Pieniny versus the Šariš units.

2.1.2 Subpieniny Unit

The **Subpieniny Unit** (Czorsztyn and Niedzica successions) occurs in several tiny slices along the northern boundary of the PKB, usually in contact with the Magura units. In the western part of the area depicted in Figure 1.16, typical Czorsztyn-type klippen (Middle–Upper Jurassic sandy-crinoidal and nodular limestones embedded in Upper Cretaceous variegated marlstones) appear for the first time north of Terchová settlement Marunovci on the top of Holešova skala Hill. This striking occurrence is not shown in any published geological map; otherwise it was only mentioned by Scheibner (1968b). Further east, a few small blocky Czorsztyn-type klippen, which are chaotically dispersed in landslides, are present in the closure of the Struháreň Brook valley east of Šipková settlement. Then another narrow strip stretches for about 3 km from the southern slopes of Janíkov vrch Hill north of Zázrivá settlement Grúne up to the saddle north of Havranský vrch Hill and Malá Havrania settlement; where again the Czorsztyn- and/or Niedzica-type klippen rest as variously sized blocks within the matrix of variegated marlstones (Fig. 2.2a, b). In the Campanian variegated marlstones occurring near Grúne settlement, Aubrecht (1997b) described intra-formational breccias passing to polymict breccias and turbidites upward, which he correlated with the so-called Záskalie breccias occurring around town Dolný Kubín in the Orava PKB sector (e.g. Marschalko et al., 1979). The last, easternmost occur-

Figure 2.2 Examples of the Subpieniny Unit (Czorsztyn and/or Niedzica Succession) in the Havrania Zone, Janíkov vrch Hill above Zázrivá-Grúne settlement (photos by D. Plašienka): a – tectonic block of Middle Jurassic red crinoidal limestones (Krupianka Fm.) amidst Upper Cretaceous variegated marlstones (Púchov Fm.); b – Lower Cretaceous formations in a blocky klippe – cherty limestones (Pieniny Fm.) in the lower part are overlain by the Beriassian–Valanginian intraformational Walentowa Breccia composed of slightly older clasts of *Calpionella*-bearing limestones.

rence is an isolated Czorsztyn-type blocky klippe east of the Kozinec–Hoľa ridge NE of Zázrivá, which was described in detail by Jamrichová et al. (2012). It is surprising that these outcrops were not known to authors who mapped the area in the past, in spite of comparatively good exposures.

Likewise, we mapped a previously not known occurrence of a Niedzica-type succession in a side gorge of the Struháreň Brook valley between Marunovci and Šípková settlements (Terchová district), in this case at the southern border of the Havrania Zone in the contact with the Pupov Zone. There the continuous, little disturbed Niedzica Succession consists of the Middle–Upper Jurassic black shales (Skrzypny Fm.), sandy-crinoidal limestones (Smolegowa and Krupianka fms), red nodular limestones (Niedzica and Czorsztyn fms) intercalated by radiolarites of the Czajakowa Fm. and overlain by pale-grey cherty limestones of the Pieniny Fm. (Tithonian–Barremian).

2.1.3 Pieniny Unit

All other rock complexes that are cropping out in the Havrania Zone have been assigned to the Kysuca Succession of the **Pieniny Unit** (Andrusov, 1931a, 1938; Haško & Polák, 1979; Aubrecht et al., 2004). However, our new results presented below permit correlation of some formations with the Šariš Unit, which is the third of the main Oravic units of the PKB (Plašienka & Mikuš, 2010; Plašienka, 2012a; Plašienka et al., 2012). What we consider to be a part of the Pieniny Unit with certainty is the western, narrow part of the Havrania Zone west of Podkýčera Hill (Fig. 1.16). There it includes numerous small, isolated klippen composed predominantly of the Lower Cretaceous cherty limestones of the Pieniny Formations and in places also Jurassic radiolarites and mid-Cretaceous spotted marlstones that are arranged in a row along the boundary of the Pupov Zone, and partly also along the northern boundary in contact with the Magura units and/or slices of the Subpieniny Unit. The central stripe of the western part of the Havrania Zone is formed by the Upper Cretaceous flysch sequence with the exotic conglomerate bodies (Snežnica and/or Sromowce fms). This stripe of the Pieniny-Kysuca formations represents an eastern prolongation from the area north of Žilina, where it is considerably wider and complete as far as the lithostratigraphic succession is considered (type locality of the Kysuca Succession; e.g. Haško & Polák, 1979; Potfaj et al., 2003; Michalík et al., 2009).

2.1.4 Rock units with problematic affiliation

Formations of unclear position and tectonic association are present only in several tiny slices in the western part of the Havrania Zone, but form much larger exposures in its widened eastern part. The oldest recognized formation of the whole area builds up the NW–SE trending rounded ridge of Dutkov vrch – Jedľovinka Hill (906 m a.s.l., GPS N49.28792°, E19.1522°) north of the centre of Zázrivá village (Figs 1.16 and 1.17c). Andrusov (1931a) found here sandstones with imprints of Arietites-type ammonites, which should indicate the Sinemurian age. He correlated these sediments with the “Gresten Beds” and assigned them to the Kysuca Succession, similarly like later by Haško and Polák (1979).

A flat-lying, but completely overturned succession begins with possibly Hettangian and/or lower Sinemurian quartzitic sandstones. Nearly massive, pure quartzites occur in places, which are almost exclusively composed of fine-grained quartz sand with quartz cement (Dutkov vrch, eastern slope of Jedľovinka Hill, Dubovské lúky, south-western foots of Podkýčera Hill). The heavy minerals from quartzites are strongly dominated by zircon and rutile, followed by less represented tourmaline, with low amounts of apatite and some garnet (Aubrecht, 2001b).

In other places, probably younger parts of the formation are formed by massive whitish to yellowish, coarse grained sandstones with carbonate cement, locally passing to fine grained conglomerates composed of quartz, dolomite and dolomitic limestone pebbles. Fossil content is poor (scarce crinoid columnaria). Overlying dark-grey sandy (and sandy-crinoidal) limestones and light-grey fine-grained carbonatic sandstones with muscovite flakes are thick-bedded with thickness of individual beds between 20 and 100 cm and with intercalations of dark calcareous claystones. At the base of the sandy layers, rip-up clasts of these claystones occur commonly. The alternation of sandstones with sole marks and shales invokes their turbiditic origin. Bed surfaces often show imprints of ammonites.

Locally, some fauna of bivalves has been found in the clayey parts. However, only five species were determined (M. Golej): *Oxytoma (Oxytoma) inequivalvis* (left and right valves), *Entolium (Entolium) corneolum*, *„Praechlamys“* cf. *palosus*, *„Chlamys (Chlamys)“* cf. *textoria* (left and right valves), *Liostrea* sp. Specimens still bear recrystallized shells. The bivalve association is represented mostly by juvenile and subadulte specimens, adult specimens are rare. Except *Liostrea*, they are epibyssate or freely swimming (*Entolium*), relatively well adapted to life on the detritic substrate. Presence of both valves indicates autochtonous or paraautochtonous origin of the fauna.

All studied fossil macrofauna was collected ex situ, due to a very bad exposure of the formation on Jedľovinka Hill. Material comes from collections of M. Sýkora, M. Rakús and J. Schlögl. Apart of ammonites and occasional crinoids, the macrofauna shows a low diversity with mainly bivalves occurring on the sandstone bed surfaces, but also inside the beds, and bivalve debris in the fine-grained conglomerates. Belemnites are rare and corroded. Ichnofossils are common on the lower surfaces of beds. The ammonites are almost exclusively preserved as imprints on the lower bed surfaces which suggest they come from the marly intercalations. Originally the ammonites were filled with marl or clay and the shells were already dissolved. They were apparently exhumed from marly layers during the deposition of the turbiditic sandstone layers. Rarely, some marl/clay ammonite moulds were documented inside the sandy beds, proving their origin from the marly intercalations.

The stratigraphical position of the formation is based on the ammonite fauna (Figs 2.3, 2.4 and 2.5a). All ammonite groups, including Lytoceratina, Phylloceratina and Ammonitina are present. Lytoceratids are rare, represented by a single specimen of *Lytoceras* sp., assigned by M. Rakús to *L.* gr. *secernendum* (Fig. 2.4C), species of the Late Sinemurian age. Phylloceratids are common, dominated by *Juraphyllites planispiroides* (Fig. 2.4A), species of the Oxynotum and early Raricostatum zones. Partschiceras striatocostatum (Fig. 2.4B) is rare (single specimen). This species has a very long stratigraphical range, appearing probably in the early Sinemurian and going up to the early Toarcian. Ammonitina are represented by oxynoticeratids and especially echioceratids, other groups are very rare. *Oxynoticeras* cf. *simpsoni* (Fig. 2.4E) is a typical species of the Oxynotum Zone. Several juvenile specimens with lanceolate whorl section, more or less flexuous simple or bifurcating ribs could not be determined on the species level. One juvenile, thickly ribbed specimen can be attributed to *Gleviceras* sp. Echioceratids are the most common group. Genus *Echioceras* is represented by species *E. raricostatum* (Fig. 2.4F) and *E. raricostatoides* (Fig. 2.4G). *Paltechioceras* is represented by numerous specimens of *P. boehmi* (Fig. 2.4H), less common P. cf. favrei and scarce *P.* cf. *hierlatzicum*. *Leptechioceras* is represented by two species, *L.* gr. *macdonnelli* (Fig. 2.4I) and *L.* cf. *meigeni* (Fig. 2.4J). Echioceratid association indicates Raricostatum Zone of the late Sinemurian, more precisely its middle part, Raricostatum and Macdonnelli subzones. A single specimen of eoderoceratid *Crucilobiceras* cf. *densinodulum* (Fig. 2.4K) is index taxon of the early Raricostatum Zone, Densinodulum Subzone.

Hettangian – Early Sinemurian age for the formation was proposed by Haško and Polák (1979), but this assignment was only based on the superposition argument and ammonites documented from another locality from the Orava region by Andrusov (1931a). However, based on ammonite fauna, collected in Jedľovinka Hill, this stratigraphical range cannot be proved as all association points exclusively to the middle and upper part of the late Sinemurian, Oxynotum and Raricostatum zones. This is not the only occurrence of the formation in the Orava sector of Pieniny Klippen Belt. Already Andrusov (1931a) noted sandstones with ammonite imprints on the bedding planes from the localities in the surroundings of Zázrivá village, in Oravský Podzámok or in Ľúty potok creek (presently called Dĺžiansky Cickov, N of Dlhá nad Oravou village). His determinations would indicate Early Sinemurian age, however, the figured surface of the slab (Pl. III, Fig. 1 in Andrusov, 1931a) from Ľúty Potok locality is covered with numerous specimens and fragments of *Echioceras raricostatoides*, not by *Schlotheimia* sp. and *Arietites (Echioceras)* sp. aff. *Ar. spiratissimus*, thus not contradicting to our stratigraphical attribution of these deposits. The same formation occurs also in the Middle Váh Valley near Chotúč (J. Schlögl, unpublished data). Although the ammonite collection from this area is much smaller mainly due to the missing outcrops, it indicates the same stratigraphic interval as at Jedľovinka area, consisting of juvenile echioceratids and oxynoticeratids. In this light, the time of deposition of this turbiditic formation seems to be synchronous at least in the western Slovakian part of the PKB.

Aubrecht et al. (2004) informally named these sediments as the Jedľovinka Formation. However, this term had been already used for another formation, thus it is invalid. Therefore, we propose the new term Dutkov vrch Formation for these sediments (formal lithostratigraphic codification will come later). Dutkov vrch Hill is located some 500 metres NW of Jedľovinka Hill, on the ridge above Grúne settlement and is formed by the Lower Jurassic quartzitic sandstones as well. Similar siliciclastic sandstones occur in comparatively large areas also north and west of Jedľovinka and Dutkov vrch hills – on the southern slopes of Janíkov vrch and Kýčerka hills between Grúne and Sihla settlements, and further west on the southern foots of Podkýčera Hill between Ráztoky (Zázrivá) and Sihelky (Terchová) settlements. In places, the

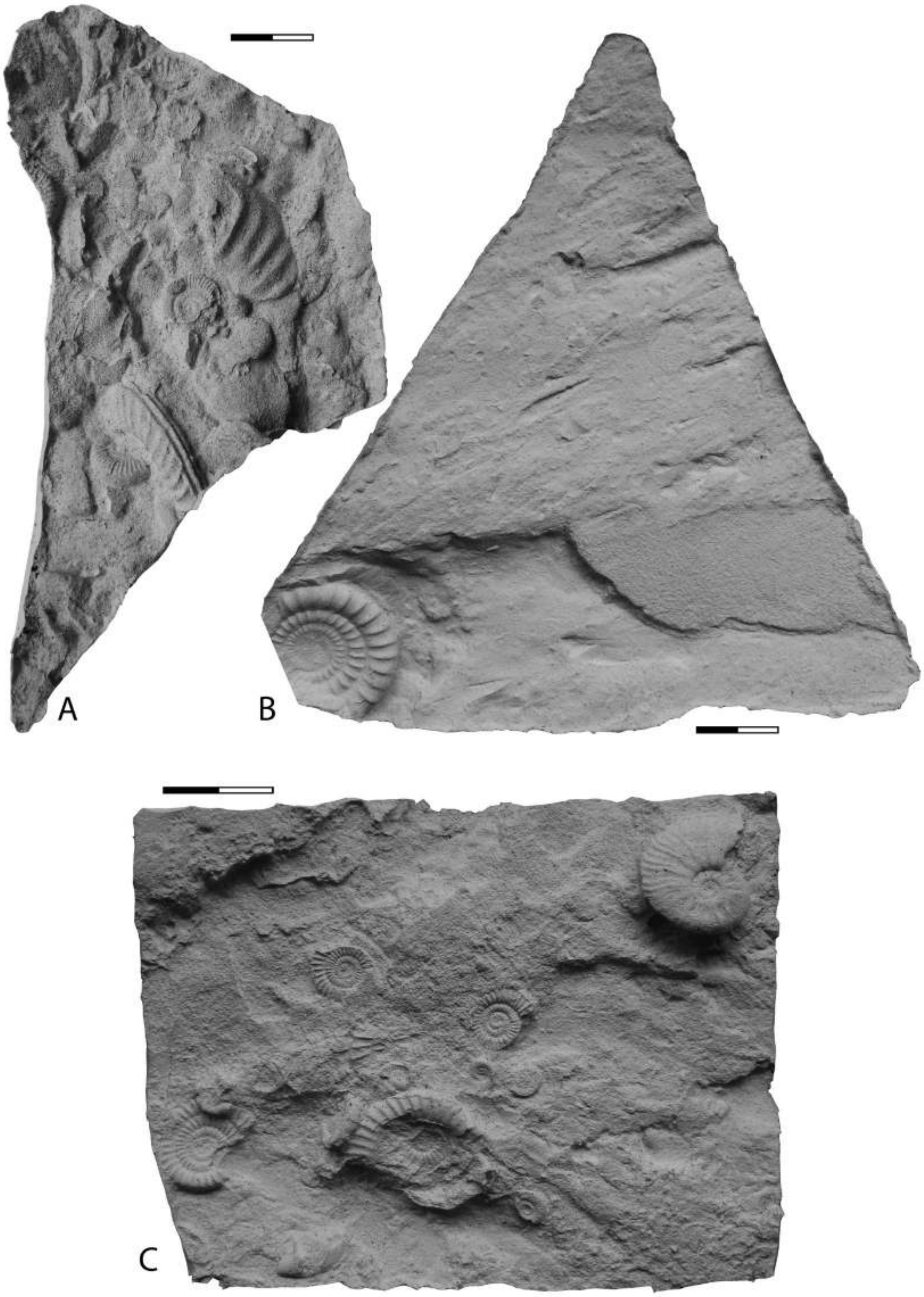


Figure 2.3 Latex cast of the lower surfaces of sandstone beds. A – imprints of fragmented echioceratid ammonites and disintegrated lithoclasts; B – mechanoglyphs (current marks) and ammonite *Echioceras* sp.; C – numerous imprints of echioceratid juveniles and *Oxynoticeras* sp. All specimens come from Jedľovinka Hill. Scale bars 2 cm.

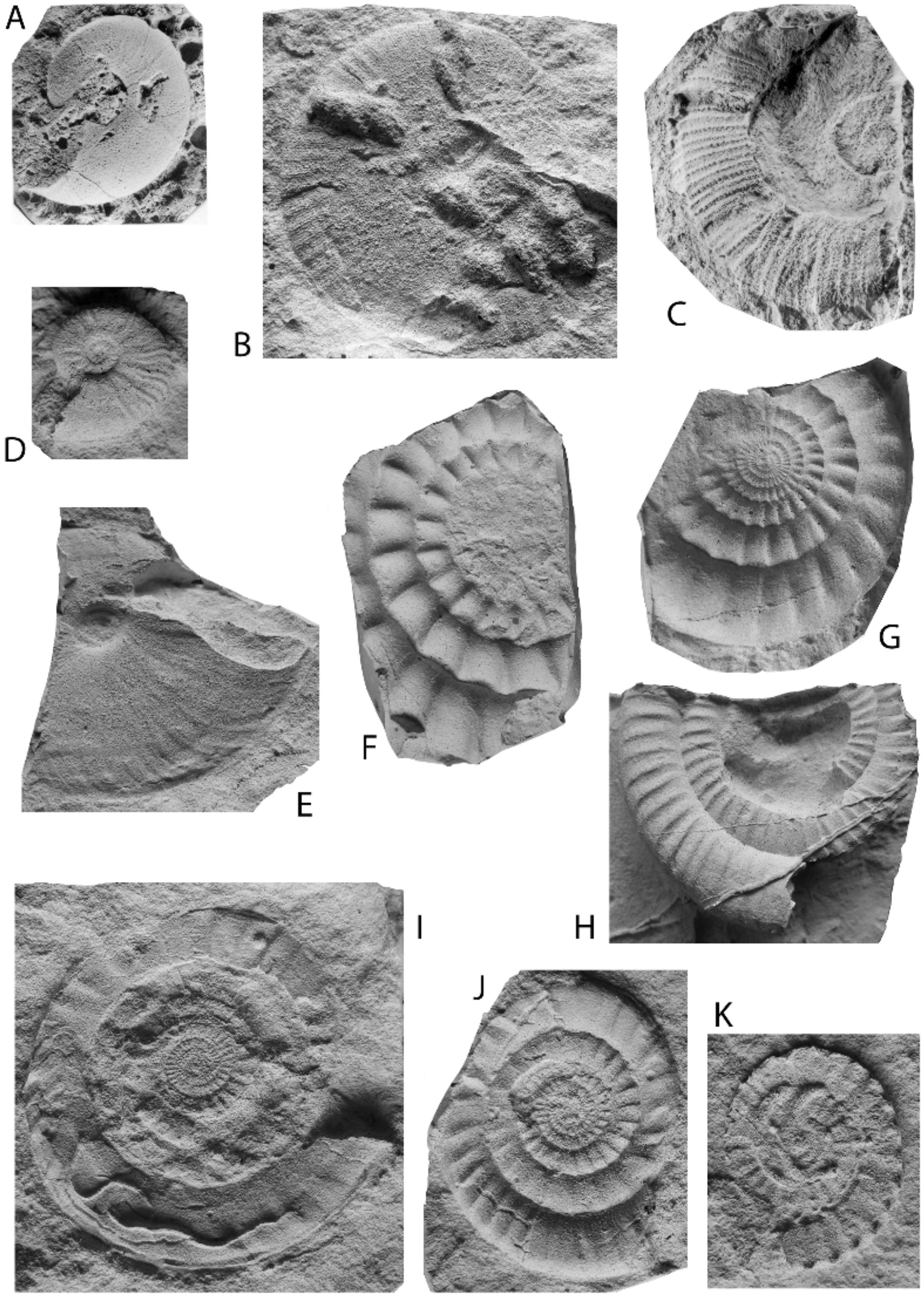


Figure 2.4 Latex casts of ammonites from the sandstone bed surfaces, Jedľovinka Hill: A – *Juraphyllites planispiroides*; B – *Partschiceras striatocostatum*; C – *Lytoceras* sp. (gr. secernendum); D – *Oxynoticeras* sp.; E – *Oxynoticeras* cf. *simpsoni*; F – *Echioceras raricostatum*; G – *Echioceras raricostatoides*; H – *Paltechioceras* cf. *boehmi*; I – *Leptechioceras* gr. *macdonnelli* (Portlock); J – *Leptechioceras* cf. *meigeni* (Hug); K – *Crucilobiceras* cf. *densinodulum*. Specimens A and B were whitened prior photography (photo by M. Rakús). Scale bar 1 cm.

upper part of the Lower Jurassic sandstone sequence contains, or are followed by, layers of spotted spiculitic and filamentous marlstones with ostracodes and clastic quartz grains (Pliensbachian?). Andrusov (1931a) mentioned also findings of bivalve-brachiopod coquinas from SW slopes of the Jedľovinka Hill. Another outcrop of quartzitic sandstones appears in the south-eastern extension of the Havrania Zone where it merges with the Plešivá Zone on the ridge between Pavláškova and Hlásna skala hills (Dubovské lúky meadows). Then similar sandstones occur also in the Plešivá and Kubín zones (see below).

On the unstable north-eastern slope and foots of Končitý vrch Hill, and in the bottom of adjacent small creek in the Končitá Valley, Haško and Planderová (1977) described bituminous black shales with beds of laminated marly limestones and spherosideritic concretions, which they defined as the so-called

Figure 2.5 Rocks of the Šariš Unit in the Havrania Zone (photos a, b and f by D. Plašienka, c–e by P. Gedl): a – imprint of echioceratid ammonite in upper Sinemurian sandstones of the Dutkov vrch Fm., Jedľovinka Hill summit; b – black shales and boudinated sandstones of the Szlachtowa Fm., Jamy settlement; c – black shales of the Skrzypny or Szlachtowa Fm., Ráztoky stream section; d – common appearance of outcrops in the Szlachowa Fm., northern ridge of Jedľovinka Hill, Š. Józsa sampling and D. Plašienka observing; e – dark siliceous shales and radiolarites of the Middle Jurassic Sokolica Fm., Čierťaž section; f – greenish- and redish-grey ribbon radiolarites of the Czajakowa Fm., Zázrivá-Grúne.

Zázrivá Beds (see Stop B26). Their Sinemurian – early Lotharingian age was indicated based on rich palynoflora. According to these authors, the Zázrivá Beds overlie the Hettangian – lower Sinemurian Gresten Beds and are overlain by the Lotharingian spotted limestones, all belonging to the Kysuca Unit. Later on, this sequence was reinterpreted by Aubrecht et al. (2004). They found imprints of thin-shelled "posidonias" (*Bositra buchi*) bivalves and graptoceratid ammonite. Hence the Aalenian age of the black shales was proven and correlated with the Skrzypny Shale Formation; therefore, usage of the term Zázrivá Beds was discarded. However, unlike other occurences of the Skrzypny Fm. and/or the Harcygrund Fm. in the Subpieniny resp. Pieniny units, the shales contain also blocks – olistoliths of black bituminous limestones, calcarenites, spotted belemnite-bearing limestones and spongolites (Aubrecht et al., 2004; see also the Zázrivka Brook section below, Stop B26).

The Jurassic age of sediments dominated by black shales and turbiditic sandstones in the PKB Orava sector and Zázrivá district was recognized already by Andrusov (1929, 1931a, 1938, 1945, 1953) and defined as the "Dogger flysch" (or "flysch Aalenian" by Birkenmajer, 1957; Andrusov, 1965). The informal term "Black Flysch" has been also frequently used. Afterward, Birkenmajer (1977) introduced the formal lithostratigraphic term Szlachtowa Formation. In the Pieniny Mts., the Cretaceous (Albian–Cenomanian) age of these deposits was proposed from time to time, however (e.g. Sikora, 1974; Oszczypko et al., 2004, 2012b). On the other hand, the early Middle Jurassic age of the Szlachtowa Fm. was documented by ammonites, thin-shelled bivalves, dinoflagellate cysts and foraminifers (Birkenmajer, 1957, 1977; Scheibner, 1968b; Birkenmajer & Gedl, 2004, 2017; Birkenmajer et al., 2008; Barski et al., 2012; Gedl, 2013; Gedl & Józsa, 2015; Segit et al., 2015). In a typical development, the Szlachtowa Fm. consists of black argilaceous shales and mudstones with variously thick beds of siliciclastic turbiditic sandstones, which are often very rich in clastic mica flakes. Upper parts contain also beds of allodapic crinoidal limestones.

Dysoxic hemipelagic sediments of the Aalenian – early Bajocian age of the Szlachtowa and Skrzypny formations can be considered as heteropic facies. According to Barski et al. (2012) and Segit et al. (2015), the Szlachtowa Formation is dominantly of early Bajocian age and occurs only in the Grajcarek (Šariš) Unit specified as the "pre-Late Albian Magura Basin". Other PKB successions (Czorsztyn, Niedzica, Czertezik) contain only the Aalenian Skrzypny Fm. followed by early Bajocian hiatus and then by the mid-Bajocian shallow-water sandy-crinoidal limestones. This situation occurs in successions derived from peripheries of by-then emerging Czorsztyn Ridge, which provided the bio- and siliciclastic material for the turbiditic sandstones of the Szlachtowa Fm. However, sediments with the typical Szlachtowa lithology have beed frequently dated as Aalenian by dinocysts as well (cf. results of P. Gedl – Birkenmajer & Gedl, 2004, 2017; Birkenmajer et al., 2008; Gedl, 2008, 2013; Gedl & Józsa, 2015). Sometimes it can be seen that the Skrzypny-type black shales are laterally replaced by, or interfingering with, the Szlachtowa-type micaceous sandstones and mudstones (see also Andrusov, 1945; Scheibner, 1968b; Birkenmajer & Gedl, 2017; Segit, 2010). These circumstances can be observed in the Končitá Valley section (stops B22, B24, B26). The crinoidal limestone allodaps occur in the lower Bajocian sequence of the Szlachtowa Fm., concurrently with uplift of the Czorsztyn Ridge. Therefore, we speculate that the more external Aalenian Szlachtowa basin was fed by siliciclastic turbidites from the northern external sources that did not reach the axial parts of the Skrzypny basin in the south (in present coordinates). During the early Bajocian uplift of the Czorsztyn Ridge, the Szlachtowa basin got a new source of shallow-water calciclastic material from the south, including olistostrome bodies described by Aubrecht et al. (2004), while non-deposition prevailed on elevated ridge areas. Similarly, the southern slopes of the Czorsztyn Ridge (Kysuca-Branisko and Pruské successions) were supplied by upper Bajocian crinoidal turbidites as well (Flaki and Samášky formations; cf. Birkenmajer, 1977; Aubrecht & Ožvoldová, 1994). In any case, character of the Bajocian sediments in the Oravic PKB successions reveals important extensional tectonic event connected with crustal rifting, Czorsztyn Ridge uplift and ensuing subsidence of the adjacent basinal domains (e.g. Plašienka, 2003a).

Within the Havrania Zone, rocks that can be affiliated with the Szlachtowa and/or Skrzypny formations occur discontinuously as isolated slices or lenses from Horná Tižina settlement (Terchová district) in the west up to Končitá and Havrania settlements (Zázrivá district) in the easternmost part of the Varín PKB sector (Figs 1.16, 2.5). At all these localities, the Szlachtowa and/or Skrzypny formations are spatially related to the Lower Jurassic clastic formations as their underlier, or with the Middle Jurassic to Lower Cretaceous deep-water pelagic formations as their overlier – but uniformly in an overturned stratigraphic succession. Based on the overall lithological character and presence of some specific formations (Szlachtowa, Opaleniec), we presuppose their assignment chiefly to the **Šariš Unit** (Fig. 2.6). However, other formations like the Czajakowa

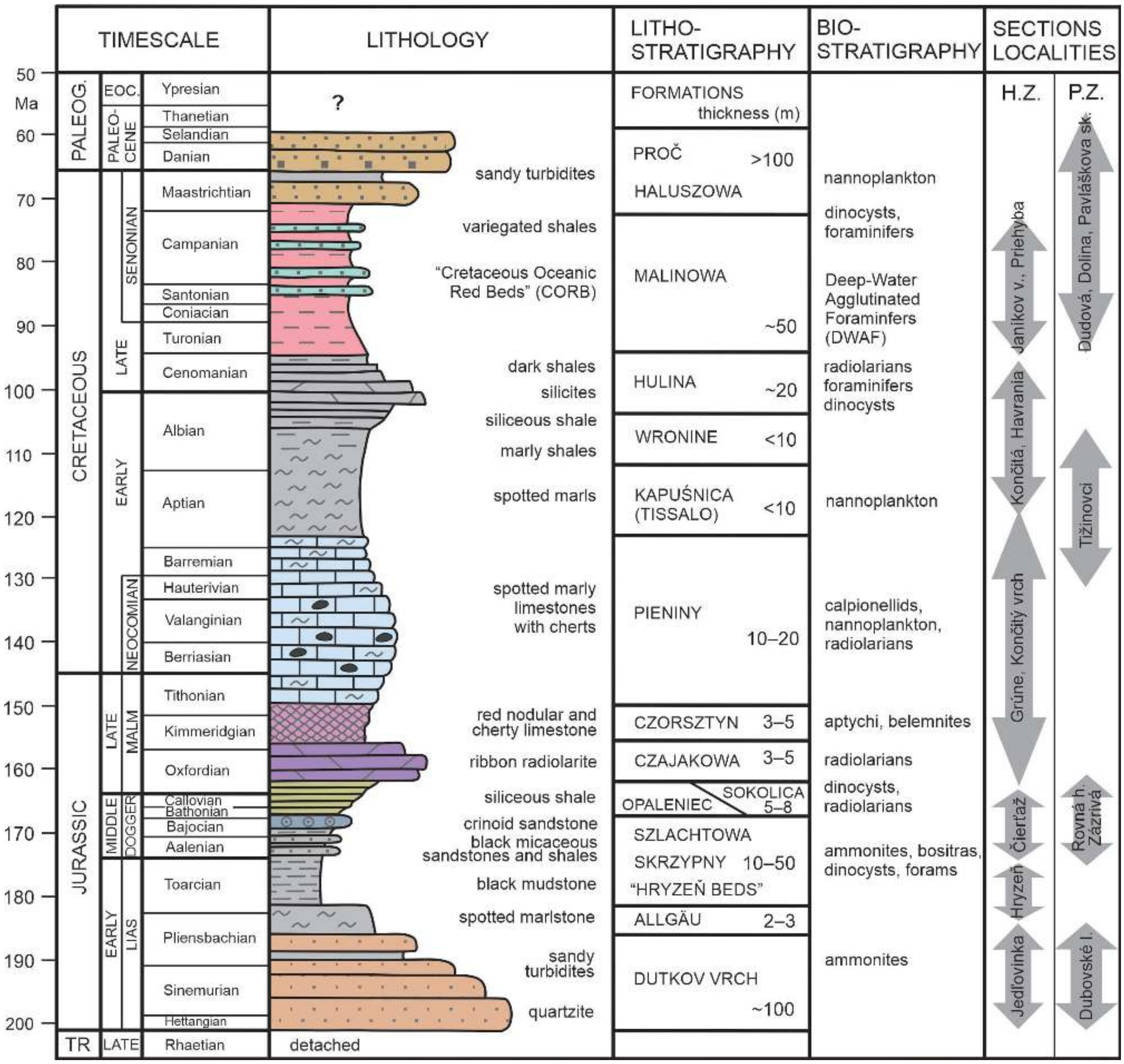


Figure 2.6 Composite lithostratigraphy of the Šariš Unit in the area concerned. The right column shows localities and profiles of the inferred Šariš Unit in the Havrania (H.Z.) and Plešivá (P.Z.) zones of the PKB.

radiolarites and Pieniny limestones, show little differences from the Pieniny Unit (Kysuca Succession), therefore their tectonic affiliation with a particular unit is locally problematic.

In general, the composition of heavy mineral spectra from the Lower to early Middle Jurassic sandstones of the Šariš Unit, as well as their palynofacies characteristics, indicate the subsidence-related progression from mature continental or beach-like sedimentary environments dominated by ultrastable ZRT assemblage and terrestrial palynoflora in massive quartzitic sandstones, through probably shallow marine deltaic settings with bedded siliciclastic-calcareous sandstones (Dutkov vrch Fm.), up to the open-marine, oxygen-depleted facies of black shales and marls with intercalations of immature, poorly sorted turbiditic sandstones to conglomerates characterized by prevalence of unstable heavy minerals and frequent lithic fragments (see the Sihla locality below). These changes reflect the accelerating Lower/Middle Jurassic rifting and development of semi-isolated marine basins supplied by the clastic material from nearby uplifted rift shoulders dominated by mechanical weathering and erosion of pre-Jurassic basement and sedimentary cover complexes.

2.1.5 Important field outcrops and sections

Besides of the Jedľovinka Hill area, we describe hereafter localities of the Lower–Middle Jurassic clastic formations (sandstones and black shales) and associated sediments that we have studied in the Havrania Zone. It is curious that most of these occurrences are shown in the old map of Andrusov (1938), but are lacking in all later maps. Localities are arranged from the west to the east:

Novosadovci settlement (Horná Tižina; GPS N49.284211°, E19.032007°; Terchová district)

An independent lenticular slice of Jurassic shales, about 300 m long and 100 m wide, is located in a strange position between two Cretaceous calcareous flysch formations – probably the Snežnica-Sromowce Fm. to the north and the Pupov Fm. to the south. These rocks are occasionally cropping out along a tight field road curve leading from Rusnákovci to Novosadovci hamlets (Horná Tižina settlement north of Terchová centre – between the cross-sections “e” and “f” in Figs 1.16 and 1.17).

Dark brownish-grey argillaceous shales contain clastic mica flakes and thin beds of turbiditic crinoidal sandstones. Samples HT7 and HT8 (Š. Józsa) yielded an assemblage of agglutinated foraminifers pointing to an upper Toarcian–Bathonian age, which shares similarities with other known occurrences of such assemblages reported by Tyszka (1994, 1999), or Gedl and Józsa (2015). Based of the lithology and age, we suppose that these “black flysch” sediments belong to the Szlachtowa Fm. (Šariš Unit).

Kvočkovci–Marunovci round tour (Terchová district)

This trip starts and ends in Kvočkovci settlement, Struháreň Brook valley, about 5 km NE from the Terchová centre. The first part follows the field way from Šmehýlovci hamlet to the north up to Holešova skala Hill, then along the ridge following the blue touristic trail to the Kováčka saddle, where the blue trail crosses the green one. The the second part follows the green trail down to the south to Marunovci settlement and then back to Kvočkovci. Rocks of the Havrania Zone and finally also the Pupov Zone are observable along the route (Fig. 2.7).

Samples Z83–Z85 (P. Gedl) were taken for palynology and organic-walled dinoflagellate cysts (Figs 2.7a and 2.8) and samples KV1–KV3 for foraminifera (Š. Józsa). In a road cut above the stream in Šmehýlovci hamlet, steeply NW-dipping grey silty-marly mudstones are exposed (GPS N49.294479°, E19.063623°). Sample Z83 yielded palynofacies composed of palynodebris (black, opaque to dark-brown phytoclasts). Palynomorphs are rare, represented by dark-coloured but generally well-preserved spores, and dinoflagellate cysts, which show a dual preservation. Some forms are darker-coloured, although relatively well preserved (these are thick-walled forms representing *Cribroperidinium*, *Tehamadinium* and *Trichodinium*); the others are pale-coloured and represented by small peridinioids (*Palaeohystrichophora infusorioides*, *Palaeohystrichophora*? sp., *Subtilisphaera*), and *Odontochitina operculata*. It is not certain if the dark forms are reworked or its colouration results from their wall thickness; they can be also resedimented from proximal areas. The age of this sample is most likely mid-Cretaceous (uppermost Albian and/or younger). Sample KV1 for foraminifers yielded some early Turonian planktonic foraminifera species. Among them, the stratigraphically important species *Dicarinella hagnyi* Scheibnerová and *Helvetoglobotruncana* cf. *praehelvetica* (Trujillo) were identified. Presumably, these sediments can be assigned to the Snežnica Fm. of the Pieniny (Kysuca) Unit.

Sample Z84 was taken from similar marls exposed in a field road above the village of Kvočkovci (GPS N49.294969°, E19.068183°; Figs 2.7b, c and 2.8). It yielded a similar palynofacies composed of palynodebris. The lack of *Cribroperidinium*-morphotype forms is a difference; dinoflagellate cysts are represented almost exclusively by pale-coloured peridinioids (e.g., *P. infusorioides*, *Spinidinium*). The latest Albian–Maastrichtian age of this sample based on palynotaxa can be more precisely determined based on deep water agglutinated foraminifera (DWAF) and planktonic foraminifera (sample KV2). The sample yielded *Caudammina gigantea* (Geroch) which occurrs in the early Campanian to Maastrichtian in the Carpathians (Geroch & Nowak, 1984; Bąk, 2000). Similar age is provided also by scarce planktonic species of *Globotruncana arca* (Cushman) and *Globotruncana linneana* (d’Orbignyi), whose first occurrence is recorded in the late Santonian (Caron, 1985). Turbiditic sandstones prevail in the upper part of this sequence, overturned bedding dips 323/50.

Higher up along the road, grey-brown marlstones with thin sandstone beds are exposed in washed-out grooves. Sample KV3 provided Upper Cretaceous agglutinated foraminifera. The presence of *Rectoprotomarssonella rugosa* (Hanzlikova) in the assemblage provides evidence for the late Santonian–Maastrichtian age (Bąk, 2000). The sample Z85 yielded a palynofacies similar to previous two sites (Fig. 2.8). Rare dinoflagellate cysts represent pale-coloured peridinioids. Lack of *P. infusorioides* makes a precise dating impossible.

Figure 2.7 Outcrops along the Kvočkovci–Marunovci section (photos by P. Gedl): a – Turonian mudstones (samples Z83 and KV1), road cut in Šmehýlovci hamlet; b – Š. Józsa and D. Plašienka documenting exposure in Campanian–Maastrichtian brownish-grey marlstones (samples Z84 and KV2); c – Š. Józsa digging for sample KV2; d – black shales with pelocarbonate concretions, Aalenian Skrzypny Fm. of the Subpieniny (Czorsztyn) Unit (samples Z86–88 and KV5A–C), road cut between the Kováčka saddle and Marunovci settlement; e – mid-Cretaceous black shales (samples Z89, Z90 and KV6), forrest road cut above Marunovci settlement; f – Albian Fleckenmergel-facies marlstones (Tissalo or Kapuśnica Fm., samples Z92 and KV7), Marunovci.

Following the forrest road uphill and approaching the ridge, typical variegated marlstones of the “couches rouges” facies (Púchov-type) appear in the scree. They are associated with two small Czorsztyn-type rocky klippen on Holešova skala Hill, which are composed of red sandy-crinoidal limestones (Krupianka Fm.) and greyish nodular limestones (Czorsztyn Fm.). Tectonic affiliation of the underlying upper Senonian marly sequence with packages of turbiditic sandstones (samples KV2–3) is problematic. Lithology and age admit its assignment to the Pupov Fm., but the position between two Oravic units, Pieniny and Subpieniny, is strange.

Passing along the green trail from the Kováčka saddle down to the south, there are some outcrops in the Paleogene flysch sandstones of the Magura Unit. However, these are located in a landsliding area. The next three samples Z86–Z88 were taken from a large outcrop of dark, vertically dipping shale with carbonaceous concretions (GPS N49.299433°, E19.077060°; Figs 2.7d and 2.9). Sample Z86 was taken from the southern part of the exposure where very frequent concretions occur. Sample Z87 was taken some 3 meters north, and sample Z88 from the northern part of the exposure, some 9 meters from Z87. All three samples yielded a similar palynofacies composed predominantly of black, opaque phytoclasts and dark-brown plant remains. Another characteristic feature of these samples is a high degree of maturity reflected by dark coloration and high alteration of both phytoclasts and palynomorphs (spores, dinoflagellate cysts and foraminifera organic linings). Sample Z86 yielded infrequent *Phallocysta* (commonly with traces of pyrite crystallization) and acritarchs. Sample Z87 yielded more frequent dinoflagellate cysts (*Phallocysta*, *Nannoceratopsis* and some thin-walled, multiple paraplate archaeopyle forms) associated by foraminifera organic linings. A similar assemblage, characterized by frequent occurrence of thin-walled, multiple paraplate archaeopyle forms, was found in sample Z88. The uppermost Toarcian–Aalenian age of these three samples can be suggested on the basis

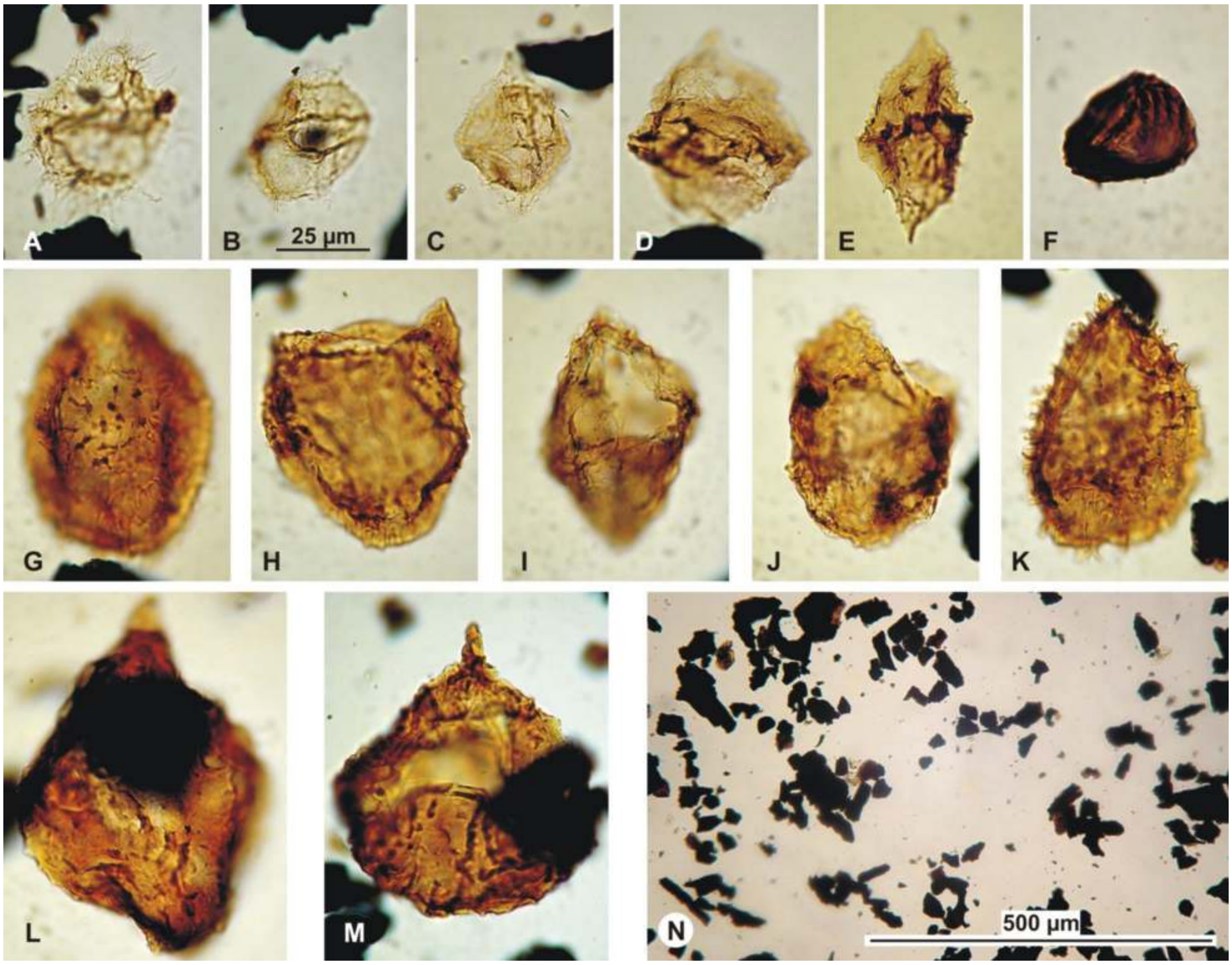
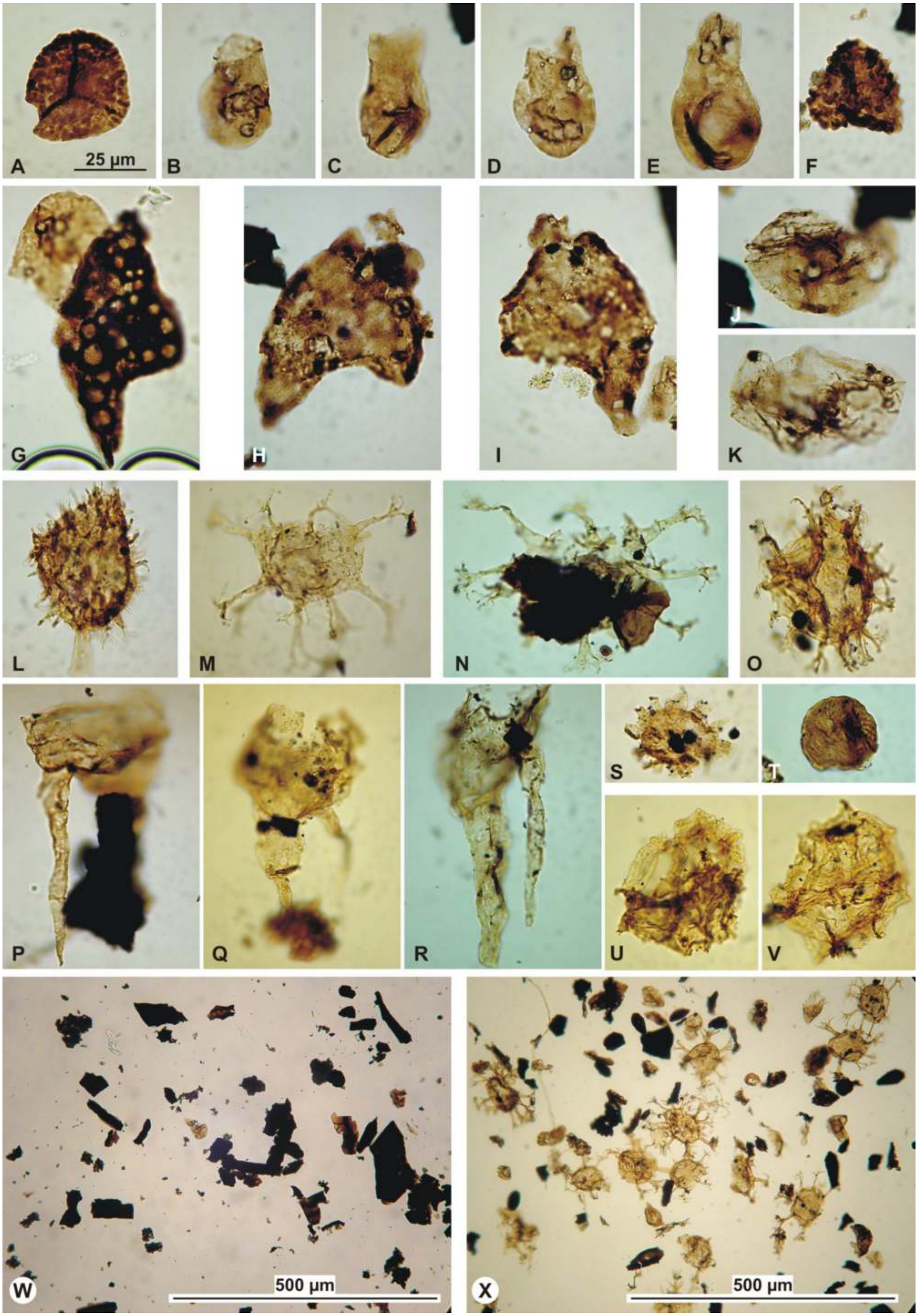


Figure 2.8 Palynology of the Kvočkovci section (samples Z83–Z85; photo: P. Gedl). Scale bar in B refers to all photomicrographs except for N. A–C: *Palaeohystrichophora infusorioides* (A, B: 83; C: 84); D: peridinioid (*Subtilisphaera*?; 84); E: *Spinidinium* sp. (84); F: spore (*Cicatricosisporites*?; 84); G, H, J, K: large gonyaulacoids representing *Tehamadinium-Trichodinium* morphotypes (83); I – *Psaligonyaulax*? sp. (83); L: *Cribroperidinium*? Sp (83); M: *Cribroperidinium edwardsii* (83); N: Palynofacies composed of black, opaque phytoclasts and dark-brown phytoclasts (83).

Figure 2.9 (next page) Palynology of the Marunovci section (samples Z86–Z93; photo: P. Gedl). Scale bar in A refers to photomicrographs A–V. A: spore (86); B–D: ***Phallocysta elongata*** (86); E: *Phallocysta elongata* (87); F: spore (87); G–I: poorly preserved specimens of *Nannoceratopsis* bearing traces of crystal (pyrite?) crystallization (G: 87; H, I: 88); J, K: *Dissiliodinium*? sp. (88); L: *Coronifera* sp. (89); M: *Oligosphaeridium* sp. (89); N: *Oligosphaeridium* sp. (90); O: *Spiniferites* sp. (90); P–R: *Odontochitina* spp. (P: 89; Q, R: 90); S: *Litosphaeridium arundum* (90); T: spore (*Cicatricosisporites*?; 90); U, V: *Pterodinium* sp. (90); W: Palynofacies of black shale (sample 87) composed ob black, opaque phytoclasts and highly altered dinoflagellate cysts; X: Palynofacies from hard “Fleckenmergels” (sample 92) characterized by an acme of *Oligosphaeridium*.


A
25 µm
B
C
D
E
F
G
H
I
J
K
L
M
N
O
P
Q
R
S
T
U
V
W
500 µm
X
500 µm

of the organic-walled dinoflagellate cysts (Fig. 2.9).

Samples KV5A–C are accompanied by rich calcareous benthic foraminiferal assemblages with dominant ophthalmidiids and spirillinids. Such assemblages are typical for the Early?–Middle Jurassic facies in the PKB (Tyszka, 1994, 1999; Gedl & Józsa, 2015). This age, lithology and dinoflagellate cyst assemblages allow their correlation with the Skrzypny Shale Formation and possibly with the Subpieniny (Czorsztyn) Unit laterally continuing from the Holešova skala klippe.

Two further samples Z89 and Z90 were taken from horizontally lying dark, loamy shale exposed in a small outcrop along the forest road (Fig. 2.7e). Both samples (taken 1.5 m from each other) yielded palynological organic matter in the same degree of maturity as in samples Z86–Z88 taken above. However, a different, mid-Cretaceous age concluded on the base of dinoflagellate cysts allows their correlation with another "dark shale" lithostratigraphic unit of the Pieniny Kippen Belt – the Tissalo or Kapuśnica Formation. These samples yielded palynofacies composed of black, opaque phytoclasts and other, highly matured land plant remains associated with frequent spores and dinoflagellate cysts. Among the latter *Odontochitina operculata*, *Pterodinium* spp., *Spiniferites ramosus*, *Circulodinium* sp., *Florentinia*? sp., *Hystrichodinium* sp., *Coronifera* sp., and *Oligosphaeridium* sp. can be listed. Presence of *Litosphaeridium arundum* allows dating these samples as Albian–lowermost Cenomanian (Fig. 2.9).

The following sample Z91 was collected a couple of meters down, from an outcrop of highly weathered pale-greyish to willow greenish shale, which coat harder, greyish mudstones. It yielded palynofacies composed almost entirely of black, opaque phytoclasts. Sporomorphs and dark-brown phytoclasts are subordinate. Dinoflagellate cysts are very rare – single *Spiniferites*? and some peridinioids were found. The age of this sample is most likely comparable with the age of samples Z89 and Z90 taken higher up, which represent a more proximal, nearshore facies compared to sample Z91.

Approaching the first houses of Marunovci settlement, grey spotted "Fleckenmergel" marlstones coated in softer, black-grey-olive mudstones contain Lower Cretaceous foraminifers (sample KV6 upper Aptian–Albian, sample KV7 further down middle Albian). The sample KV6 (Fig. 2.7f) contained some subordinate smaller agglutinated foraminifera, but is dominated by calcareous benthic foraminifera belonging exclusively to poorly preserved epistominids, mostly *Epistomina spinulifera polypioides* (Eichenberg). This species occurrs in the latest Aptian– Albian (Jendrejáková, 1968; Salaj & Samuel, 1966). The sample KV7 yielded poorly preserved planktonic foraminifera. The Middle Albian age might be suggested upon the first occurrence of specimen similar to early single-keeled species ?*Pseudothalmanninella* cf. *subticinensis* (Gandolfi) found among larger many-chambered morphotypes with globular chambers most likely belonging to *Ticinella* spp. These larger many-chambered trochospiral taxa are also typical in the latest Aptian as *Paraticinella rohri* (Bolli) (Ando et al. 2013), formerly referred to as *Paraticinella eubejaouaensis* (Randrianasolo and Anglada).

Sample Z92 (Figs 2.7f and 2.9) yielded a unique palynological content – a mass occurrence of *Oligosphaeridium*. Its acme consists chiefly of *O. complex*, rare *O. poculum* is also present. There are almost no other dinoflagellate cysts. Besides dominating *Oligosphaeridium* specimens, frequent sporomorphs, including pollen grains occur. Such a palynofacies points at a proximal sedimentary setting. The mid-Cretaceous (latest Aptian–Albian) marly sequence (samples Z89–Z92 and KV6–KV7) may be best correlated with the Pieniny (Kysuca) Unit, but its assignement to the Šariš Unit cannot be excluded either.

Down along the green trail below Marunovci, sandstones and claystones of the Pupov Formation are exposed in the lowermost part of the section in a road cut below a small chappel (GPS N49.291432°, E19.069417°). Moderately north-dipping packets of bedded calcareous turbiditic sandstones are inserted within claystone intervals. Sample Z93 taken from pale-grey marls yielded palynofacies dominated in over 90% of black, opaque phytoclasts. Remaining particles are sporomorphs and dark-brown phytoclasts. Dinoflagellate cysts are very rare: *Spiniferites* and *Pterodinium* could be determined. The age of this sample cannot be precisely estimated; most likely it represents the Late Cretaceous. The sample KV8 contained only some undeterminable calcareous foraminifera forms.

Some 1.5 km east of Marunovci settlement, the amphitheatre-like closure of the Struháreň Brook valley 500 m NE from Balátovci settlement (approx. GPS N49.299890°, E19.096878°) is a vast landsliding area with several small, obviously transported outcrops of black shales with either sphaerocarbonate concretions or micaceous sandstones (Skrzypny and Szlachtowa fms, respectively) occur in association with blocky klippen of red nodular limestones (Czorsztyn Fm.). Immediately to the east, on the south-western foots of Podkýčera Hill (Sihelky), there are numerous clasts of quartzitic sandstones found in the debris. Quatzites are of the same time as at Jedľovinka Hill (Dutkov vrch Fm., see above).

Black shales and micaceous sandstones appear again in the valley south of Podkýčera Hill near hamlet Dolina (GPS ca N49.293526°, E19.111572°) and in a gully below hamlet Jamy on the south-eastern foots of Pokrýčera hill (GPS N49.297115°, E19.122530°; Fig. 2.5b).

Sihla settlement – small rock cliff (GPS N49.296°, E19.137381°; Zázrivá district)

This isolated rocky outcrop is located near hamlet Sihla north of Zázrivá, on a ridge about 200 metres south of the elevation point 885. Here, Méres et al. (2012) investigated composition of massive coarse-grained, siliciclastic lithic sandstones to microconglomerates. Clastic components consist of quartz (50%), feldspar (7%), mica (2%) and various lithoclasts (up to 26.5%) embedded in a pelitic, sericite-quartzose matrix (15%). The lithoclasts are represented by carbonates – probably Triassic dolomites and micritic limestones sometimes with autigenic plagioclase, silicites, metamorphic rocks, granitoids, basalts and rhyolites. Garnet dominates in the heavy mineral concentrates (up to 94%), while apatite (4%), staurolite and the stable zircon-rutile-tourmaline association (ZRT; 2%) are subordinate only. Microprobe analyses of garnets revealed predominance of almandine (66–88%) over grossularite (1.3–27%), pyrope (3–17%) and spessartine (1.1–9%). The ZRT index as low as 2, compositional variability and weak alteration of lithoclasts point to poor sorting and weak mineral maturity, the low degree of chemical and mechanical weathering in source areas and hence the short and rapid transport of clastic material. The source area was a continental crust with granitoids and medium- to high-grade metamorphic rocks (gneisses, micaschists, orthogneisses, amphibolites), carbonates and a lesser amount of volcanic rocks. The lack of chromian spinels among the heavy minerals, which are otherwise common in the Cretaceous or Paleogene sandstones, might indicate the Jurassic age. These characteristics, composition of lithoclasts and prevalence of garnet in heavy mineral spectra closely match those described by Krawczyk et al. (1987) and Łoziński (1956) from the Szlachtowa Formation in the Polish Pieniny Mts. Hence, we presume the early Middle Jurassic age of the analysed sandstones and their compositional affinity to the Szlachtowa Fm.

Ráztoky settlement – section in the bedrock of the Ráztoky Brook (Zázrivá district; GPS from N49.290347°, E19.135877° to N49.292299°, E19.137071°)

The contact of lithologically similar dark grey shales of the Upper Cretaceous Pupov Fm. and black shales of the Skrzypny/Szlachtowa Fm. can be determined in this section. In the lower part, samples Z54–Z58 (P. Gedl) collected from soft marly shales and harder marls yielded very few dinoflagellate cysts, mainly poorly preserved and rather not age-diagnostic species. Their palynofacies is composed of black, opaque phytoclasts (from 70 to 98%), highly altered dark-brown cuticles, and rare sporomorphs. Preservation of very rare dinoflagellate cysts is bimodal. Some specimens are darker, very poorly preserved, and indeterminable. The other are lighter and better preserved (*Palaeohystrichophora infusorioides*, *Spiniferites* sp., *Senoniasphaera*?, *Glaphyrocysta*?). Presence of *P. infusorioides* suggests the Late Cretaceous age of these marly shales (Fig. 2.10). Sample Z58 contained resedimented (abraded by transport) globotruncanids that might indicate their recycling into the upper Senonian or younger strata (probably the Zázrivka beds, Fig. 2.21f).

A different palynological content was found in samples Z59–Z61 from black argillaceous shales, which exposures start some 200 metres from the previous samples, and continue on a distance of some 300 metres (Fig. 2.5c). Sample Z59 (black shale) yielded very frequent, highly altered *Nannoceratopsis* specimens representing most likely *N. deflandrei*. Following samples yielded similar dinoflagellate assemblages accompanied by *Dissiliodinium* specimens: Z60 (8 metres above the stream) and Z61 (some 300 metres above; Fig. 2.10). Sample Z59 can be dated as Toarcian (a similar assemblage was found in sample Z42 from the Hryzeň section, see below), whereas remaining two samples are presumably slightly younger, Toarcian–Aalenian (?).

Calcareous benthic foraminiferal assemblage with dominant ophthalmidiids and spirillinids (similar to samples KV5A–C) was recovered from sample Z61 that also points to the Jurassic (most likely late Toarcian–Bajocian) age of the black shale sequence. Thus this sequence is akin to both the Skrzypny and Szlachtowa formations. Higher up in the gully, black shales are disappearing at the expence of fine-grained siliciclastic sandstones of the Dutkov vrch Fm. As visible also further east (Jedľovinka area), the whole sequence is overturned. We presume that this Lower–Middle Jurassic sandstone-black shale succession belongs to the Šariš Unit.

Surroundings of Jedľovinka Hill

On the ridge and slopes of Jedľovinka Hill, there are several sporadic small outcrops in black shales underlying in an overturned position the sandstone-dominated Dutkov vrch Fm. Samples Z22–28 and Z140–142 (P. Gedl) yielded mutually comparable palynofacies composed of land-derived palynodebris including various proportions

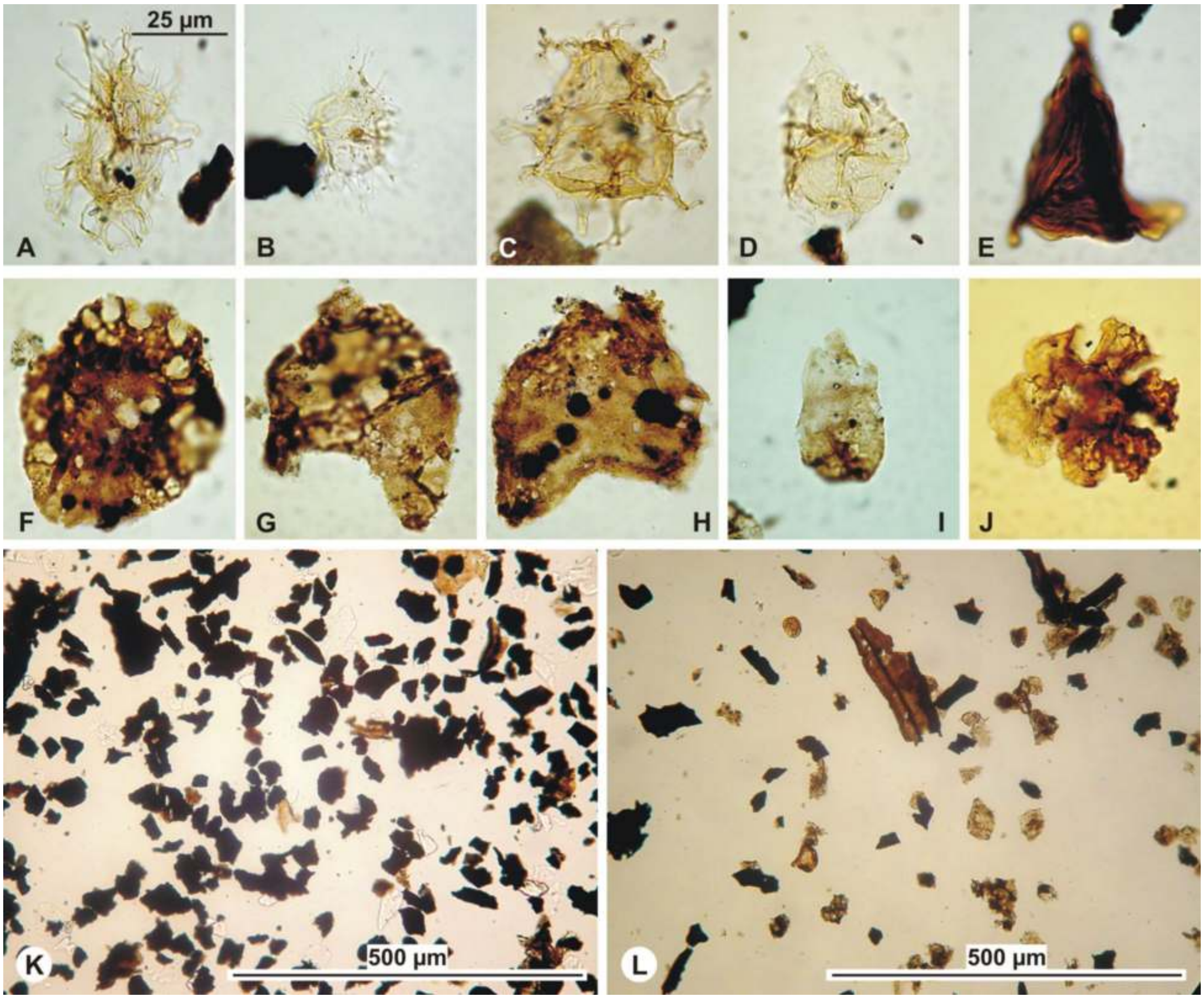
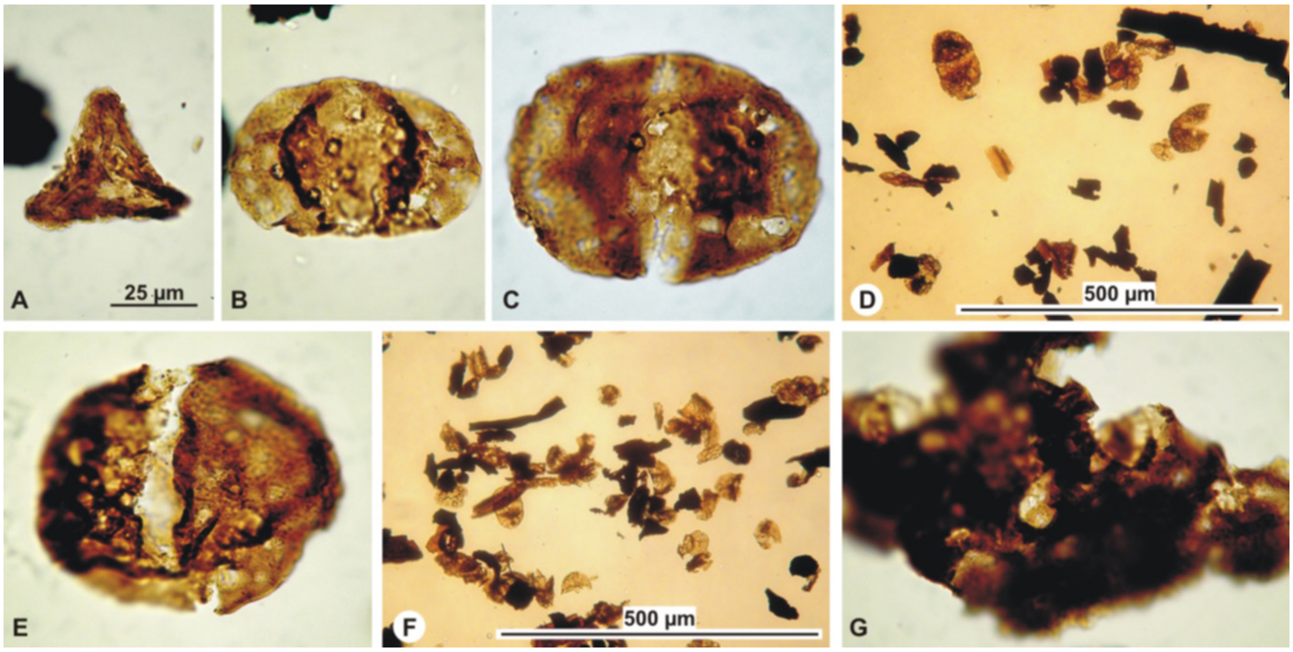


Figure 2.10 Palynology of the Ráztoky section (samples Z54–61; photo: P. Gedl). Scale bar in A refers to photomicrographs A–J. A: *Spiniferites* sp. (54); B: *Palaeohystrichophora infusorioides* (55); C: *Spiniferites* sp. (56); D: peridinioid (*Subtilisphaera*? sp.; 56); E: spore (55); F: spore (59); G, H: *Nannoceratopsis* spp. (59); I: *Phallocysta elongata* (61); J: foraminifera organic lining (60); K: palynofacies of sample 58; L: palynofacies of sample 61.



of cuticles, dark-brown and black phytoclasts and sporomorphs, mainly pollen grains, with moderate degree of maturity (Fig. 2.11). Neither dinoflagellate cyst, nor foraminifera organic linings have been found, hence no dating was possible. Presence of some agglutinated foraminifers and ostracods in few samples indicate the Sinemurian age of these deposits (Š. Józsa). On the northern Jedľovinka ridge, sandstones of the Dutkov vrch Fm. are underlain by the Szlachtowa-type flysch sediments (Fig. 2.5d) that were, however, barren of valuable microfossils. The lack of marine palynomorphs, but occasional presence of marine fauna suggests that strata exposed in the Jedľovinka sections might represent a proximal deltaic environment with high influx of terrestrial material.

Čierťaž section (GPS N49.285052°, E19.150854°; Zázrivá district)

In the lower part of the gully on the southern slopes of Jedľovinka Hill, a sequence of dark marls and calcareous sandstones is occasionally exposed. We correlate them with the Pupov Fm. Higher up, a succession of black and siliceous shales was studied and sampled. Hence the section again crosses the contact of the Pupov Zone to the SW from the Havrania Zone to the NE, similarly as in the Ráztoky section. In both cases these contacts are formed by the regionally important Ráztoky fault (Fig. 1.16).

Samples Z64–Z66 (P. Gedl) yielded palynofacies similar to those found in samples Z22–Z28 from the surroundings of Jedľovinka Hill by domination of terrestrial elements, i.e., palynodebris and sporomorphs. But they differ by occurrence of aquatic palynomorphs: foraminifera organic linings, acritarchs and dinoflagellate cysts (Fig. 2.12). The latter are infrequent; particularly very rare specimens have been found only in the sample Z64. These are poorly preserved *Nannoceratopsis* and much better preserved thin-walled specimens with multiple paraplate archaeopyles. The age of this sample cannot be precisely determined: most likely it represents Toarcian or Toarcian–Aalenian. The following sample Z65 (taken some 30 metres upstream, at its left bank, just below over 1 metre thick sandstone layer) is slightly younger, most likely latest Toarcian–Aalenian. It yielded *Nannoceratopsis dictyambonis* and *Phallocysta* sp. Even younger, Aalenian, could be the following sample Z66, collectred some 5 metres upstream from a shale exposure, which yielded *Nannoceratopsis evae*, *Phallocysta* sp. and *Dapsilidinium* sp. Dinoflagellate cyst assemblages are generally similar to those from the Skrzypny Shale Formation. However, palynofacies of samples Z64–Z66 closely resembles samples Z22–Z28 and differs from the typical one of the Skrzypny Fm. (see the Končitá Valley profile – stop B26, samples Z9–Z11 for comparison).

The foraminiferal assemblages in samples Z64–Z67 (Š. Józsa) differ from the above described Jurassic samples by decreased content of ophthalmidiids and spirillinids, but increased proportion of agglutinated foraminifera, mainly trochamminids and nodosarids. Such Jurassic foraminiferal assemblages with increased agglutinated foraminifera are similar to those reported from the Pieniny and Šariš segments of the PKB (Tyszka, 1994, 1999; Gedl & Józsa, 2015). The presence of common radiolaria among scarce spirilinids in the sample Z66 resembles samples from the Toarcian Hryzeň section (see below). The foraminiferal association supports the late Toarcian–Aalenian age of these samples determined by organic walled dinoflagellate cysts.

A different palynofacies and dinoflagellate cyst assemblage was found in dark spotted siliceous shales and radiolarites exposed in a neighbouring outcrop (sample Z67; Fig. 2.5e). This sample yielded palynofacies dominated by black, opaque phytoclasts and poorly preserved dinoflagellate cysts (Fig. 2.12). Their assemblage is composed of highly damaged specimens, mainly representing the *Systematophora-Adnatosphaeridium* morphotype and surprisingly well-preserved specimens of *Chytroeisphaeridia chytroides*. This association can be correlated with an assemblage found in the Sokolica Radiolarite Formation of presumably Oxfordian age exposed at Flaki, Poland, especially with the one from the sample Flk9 (Gedl, 2008).

Samples Z138 and Z139 come from outcrops located along the forest path above the gully, some 100 metres east of the elevation point 853 (GPS N49.2853889°, E19.1527983°). Samples were taken from radiolarite beds (Z139) interlayered by softer dark shale (Z138). Sample Z138 (dark shales) yielded black, opaque phytoclasts and frequent sporomorphs associated by less common but equally well preserved dinoflagellate cysts (however, some specimens are very poorly preserved). Radiolarite sample (Z139) yielded less frequent and much worse preserved dinoflagellate cysts, although relatively frequent *Chytroeisphaeridia chytroides* show an outstanding preservation. Both samples most likely represent

Figure 2.11 Palynology of the Jedľovinka Hill outcrops (samples Z140–142; photo: P. Gedl). Scale bar in A refers to all photomicrographs except for D and F. A: spore (140); B, C: pollen grains (both 140); D: palynofacies of sample 140; E: pollen grain (140); F: palynofacies of sample 141; G: highly degraded land plant tissue (142).

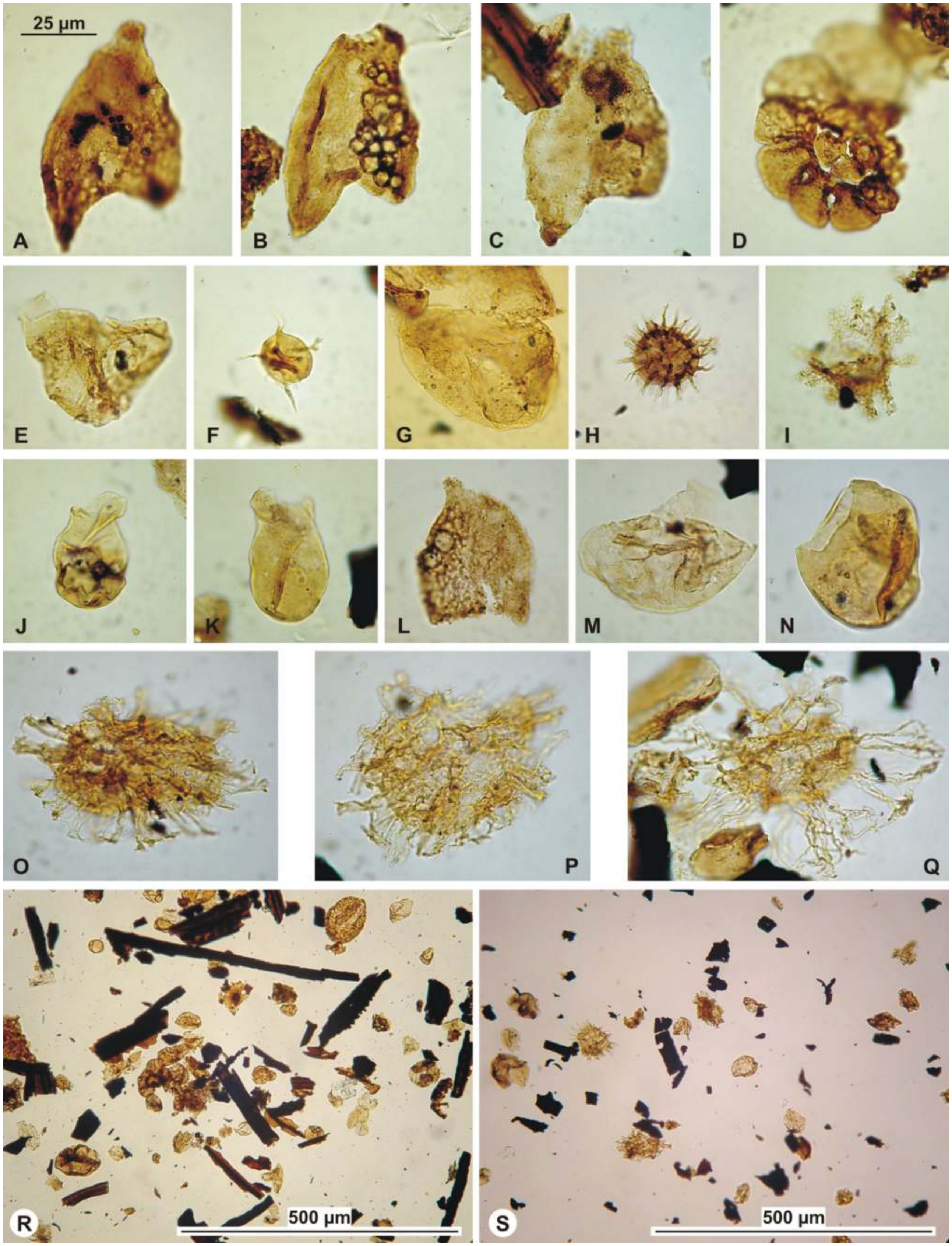


Figure 2.12 Palynology of the Čierťaž section (samples Z64–67; photo: P. Gedl). Scale bar in A refers to photomicrographs A–Q. A: *Nannoceratopsis gracilis* (64); B: *Nannoceratopsis gracilis* (65); C: *Nannoceratopsis* sp. (65); D: Foraminifera organic lining (64); E: *Dissiliodinium*? sp. (64); F: acanthomorphic acritarch of *Veryachium*-type (64); G: *Dissiliodinium* sp. (65); H, I: acanthomorphic acritarchs (65); J, K: *Phallocysta elongata* (66); L: *Nannoceratopsis evae* (66); M: *Dissiliodinium* sp. (66); N: *Chytroeisphaeridia chytroides* (67); O: *Adnatosphaeridium* sp. (67); P: *Adnatosphaeridium* sp. (67); Q: *Systematophora* sp. (67); R: Palynofacies of black shale (sample 65) composed almost entirely of terrestrial elements; S: Palynofacies of dark radiolarites (sample 67) with frequent dinoflagellate cysts.

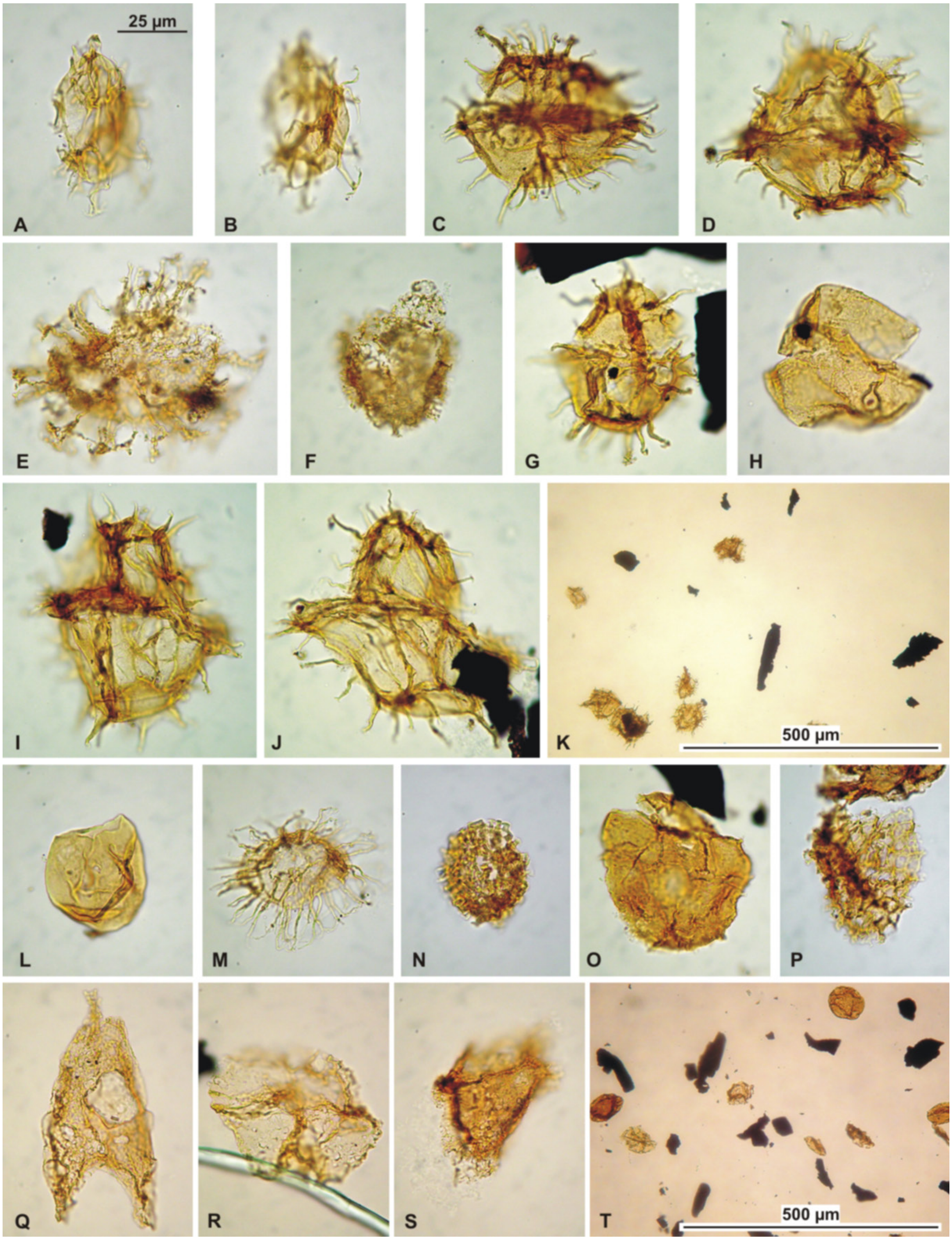


Figure 2.13 Palynology of the Čierťaž and Končitý sections (samples Z136–139; photo: P. Gedl). Scale bar in A refers to all photomicrographs except for K and T. A, B: *Spiniferites ramosus* (the same specimen, various foci; 136); C: *Ctenidodinium cornigerum* (137); D: *Ctenidodinium cornigerum* (137); E: poorly preserved specimen of *Adnatosphaeridium caulleryi* (137); F: poorly preserved specimen of *Ellipsoidictyum*? sp. (137); G: *Ctenidodinium cornigerum* (137); H: *Mendicodinium* sp. (137); I: *Ctenidodinium cornigerum* (137); J: *Ctenidodinium combazii*? (137); K: palynofacies of sample 137; L: *Chytroeisphaeridia chytroides* (138); M: *Impletosphaeridium varispinosum* (138); N: *Chlamydophorella* sp. (138); O: *Lithodinia jurassica*? (138); P: *Ellipsoidictyum*? sp. (137); Q: *Nannoceratopsis pellucida* (139); R: *Atopodinium prostatum* (139); S: *Meieurogonyaulax caytonensis* (139); T: palynofacies of sample 138.

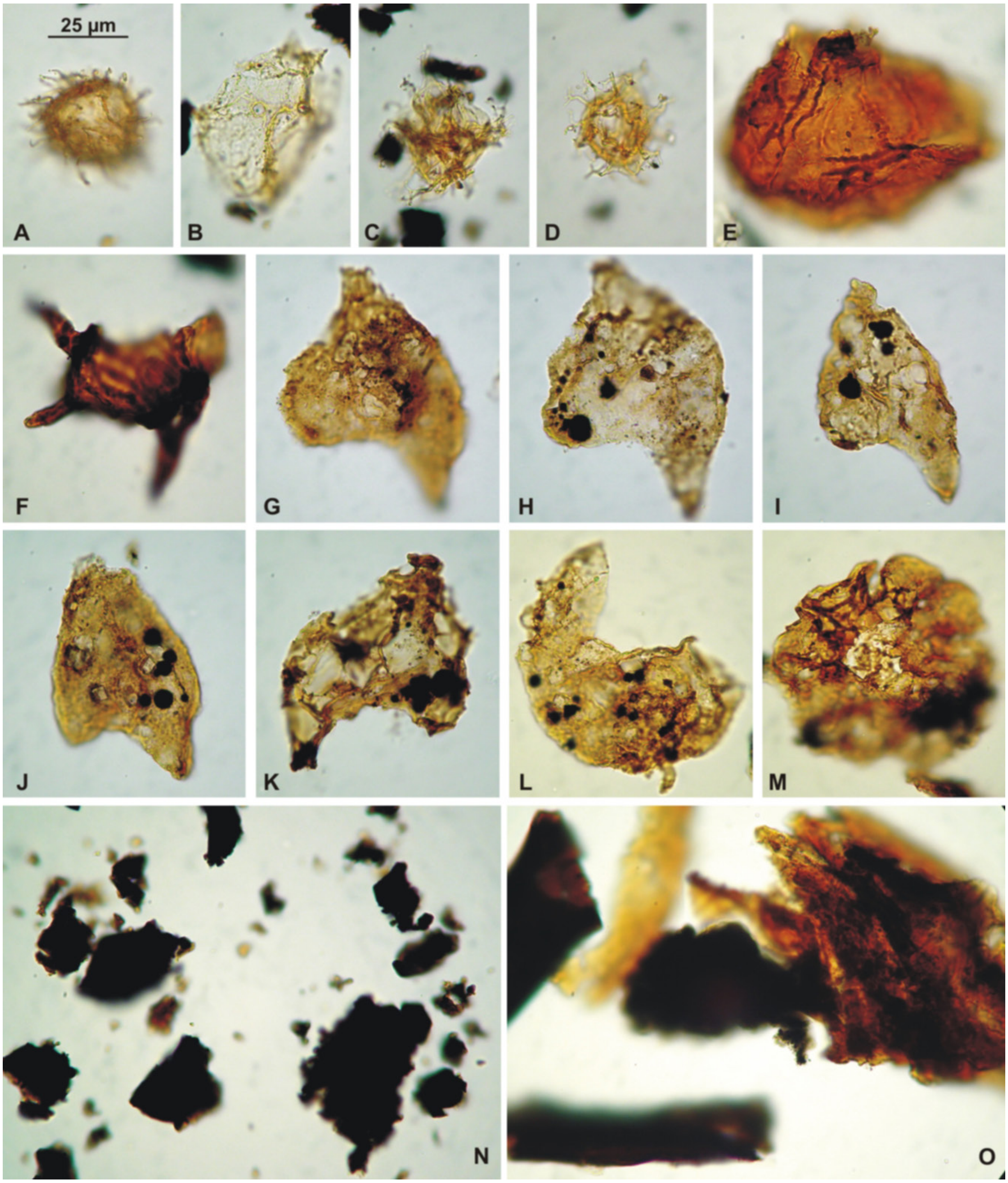


Figure 2.14 Palynology of the Končitý Hill section (samples Z130 and Z131; photo: P. Gedl). Scale bar in A refers to all photomicrographs. A, B: undetermined dinoflagellate cysts (both 130); C, D: poorly preserved specimens of *Spiniferites*? sp. (both 130); E: *Cribroperidinium*? sp. (130); F: spore (*Appendicisporites*? sp.) (130); G–J: *Nannoceratopsis gracilis* (all 131); K: *Nannoceratopsis dictyambonis*? (131); L: *Dissiliodinium*? sp. (131); M: foraminifera organic lining (131); N: palynofacies of sample 130; O: palynofacies of sample 131.

Bathonian – presence of *Atopodinium prostatum*, *Impletosphaeridum varispinosum* and *C. chytroides* (Fig. 2.13). Most probably, these samples represent the Opaleniec Fm. passing into the overlying Sokolica Fm.

Končitý section – narrow gully between Jedľovinka-Čierťaž and Končitý vrch hills (GPS in the middle part N 49.284399°, E19.159394°; Zázrivá district)

Samples Z130–Z136 (P. Gedl) were taken from a series of small exposures along a narrow steep gully creek some 300 metres west of Končitý vrch Hill (829 m a.s.l.).

Sample Z130 comes from dark shales exposed in the lowermost part of the section studied. It yielded large amount of palynological organic matter composed almost entirely of black, opaque phytoclasts with uneven ridges. Cuticles are rare, being commonly large and dark-coloured showing high maturity. Palynomorphs are represented by dark-coloured, but generally well preserved spores and less frequent pollen grains (Fig. 2.14). Some of the latter are poorly preserved. A single specimen questionably attributed to the genus *Appendicisporites* was found. Dinoflagellate cysts are very rare, rather light-coloured but poorly preserved. Most of them are indeterminable, but some may represent *Spiniferites*. A single thick-walled specimen of *Cribroperidinium*? was found. Precise age of sample 130 cannot be determined but most likely it is Cretaceous (co-presence of *Spiniferites*, *Cribroperidinium*? and *Appendicisporites*?). If so, the shales may be attributed to the Pupov Formation.

Sample Z131 is a siliceous black shale taken from the creek bottom (covered with travertine) some 150 m above the sample 130 (GPS coordinates: N49.283850°, E19.159267°; 728 m a.s.l.). It yielded palynofacies composed of overwhelming land-plant detritus: cuticles, dark-brown and black (opaque) phytoclasts, commonly elongated. Palynomorphs are represented by rare spores, foraminifera organic linings, and much more frequent, relatively well preserved dinoflagellate cysts (Fig. 2.14). Their assemblage is almost entirely composed of *Nannoceratopsis* (mainly *N. gracilis*). Very rare proximate forms resembling *Dissiliodinium* were found. The *Nannoceratopsis*-dominated assemblage suggests its Early Jurassic age, most likely late Toarcian (presence of *N. dictyambonis*?). Lack of dinoflagellate cyst species, which commonly occur in the Aalenian–Bajocian of the Pieniny Klippen Belt, rather excludes a younger age.

Following samples come from another small exposure that crops out some 50-m higher, in the right (eastern) creek bank, next to a block of Pieniny-type marly limestones. Two dark mudstone samples (Z132 and Z133) were taken from thin-layered, rhythmically alternating siliceous shale-silicite sequence. Samples were taken some 120 cm from each other. Both samples yielded similar palynofacies composed of black, opaque phytoclasts and moderately preserved commonly questionably determinable dinoflagellate cysts (Fig. 2.15). Dinoflagellate cysts assemblages are composed of proximate forms with apical archaeopyle representing (*Lithodinia* incl. *L. caytonensis*?, *Sentusidinium*, *Ellipsoidictyum*), 1P archaeopyle gonyaulacoids (*Tehamadinium*?, *Acanthaulax*?, *Cribroperidinium*?, *Rhynchodiniopsis*? *regalis*), 2–3P archaeopyle gonyaulacoids (*Diacanthum*?), *Pareodinia*, *Nannoceratopsis* (incl. *N. pellucida*?), multiple paraplate archaeopyle gonyaulacoids (*Dissiliodinium*?), and *Endoscrinium*. The mid-late Bajocian age of these assemblages can be suggested. It seems to be younger than an assemblage with *Dissiliodinium giganteum* known from the lower Bajocian of the PKB, and older than late Bajocian–Bathonian assemblages with characteristic *Ctenidodinium* specimens. Accordingly, this sequence could be attributed to transitional beds between the Opaleniec and Sokolica formations.

Some 50 m above (754 m a.s.l.), thick sandstone beds occur, which make a steeper course of the creek. Just below these sandstone beds an outcrop of dark, soft, massive shale occur. Two samples, Z134 and Z135 were taken some 100 cm from each other. Both samples yielded a similar palynofacies composed of land plant palynodebris and very frequent sporomorphs (mainly spores). Aquatic palynomorphs are represented by dinoflagellate cysts and rare foraminifera organic linings (Fig. 2.15). There are no other aquatic palynomorphs except for single specimens of acritarch Micrhystridium. Dinoflagellate cyst assemblage in sample Z134 is composed in 99% of *Nannoceratopsis* (mainly *N. gracilis* and *N. deflandrei*, rare specimens of *N. evae* occur); very rare specimens of *Phallocysta elongata* and *Scriniocassis*? Were also found. Sample Z135 yielded, in turn, less frequent dinoflagellate cysts dominated by *P. elongata* (rare *Nannoceratopsis*, including *N. dictyambonis* and *N. evae*?, and some thin-walled forms, possible *Dissiliodinium*). The co-occurrence of *P. elongata* and N. evae may indicate early Aalenian age of both assemblages.

Some 100 m higher the creek (783 m a.s.l.) thin-bedded flysch strata crop out. Sample Z136 was taken from pale, marly shale. It yielded palynofacies composed of black, opaque phytoclasts and highly altered cuticles; rare, poorly preserved sporomorphs occur. No dinoflagellate cysts have been found except for one specimen of excellently preserved *Spiniferites ramosus* (Fig. 2.13). Its presence may indicate Cretaceous age of the sample studied, but its state of preservation contrasts with preservation of phytoclasts and may be a result of contamination.

Sample Z137 was taken from an outcrop exposed along a forest path that traverses the southern slope at the height of 837 m a.s.l., some 150 m from its crossing with the creek (GPS N49.285067°, E19.156233°). Exposure shows almost vertically dipping radiolarite beds and siliceous black shales. Sample 137 taken from shale yielded an outstanding

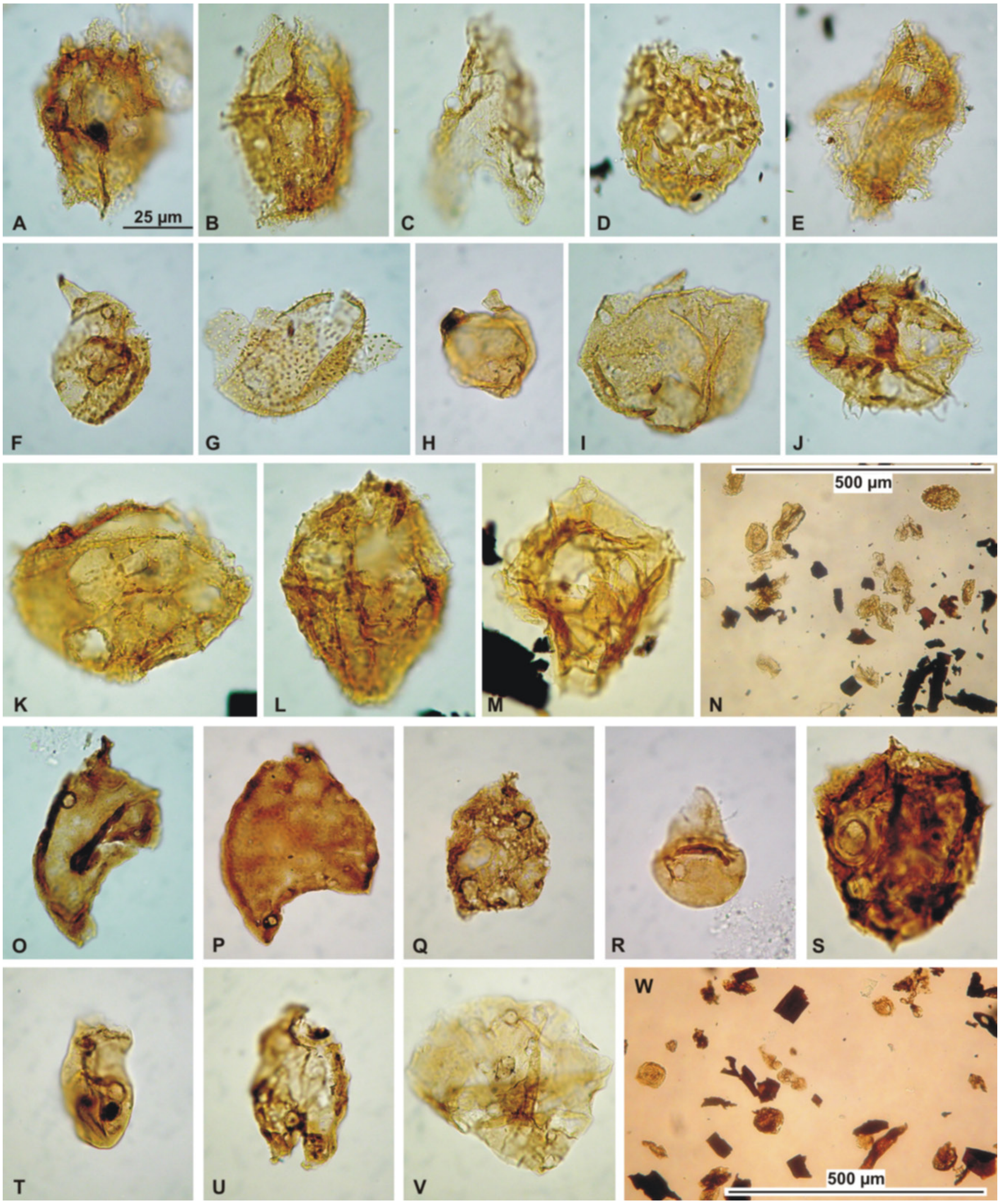


Figure 2.15 Palynology of the Končitý section (samples 132–135; photo: P. Gedl). Scale bar in A refers to all photomicrographs except for N and W. A, B: *Meieurogonyaulax caytonensis* (both 132); C: *Nannoceratopsis pellucida* (132); D: *Ellipsoidictyum*? sp. (132); E: *Rhynchodiniopsis*? *regalis* (133); F: *Pareodinia* sp. (132); G: *Sentusidinium* sp. (132); H: *Pareodinia*? sp. (132); I: undetermined taxon (132); J: *Dichadogonyaulax*? sp. (132); K: *Diacanthum*? sp. (132); L: *Korystocysta*? sp. (132); M: *Endoscrinium* sp. (133); N: palynofacies of sample 132; O, P: *Nannoceratopsis* spp. (134); Q: *Nannoceratopsis evae* (134); R: *Phallocysta elongata* (134); S: *Scriniocassis*? sp. (134); T: *Phallocysta elongata* (135); U: *Nannoceratopsis dictyambonis* (135); V: thin-walled taxon, possible *Dissiliodinium* sp. (135); W: palynofacies of sample 134.

palynofacies composed of black opaque phytoclasts and frequent dinoflagellate cysts represented in 90% by an acme of *Ctenidodinium cornigerum* associated by *Mendicodinium* (Fig. 2.13). This assemblage represents most likely Bajocian, although due to its almost monospecific composition it may also represent Bathonian. Presumably, this outcrop represents the Sokolica Radiolarite Formation.

In a stratigraphically overturned succession, the Lower Jurassic to Bajocian clastic sequence forming the Dutkov vrch – Jedľovinka ridge is followed by the Bathonian to Lower Cretaceous deep-water pelagic sediments that occur in klippen around settlement Grúne east of the Čierťaž section, as well as westward around Končitý vrch Hill. This succession consists of spotted greenish-grey marly and dark grey siliceous shales (Opaleniec and Sokolica fms, late Bajocian–Bathonian–Callovian; Fig. 2.5e) and klippen with red ribbon radiolarites (Czajakowa Fm., Oxfordian–Kimmeridgian; Fig. 2.5f), reddish and grey pseudonodular marly limestones with red cherts (Czorsztyn Fm., Kimmeridgian–Tithonian), and pale grey marly spotted and cherty limestones (Pieniny Fm., Tithonian–Barremian).

Pazderovci section – ridge between Malá and Veľká Havrania settlements (GPS N49.301662°, E19.180567°; Zázrivá district)

Four samples were taken from exposures along the field road on a ridge between Malá and Veľká Havrania (Pazderovci) settlements. Going down the ridge from north to south, first strongly disintegrated Pieniny-type limestones are cropping out at the contact with the Magura formations. Then an imbricated succession of alternating black siliceous shales or silicites and spotted marly limestones is present.

Palynological organic matter from all samples is characterized by a high degree of maturity (P. Gedl). Sample Z29 representing soft, dark shale yielded palynofacies composed of black (up to 90%), dark-brown phytoclasts and palynomorphs including very rare, poorly preserved dinoflagellate cysts questionably determined as *Nannoceratopsis*. A similar palynofacies but with better preserved dinoflagellate cysts was found in a following sample collected from soft, dark shale (Z30) taken some 2–3 metres from sample Z29. Presence of, i.a., *Nannoceratopsis dictyambonis* and *Phallocysta elongata* suggests the Aalenian age, and these dark shales can be included in the Skrzypny Shale Formation (Fig. 2.16).

Dark, siliceous, spotty marls (Z31) and dark radiolarites (Z32) coated by black Mn-oxides are cropping out farther south along the road. Sample Z31 yielded palynofacies composed almost entirely of black, opaque phytoclasts. Dinoflagellate cysts and sporomorphs are dark-brown, moderately to poorly preserved. Presence of thick-walled *Cribroperidinium* morphotypes suggests the Cretaceous age (Aptian?).

Sample Z32 (radiolarites) yielded an extremely altered palynomorphs, which due to high maturity degree are not determinable even at the generic level. Some specimens resemble by shape and morphology preserved Middle Jurassic taxa like *Meiourogonyaulax/Lithodinia*, *Ctenidodinium*, *Rhynchodiniopsis* and *Dissiliodinium/Kallosphaeridium* (Fig. 2.16). Any of specimens found bears similarities with typical Cretaceosu genera found in the PKB. This extremely poorly preserved assemblage bears a superficial similarity with Bathonian assemblages described from the Sokolica Radiolarite Fm. in Polish sector of the PKB. Therefore, an analogous age can be suggested for radiolarites, from which sample 32 was taken.

Samples Z29 and Z30 (Š. Józsa) yielded a foraminiferal assemblage with dominant ophthalmidiids and spirillinids and subordinate trochaminids and nodosarids. Such assemblages share signifficant similarities with the ?Lower–Middle Jurassic assemblages reported from the Pieniny and Šariš sector of the PKB (Tyszka, 1994, 1999; Gedl & Józsa, 2015). The planktonic foraminifera from the sample Z31 point to the late Albian age, based on the first occurrence of *Rotalipora appenninica* (Morrow) in the assemblage.

Preliminarily, we range this tightly imbricated succession to the Šariš Unit. Interesting is the presence of mid-Cretaceous spotted marly and siliceous shales that perhaps could be correlated with the Wronine and/or Hulina formations (see Fig. 2.6).

Upper Cretaceous formations characteristic for the Šariš Unit occur in some places within the Havrania Zone as well. Along the narrow northernmost strip of the Havrania Zone, W–E striking elongated lenses of deep-water pelagic sediments squeezed between rocks of the Subpieniny Unit (Czorsztyn Succession) and Paleogene flysch sediments of the Magura units are present. This situation can be observed for instance in the field road grooves on the southern ridge of Janíkov vrch Hill above Grúne settlement (GPS N49.299122°, E19.147031°) and in the saddle Priehyba between Javorinka and Havranský vrch hills (GPS N49.301556°, E19.166124°; Zázrivá district). Variegated, mostly cherry-red, non-calcareous shales with beds of turbiditic quartzose sandstones (supposedly the Upper Cretaceous Malinowa Fm.) are cropping out in these occasional exposures.

The Hryzeň Hill section (GPS N49.283299°, E19.175561°; Zázrivá district)

Hryzeň Hill is a narrow side ridge on the left

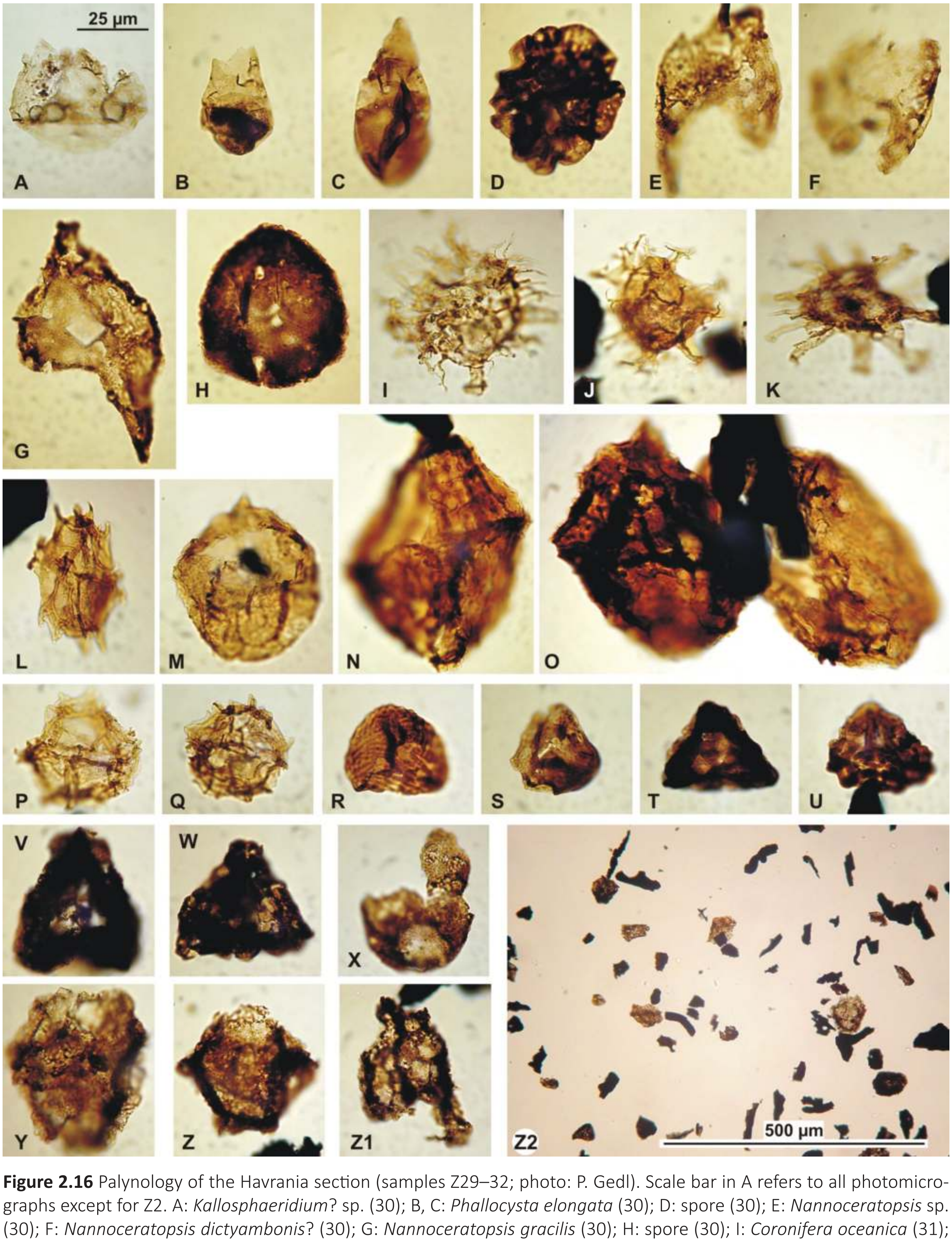


Figure 2.16 Palynology of the Havrania section (samples Z29–32; photo: P. Gedl). Scale bar in A refers to all photomicrographs except for Z2. A: *Kallosphaeridium*? sp. (30); B, C: *Phallocysta elongata* (30); D: spore (30); E: *Nannoceratopsis* sp. (30); F: *Nannoceratopsis dictyambonis*? (30); G: *Nannoceratopsis gracilis* (30); H: spore (30); I: *Coronifera oceanica* (31); J: *Spiniferites* sp. (31); K: *Florentinia*? sp. (31); L: *Spiniferites* sp. (31); M: *Cribroperidinium*? sp. (31); N: *Cribroperidinium orthoceras* (31); O: two specimens of *Cribroperidinium* sp. (31); P, Q: *Pterodinium* spp. (31); R–U: spores (31); V, W: spores (32); X: *Kallosphaeridium*? sp. (32); Y, Z: poorly preserved dinoflagellate cysts (32); Z1: *Nannoceratopsis* sp. (32); Z2: palynofacies of sample 32.

Figure 2.17 The Hryzeň section (photos P. Gedl): a – Toarcian black anoxic siliceous shales (sample Z41); b – Fleckenmergel-facies spotted marly limestones (sample Z42).

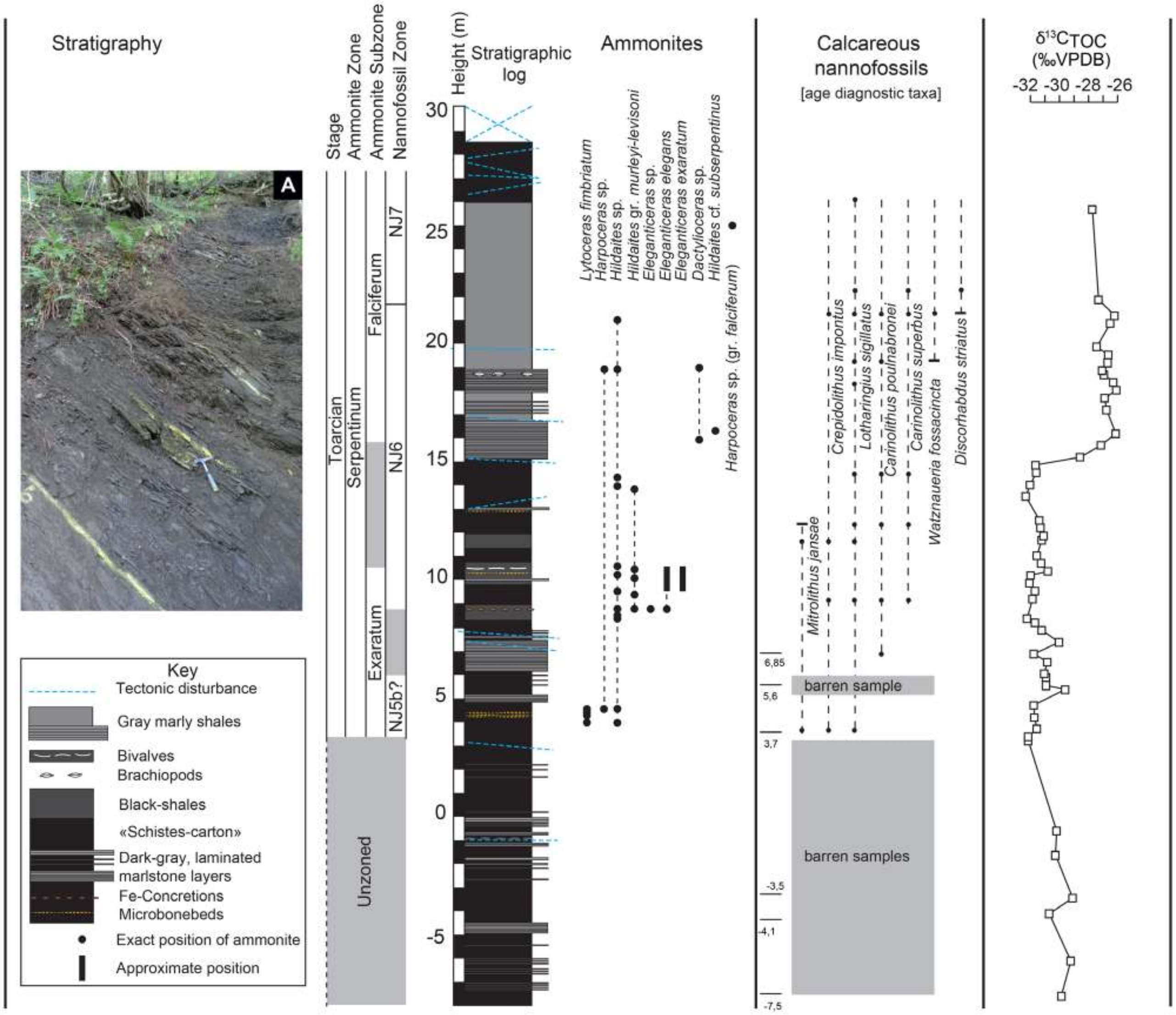


Figure 2.18 Lithology, biostratigraphy and $\delta^{13}C_{TOC}$ of the Hryzeň succession with distribution of important ammonite and calcareous nannofossil taxa (Suan et al., 2018). A – Field view of the Lower Toarcian black shale succession between 6 m and the bottom of the section (upper right corner, overturned stratigraphical position).

side of the Kozinský potok Brook Valley (Kozinská settlement), approximately 800 m east-northeast of Zázrivá Centre and 300 m east of the crossroad Končitá–Havranská–Kozinská (stop B22 below). The ridge is predominantly formed by grey spotted marly limestones that most probably belong to the middle Lower Jurassic Krempachy Marl Formation (or Allgäu Fm., see Fig. 2.6). In the middle part of the ridge, there are signs of old mining attempts in black, brown weathered Mn-bearing shales. In addition, clasts of micaceous quartzitic sandstones and black crinoidal limestones occur in the debris. The latter resemble allodapic limestones occurring in the upper part of the Szlachtowa Fm. Together with the black shale profile in a coomb bellow the ridge (Figs 2.17 and 2.18A), we tentatively affiliate all these rock formations with the Šariš Unit (Grajcarek Succession – cf. Suan et al., 2018).

The black shale sequence at the washed-out bank of the Kozinský potok Brook on foots of Hryzeň Hill was studied by Schlögl et al. (2012) and later in detail by Suan et al. (2018). Based on the ammonites and calcareous nannofossils (Figs 2.18 and 2.19), the early Toarcian age was proposed for this sequence and was related to the Toarcian Oceanic Anoxic Event (T-OAE). Informally, this sequence is designated as the "Hryzeň beds" in Fig. 2.6. The locality records organic-rich sedimentation at the margin of NW-European shelf and provides the first record of the T-OAE from the whole Pieniny Klippen Belt (Suan et al., 2018). The studied section is 36 meters thick and is in a stratigraphically reversed position, with a dip of strata oriented to the SW. The succession is affected by tectonic complications (Fig. 2.18) consisting of minor faults with centimeter to decimeter scale slip that do not disturb the stratigraphy significantly, however. The lower and middle parts of the studied section are essentially composed of dark-grey to black and finely laminated shales (black shales or "schistes-carton") interrupted by dark grey laminated siltstone-mudstone beds in places. Black shales are locally rich in macrofauna, including ammonites, soft bodied cephalopods (Schlögl et al., 2012), bivalves, crustaceans and fish remains, which are mostly represented by disarticulated specimens and rare, articulated ones. Marls in the upper part of the succession show a grey colour.

Geochemical analyses (Suan et al., 2018) show that the lowermost Serpentinum ammonite Zone records high total organic carbon (TOC) contents (2 to 5 wt%)

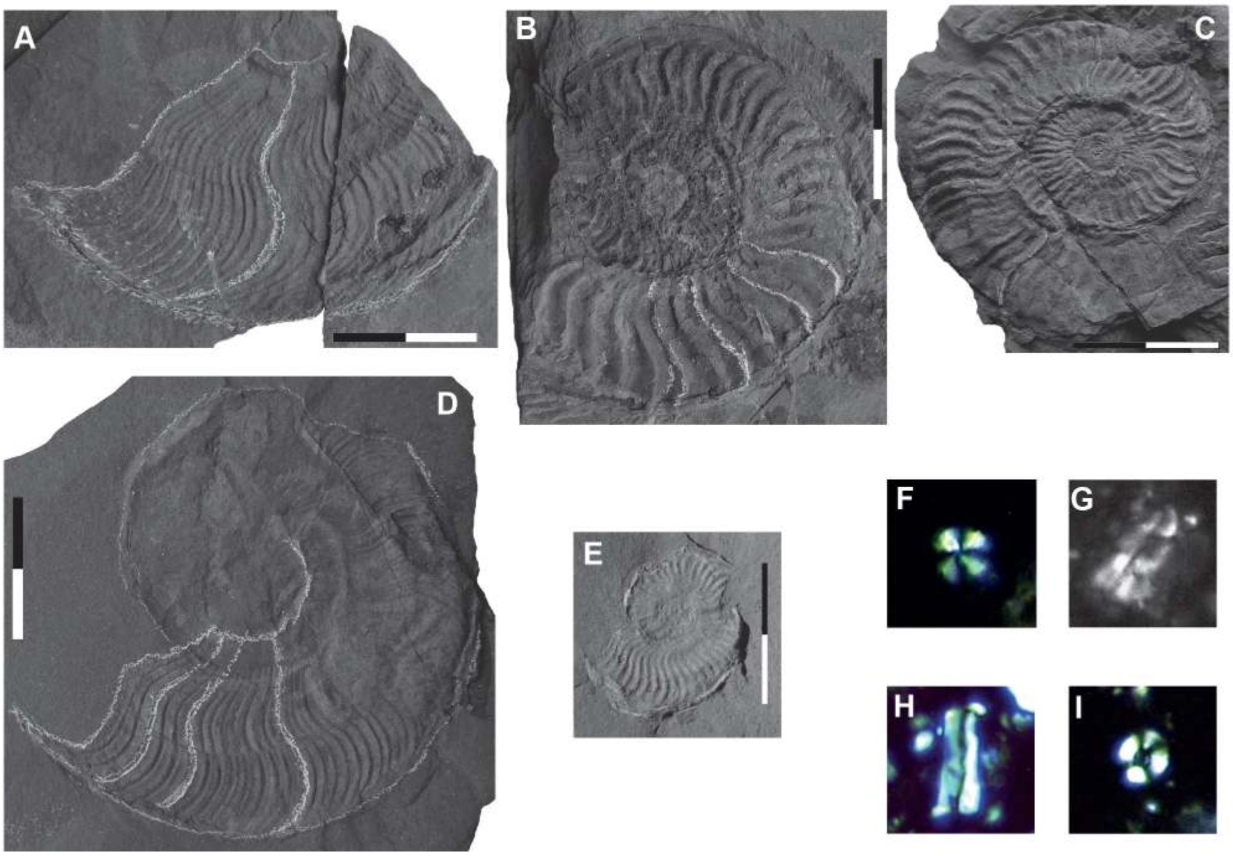


Figure 2.19 Some important ammonite and calcareous nannofossil taxa from the Hryzeň section (Suan et al., 2018). A – *Eleganticeras elegans*; B and C – *Hildaites* gr. *murleyi-levisoni*; D – *Eleganticeras exaratum*; E – *Eleganticeras* sp. juv.; G – *Watznaueria fossacincta*; H – *Carinolithus superbus*; I – *Carinolithus poulnabronei*; J – *Lotharingius sigillatus*. Scale bars for A–E are 2 cm.

and very low organic carbon isotope values (from −30 to −32‰) characteristic of the T-OAE negative carbon isotope excursion in coeval sites (Fig. 2.18). The size of the pyrite framboids, the high S contents independent on TOC, low sulfur isotope values ($\delta^{34}S < -15‰$) and predominance of amorphous fraction in palynofacies indicate that the deposition of this interval took place under sulphidic and anoxic conditions (euxinia) interrupted by brief events of improved oxygenation. The total sulfur contents are exceptionally high (4–12 wt%), a feature that can be explained by enhanced syngenetic pyrite formation due to the combination of euxinic conditions and high export of reactive iron from suboxic porewaters of adjacent shallower marginal sediments.

Ammonites and calcareous nannofossils provide the base for the biostratigraphy of the black shales. Co-occurrence of scarce *Eleganticeras elegans* (Fig. 2.19A) and E. exaratum (Fig. 2.19D), and common *Hildaites* ex. gr. *murleyi-levisoni* (Fig. 2.19B, C) in the middle part of the section indicates the early Toarcian Exaratum Subzone of the Serpentinum Zone (Fig. 2.19). Overlying grey marls are poor in ammonites, however *Hildaites* cf. *subserpentinus* and Harpoceras ex. gr. falciferum indicate the Falciferum Subzone of the late Serpentinum Zone. The first occurrence (FO) of calcareous nannofossil *C. superbus* (Fig. 2.19H) marks the base of the NJ6 zone and the FO of *Discorhabdus striatus* characterizes the base of the NJ7 zone (Bown & Cooper, 1998; Mattioli & Erba, 1999).

Seven samples (Z34–Z41, P. Gedl; Figs 2.17 and

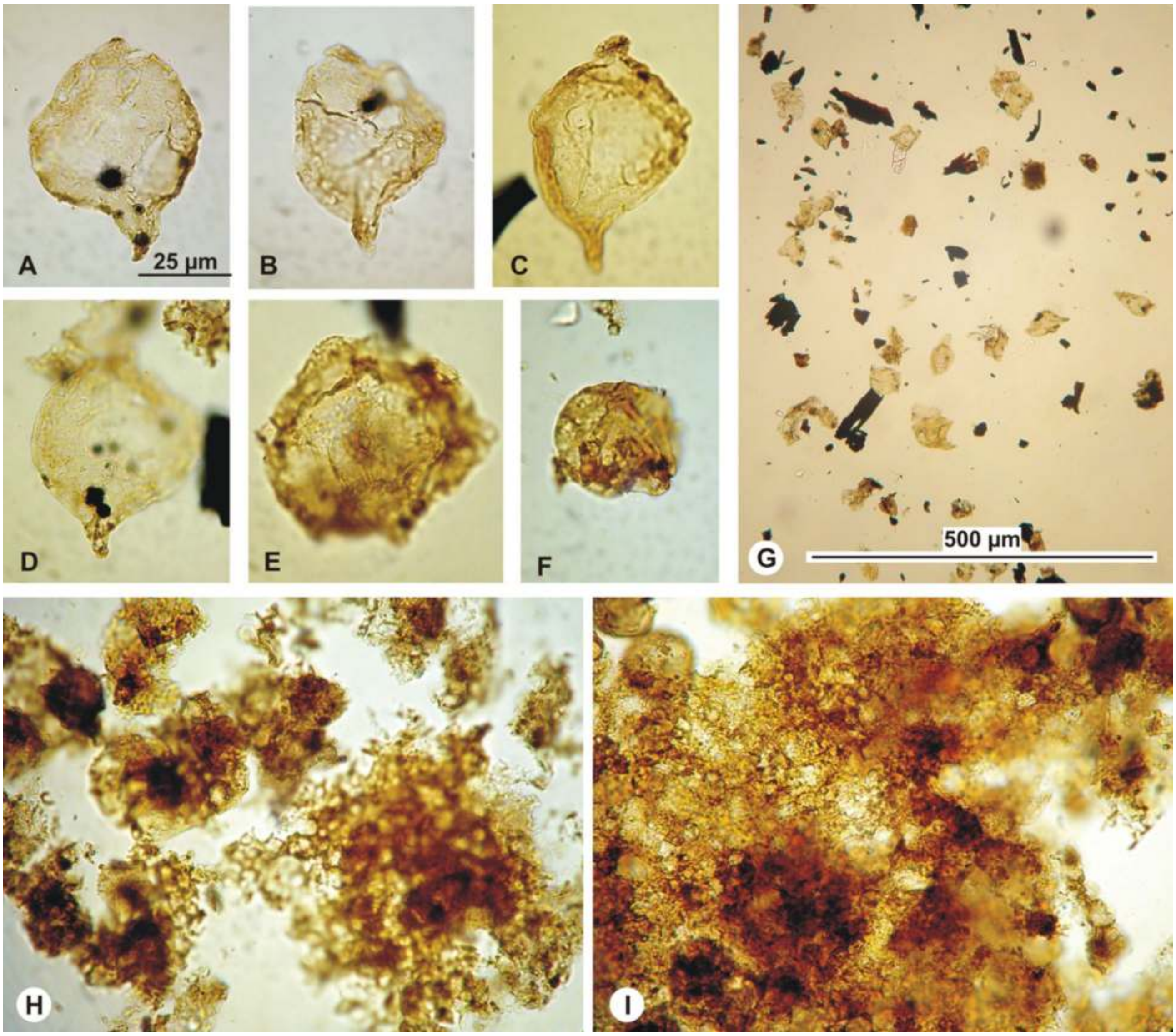


Figure 2.20 Palynology of the Hryzeň section (samples Z34–42; photo: P. Gedl). Scale bar in A refers to all photomicrographs except for G. A, B: *Nannoceratopsis magnicornus* (42); C: *Nannoceratopsis* sp. (42); D: *Nannoceratopsis magnicornus* (42); E: *Scriniocassis* sp. (42); F: sporomorph (41); G: palynofacies of the Krempachy Marl Formation exposed in the lowermost part of the succession studied (42); H, I: structureless organic matter dominating in shaly part of the Krempachy Marl Formation exposed (41).

2.20) collected from the overturned succession of black Toarcian shales at the Hryzeň section yielded palynofacies dominated by amorphous organic matter and fine palynodebris composed of land-derived plant remains (cuticles, black, opaque phytoclasts). Palynomorphs are represented by infrequent sporomorphs and aquatic forms representing acritarchs, prasinophyceans and some specimens of uncertain origin (possibly of Dinoflagellate affinity). Proportion of these palynofacies elements varies from sample to sample. Cuticles predominate in samples from the eastern part of the exposure (Z34–Z37; presumably upper part of the succession? see Suan et al., 2018), whereas amorphous organic matter occurs in samples from the middle and western part of exposure (Z38, Z41; basal part of the succession?). Similar results were obtained by Segit (in Suan et al., 2018), although precise correlation is difficult due to lack of precise sample location and tectonic disturbances.

All these data demonstrate that accumulation of black shale from the Hryzeň section took place during Toarcian Anoxic Event in a basin influenced by terrestrial input and stratified water column with anoxic conditions at least in the bottom part. Changes of palynofacies show some fluctuations in the oxygen regime, from anoxic (reflected by amorphous organic matter) to slightly better ventilated in samples where palynodebris is preserved.

A completely different palynofacies was found in marls that crop out in the westernmost part of the Hryzeň section. A sample Z42 from the Krempachy Marl Formation (or Allgäu Fm.) exposed just at the stream level yielded a very rich dinoflagellate cyst assemblage (mainly *Nannoceratopsis magnicornus*). Their presence and simultaneous lack of amorphous organic matter points at well ventilated water column during accumulation of this part of the Krempachy Fm. Presence of *N. magnicornus* suggests the Upper Pliensbachian age of this part of the Krempachy Marl Fm., which is older than the Toarcian black shales exposed above. However, the here outcropping Fleckenmergel/Fleckenkalk-facies strata (Fig. 2.17B) can represent an amalgamated body of similar lithofacies of different ages, as suggested by ammonites of the genera *Dumortieria* and *Pleydelia* collected here by Schlögl et al. (2012), which indicate the late Toarcian age.

2.2 Pupov Zone

In the eastern segment of the Varín PKB sector, the Pupov Zone embraces its substantial part that stretches in a 2–3 km wide belt in the centre of the PKB between the Havrania Zone in the north and the westward wedging-out narrow Plešivá Zone to the south. The easternmost part of the Pupov Zone is obliquely cut by the Ráztoky Fault (Fig. 1.16). The zone is almost exclusively built up by the Senonian calcareous flysch – the Pupov Formation intercalated by variegated marlstones of the Campanian Púchov (Gbeľany) Formation. Strangely enough, this zone is devoid of any klippen. The Pupov Zone and Pupov Fm. are named after the broad Pupov Hill (1,096 m a.s.l.) which dominates the PKB topography in this region.

Unlike the bounding and internally strongly imbricated Havrania and Plešivá zones, the Pupov Zone has a relatively simple structure with moderately north-dipping sedimentary formations. However, according to sole marks of turbiditic sandstones, the bedding of the Pupov Fm. is overturned at the majority of outcrops. This makes interpretation of the general structure of the zone difficult, since regognizable mesoscopic fold structures are very rare. Hence the entire homoclinally north-dipping Pupov flysch complex appears to be overturned due to back-tilting and back-thrusting, whereby the whole stratigraphic succession was probably completely back-rotated. In our opinion, the strips of Campanian variegated marls within the Pupov flysch (originally interpreted as tectonic windows of the Kysuca-Pieniny Unit from below the Manín Unit by Haško, 1978b and Haško & Polák, 1979) represent sheared synclines and indicate doubling of the Pupov Fm. Accordingly, the Pupov Fm. occupies the central position in the PKB syclinorium and attains the thickness of up to 1,000 metres.

2.2.1 Pupov Formation

The Pupov Formation (defined as Pupov Beds by Andrusov, 1938, 1945) consists of several members. The lower, Coniacian–Santonian part is composed of monotonous flysch complex of alternating beds of fine-grained calcareous sandstones and grey calcareous claystones and mudstones. The turbiditic nature of sandstones is revealed by typical features of Bouma sequences like sporadic graded bedding, various sole marks, current ripples, and by the parallel or convolute lamination often accentuated by plant debris in upper parts of sandstone beds.

Turbidite sequences grade from distal mud turbidites with scarce thin laminae of fine-grained sandstones to siltstones up to proximal with prevalence of thick-bedded, occasionally amalgamated calcareous sandstones. Bodies of pebbly mudstones and conglomerates occur in places, which become to be more frequent westward (e.g. Panská Lúka settlement of Terchová village). Preliminarily, we name this typical flysch sequence as the "Veľhora beds", since the best outcrops currently occur along new forrest roads around massive Veľhora Hill (Mravečník, 993 m a.s.l.) west of Terchová (Figs 1.16 and 2.21a).

The Veľhora beds are overlain by the Campanian – lower Maastrichtian, Púchov-type variegated marlstones. In the Varín sector, these marlstones have been termed "Gbeľany beds" (e.g. Haško & Samuel, 1977). Their thickness is estimated to about 50 metres (Fig. 2.21c). In the Terchová area, the uppermost part is composed of probably Maastrichtian, several dozen metres thick shallow-water gritty siltstones used as natural facing and sharpening stone (quarry on Kýčera Hill above Terchová; Fig. 2.21d). We designate this sequence informally as the "Poľany beds" (named according to the Poľany saddle northeast of the Kýčera quarry). The reason to choose this name is that the term Kýčera Beds, which would be fitting better, is already formally occupied by another sedimentary formation. Probably the youngest part of the Pupov Fm. is exposed in the easternmost, wedging-out part of the Pupov Zone, mainly in the Zázrivka Brook bedrock in village Zázrivá. There, the thin-bedded to laminated, mud-rich distal turbidites and in part bioturbated hemipelagites show the Campanian to Maastrichtian age, but contain nannoplankton species of the earliest Paleogene NP1 zone in places (see the Zázrivka bedrock section B below; Fig. 2.21e). Preliminarily, we name these sediments as the "Zázrivka beds". Its thickness is difficult to estimate; it probably reaches several hundred metres.

There are two basic problems with the Pupov Formation – its age and tectonic attribution to a particular unit. Flysch formations are usually poor in fossils; moreover, microfossils are often redeposited from older formations. This is valid also for the Pupov Fm., where previous biostratigraphic data are very rare and documentations of localities or sections are inadequate. For instance, Andrusov (1938) attributed the Albian–Cenomanian age to the Pupov Fm., Andrusov and Scheibner (1960) and Scheibner (1968b) assumed the Santonian–Campanian age, Andrusov and Samuel (1973) early Senonian, Haško (1977) Coniacian to early Santonian, or Haško and Polák (1979) Albian to early Santonian and Potfaj et al. (2003) Turonian–Santonian. As pointed out by Potfaj et al. (2003), the Pupov Fm. is lithologically very similar to the Turonian–Santonian? Snežnica and Sromowce formations of the Kysuca Succession, therefore their distinguishing in the field is almost impossible. Nevertheless, our recent biostratigraphical data specified below indicate that substantial part of the Pupov Formation is of Coniacian–Santonian age, but its upper levels above the Campanian variegated marls reach the late Campanian–Maastrichtian or even Paleocene age.

Tectonic affiliation of the Pupov Fm. is even more complicated problem. Considering its lithology, age and structural position, it has no direct analogues in the PKB structure. Andrusov (e.g. 1938) attributed all Upper Cretaceous flysch formations of the Varín sector to the Pieniny (Kysuca) Unit, while Andrusov and Scheibner (1960) united all Senonian formations of the PKB to the "third sedimentary cycle" discordantly overlying various Jurassic–Lower Cretaceous successions. Later on Scheibner (1968b) correlated these sediments with the Klape Unit (Albian–Turonian) that overrode the Kysuca Unit before the late Santonian and then was transgressed by the Pupov Fm. ranging up to the Danian – the view that can be partly accepted. However, this model, which was based on the supposed Late Cretaceous age of the nappe overthrusting of PKB units, was abandoned in the 1970-ties, when the concept of "Laramian" folding as the main thrusting event in the PKB was generally adopted (e.g. Andrusov, 1974). Therefore, Began and Samuel (1975), Haško (1977, 1978b), Haško and Samuel (1977), Haško and Polák (1979) connected the Pupov Fm. with the Klape resp. Manín nappe units, i.e. as the upper level of the undivided Albian to Santonian–Maastrichtian? flysch succession (see also Bezák et al., 2009). The nappe position of the Manín-Klape Unit was documented by tectonic windows of Campanian variegated marls (Púchov and/or Gbeľany beds) affiliated with the Kysuca Unit (e.g. Haško, 1978b). However, we presume that these supposed windows do not exist and the Púchov marls overlie in a normal stratigraphic succession the Coniacian–Santonian Veľhora beds of the Pupov Formation. On the other hand, connection of the Pupov Fm. with some "non-Oravic" unit (Klape or Drietoma) as its post-thrusting, Gosau-type cover cannot be documented either (but see stop A4 below). Therefore, the presence or absence of of these Fatric units in the Terchová–Zázrivá area of the PKB remains questionable.

Summing up, we presume that the lower part of the Pupov Fm. is composed of the Coniacian–Santonian calcareous turbiditic sandstones with marly intercalations (Veľhora beds), followed by Campanian grey and variegated marlstones (Gbeľany beds). The uppermost sequence is composed of probably Maastrichtian shallow-water sandstones and siltstones (Poľany beds). In turn, the youngest hemiturbidites (Zázrivka beds) show deepening of the sedimentary environment again. Supposedly, the Paleocene–Middle Eocene sediments of the Myjava-Hričov Group exposed west of village Varín around village Teplička nad Váhom (Fig. 1.4; cf. Samuel & Haško, 1978), and especially the succession described at Hradisko locality near Žilina (e.g. Samuel, 1972; Hansen et al., 1990) might represent the continuation of the Senonian succession of the Pupov Fm. Furthermore, loose blocks of Paleocene reefs (Thanetian; Buček & Köhler, 2017) occurring near settlement Berešíci (Terchová district) described by Scheibner (1968a) indicate the close connections of the Pupov Fm. with the "Peri-Klippen Paleogene" (Myjava-Hričov Group), too (see also Fig. 3.19 below).

Although not definitely clear, we consider the Pupov Fm. as an element of the post-thrusting, wedge-top basins associated with the Gosau Group (cf. Plašienka & Soták, 2015 and references therein). If so, the Pupov Fm. might represent the upper, post-thrusting, but still syn-orogenic sequence transgressing over the Klape and/or Drietoma Unit.

2.2.2 Important field outcrops and sections

The Pupov Formation covers quite large areas, but good outcrops or sections are rare. These are either bedrock exposures of incised creeks, or artificial cuts of forest roads. In the first case, the quality of outcrops is affected by seasonal changes, while the road cuts are quickly destroyed by slope movements and covered by scree and vegetation. Comparatively good, but discontinuous exposures can be found for instance in the Hlboké Valley NW of Vyšné Kamence settlement (Terchová, green touristic trail), along the wriggling forest road west from the Lutiška saddle and up the summit of Veľhora (Mravečník) Hill (993 m a.s.l. Fig. 2.21a), forest road from Šípková settlement (Struháreň stream valley, Terchová) towards SE on the northern slopes of broad Pupov Hill, Tesná dolina Valley between Pupovec and Pupovček hills NW of Dolina settlement (Zázrivá), or several exposures in the main and side stream bottoms around Ráztoky settlement (Zázrivá). These belong mostly to the Veľhora beds, the latter to the Zázrivka beds (Fig. 2.21f). Then the probably best exposed profile of the upper part of the Pupov Fm. (Zázrivka beds) is present in bedrock exposures of the Zázrivka Brook in Zázrivá Centre (Fig. 2.21e; see the Zázrivka field section B below).

At all these localities, the Pupov Fm. is formed by various parts of deep-marine turbiditic fans – from distal sequences composed mainly of claystones and mudstones with thin beds of fine-grained calcareous sandstones or siltstones, through regularly bedded sequences of alternating shales, marls and sandstones, up to proximal, thick-bedded sequences dominated by sandstones and containg also conglomerated bodies in places. Stratification is mostly steeply N-dipping, but various sole marks indicate almost uniformly the overturned bedding. Where available, the foraminiferal assemblages point to the Senonian (Coniacian–Santonian to early Campanian) age of this lower part of the Pupov Fm. (Veľhora beds). The Santonian age was confirmed also by finding of a single specimen of bivalve *Inoceramus balticus* (Fig. 2.21b). Samples for calcareous nannoplankton (elaborated by M. Jamrich) taken from the bedrock and banks of the Ráztoky Stream (ZN24 – GPS N49.277974°, E19.157460° and ZN25 – N49.286573°, E19.135053°) yielded, i.a., Campanian to Paleocene species ?*Prinsius dimorphosus*, *Reinhardtites anthophorus*, ?*Fasciculithus* sp., *Eiffellithus eximius*, *Uniplanarius trifidus*, *Zeugrhabdotus diplogrammus*, *Reinhardtites levis*. Hence this locality would represent the Zázrivka beds.

As it follows from these scarce biostratigraphic data, the lower Coniacian–Santonian–Campanian part of the succession is formed predominantly by thick-bedded, sandstone-rich turbidites, which are gradually passing upwards into the upper Campanian–Maastrichtian shale-mudstone sequence (Fig. 2.21c). In the Terchová district, this thinning- and fining-upward succession is followed by non-turbiditic, thin-bedded or laminated, very fine-grained gritty quartzose-calcareous sandstones to siltstones with bivalve burrows, which indicate shallowing of the sedimentary environment during deposition of the Poľany beds. The Poľany beds of the Pupov Formation are partially exposed around Oblaz Hill with touristic scenic vista tower "Heart of Terchová" (GPS N49.261381°, E19.027762°), but perfectly in the Terchová-Kýčera quarry (GPS N49.268612°, E19.056171°). There, the fine-grained, in part laminated calcareous sandstones to siltstones with uneven bedding planes and typical cm-sized "nipples" – probably bivalve burrows – are exploited as the facing stone, which is frequently visible on buildings, pavements or walls in surrounding regions (Fig. 2.21d). The finest siltstones are composed of calcite particles sized 10–20 µm and disseminated larger (40–60 µm) abrasive quartz grains. During mining, these gritstones are selectively extracted and then elaborated as the high-quality whetstone known under the trade mark "Rozsutec". Badly preserved tiny globular chambered both biserial (heterohelicids) and trochospiral morphotypes (muricohedbergellids) of planktonic foraminifera enable only a very rough age determination to the ?Turonian–Santonian–Maastrichtian.

Figure 2.21 Phototable of the Pupov Formation (photos a–e shot by D. Plašienka, f by P. Gedl): a – thick-bedded calcareous turbiditic sequence of the Veľhora beds (Coniacian–Santonian), northern slopes of Mravečník Hill, Š. Józsa for the scale; b – specimens of bivalve *Inoceramus balticus* and *Helmintoides* trace fossils, Pupov Hill (collection of A. Drengubiak, Zázrivá); c – greenish-grey and pinkish marlstones and silty mudstones of the Campanian Gbeľany beds, bedrock of the Struháreň Brook in Terchová-Holúbkovci; d – non-turbiditic calcareous siltstones (Poľany beds, Maastrichtian?) exploited in the Kýčera quarry in Terchová; e – thin-bedded distal turbiditic sequence of the Campanian–Maastrichtian–Paleocene Zázrivka beds, Zázrivka Brook bedrock, Zázrivá; f – calcareous shales with occasional beds of turbiditic sandstones, Zázrivka beds in the lower part of the Ráztoky section.

2.3 Plešivá Zone

The southernmost, Plešivá Zone stretches as about 1 km wide, W–E trending belt from Terchová village eastward, through the Rovná hora (Podkopec) saddle to the Demkovská settlement and further to the Plešivá Valley and settlement of the Zázrivá district (Fig. 2.1). Its easternmost part merges with the Havrania Zone, as the Pupov Zone wedges out near the Zázrivá centre. Both the Havrania and Plešivá zones then continue into the N–S trending Revišné Zone. The Plešivá Zone is distinctly fault-bounded. The northern boundary is formed by the steeply north-dipping backthrust of the Pupov Fm. over various formations of the Plešivá Zone, while the southern limit is also a steeply north-dipping backthrust of the Plešivá complexes over the Paleogene rocks of the CCPB. In the western part near Terchová, the southern PKB boundary is followed also by tiny slices of uppermost Cretaceous to Paleocene sediments assigned to the so-called "peri-Klippen Paleogene" or Myjava–Hričov Group (cf. Plašienka & Soták, 2015 and references therein).

The Plešivá Zone consists of tightly imbricated slices of various units and formaitons, sometimes of problematic affiliation. In the southern marginal position, there are discontinuous lenses of the Subpieniny Unit, composed of Campanian–Maastrichtian variegated pelagic marlstones (Terchová, Rovná hora saddle). Another slice in the Zázrivá–Plešivá area contains also a small klippe composed of Jurassic–Lower Cretaceous limestones described as the Czertezik Succession by Haško (1976). Presence of the Pieniny Unit (Kysuca Succession) is questionable – slices of Lower Cretaceous schistous marly spotted limestones (Pieniny Fm.) occurring near Terchová, Rovná hora saddle, Demkovská (Kozárikove or Janky skalky klippen) and western ridge of Dudová Hill south of Zázrivá-Centre may well belong also to the Šariš Unit, or even their affiliation with the Klape Unit (Mráznica Fm.) cannot be excluded. Nevertheless, the flysch sandstones and polymict exotic conglomerates occurring on the northern slopes of the Plešivá Valley belong most probably to the Snežnica–Sromowce Formation.

The northern strip of the Plešivá Zone, in contact with the Pupov Zone, is characterized by slices of some rock formations typical for the Šariš Unit – Lower Jurassic quartzites (Dubovské lúky ridge), micaceous black shales and sandstones of the "Black Flysch" (Middle Jurassic Szlachtowa Fm.), grey siliceous shales and red radiolarites (Sokolica and Czajakowa fms), calcite-free cherry-red shales with thin turbiditic beds of siliciclastic sandstones (Upper Cretaceous Malinowa Fm., Pavláškova skala Hill) and also calcareous sandstones and breccias of possibly (not proven yet) the Maastrichtian–Paleocene Jarmuta-Proč Formation. The Malinowa Formation (Birkenmajer, 1977) with the typical DWAF biofacies (Deep Water Agglutinated Forams like *Uvigerinammina jankoi*) is very characteristic for the Šariš Unit (Fig. 2.6).

2.4 Regional field sections

There are two instructive sections across the Plešivá Zone, which have been studied in detail and where its imbricated structure can be documented. The first, about 1 km long section (A) is located in the Rovná hora (Podkopec) Pass between Terchová and Zázrivá villages and transects the whole Plešivá Zone from the southern borderline with the Paleogene sediments of the CCPB, up to the northern boundary against the Pupov Zone composed of the Pupov Formation. The second section (B) is a composite one and includes the Plešivá Zone, a part of the Pupov Zone and a part of the Havrania Zone. It follows the Zázrivka Brook in Zázrivá village with numerous bedrock outcrops. Besides these, the Krištofíkovci profile (C) and some other short sections or individual outcrops provide additional information about the structure of this complicated structural zone. These sections and numerous outcrops around were documented and sampled mainly by P. Gedl, Š. Józsa, J. Soták and D. Plašienka over the last 15 years.

(A) The Rovná hora – Podkopec section

The section starts at the sheepfarm restaurant Syrex in the Rovná hora saddle between Rozsutec and Pupov hills and continues northward, upslope the ridge in the direction to Pupov Hill. Several imbrications of different PKB units are occasionally exposed along the profile. We briefly describe the lithology, obtained biostratigraphic data and possible tectonic affiliation of the exposed rock complexes.

Exposures within the Rovná hora section include artificial exposure just behind the restaurant building (samplas Z43–Z45; RH1–RH3), and outcrops along a field road leading to the north (Z46–Z48). Biostratigraphic data were gathered by P. Gedl (dinoflagellate cysts) and Š. Józsa (foraminifers).

STOP A1

GPS: N49.264847°, E19.104639° – outcrop just behind the restaurant building, it was sampled when the restaurant was constructed, nowadays this part is not exposed (Fig. 2.22a)

The exposure showed a tectonic contact between variegated marls (eastern part) and greenish-grey argillaceous shales with Mn-coatings to the west (Fig. 2.22b). Sample Z44 collected from the marly unit 40 cm from the contact yielded black, opaque phytoclasts only. The neighbouring sample Z43 taken from the dark shales 50 cm from the contact yielded rich assemblage of Aptian–Albian dinoflagellate cysts and sporomorphs. A similar assemblage occurs in sample Z45 (western part of the exposure). Both samples yielded, i.a., *Cribroperidinium edwardsii*, *Prolixosphaeridium*, *Tanyosphaeridium*, *Pterodinium*, *Gonyaulacysta dutina*, *Psaligonyaulax deflandrei*, *Kiokansium polypes*, *Cassiculosphaeridia reticulata*, *Codoniella campanulata*, *Pseudoceratium eisenackii*, and *Tenua hystrix*. No *Palaeohystrichophora infusorioides* was found there; this species is widespread in latest Albian–Late Cretaceous of the PKB (Fig. 2.23).

Samples RH1 and RH3 (Š. Józsa) taken from reddish marls provided poorly preserved planktonic, calcareous benthic and agglutinated forminifers of the ?late Santonian to early Campanian age. Among the agglutinated foraminifera, *Goesella rugosa* (Hanzlikova) was found. The planktonic foraminiferal assemblage yielded *Globotruncanita elevata* (Brotzen), *Globotruncana arca* (Cushman), *Globotruncana lapparenti* Brotzen, *Globotruncana linneiana* (d'Orbigny), *Archaeoglobigerina cretacea* (d'Orbigny), *Archaeoglobigerina blowi* Pessagno, *Heterohelix* cf. *globulosa* (Ehrenberg), *Muricohedbergella* sp. and *Macroglobigerinelloides* sp. In contrast, the sample RH2 from dark grey shales contained only agglutinated and calcareous foraminifers of most likely the early Albian age. Chracteristic taxa for this age such as *Spiroplectinata annectens* (Parker & Jones), *Clavulinoides gaultinus* (Morozova), *Falsogaudryinella tealbyensis* (Bartenstein) *Bulbobaculites problematicus* (Neagu) and *Osangularia schloenbachi* (Reuss) were determined.

The Upper Cretaceous (Campanian) red and greenish-grey, Púchov-type marlstones are typical especially for the Subpieniny (Czorsztyn) Unit. Tectonic assignation of mid-Cretaceous (Albian?) dark-grey, slightly calcareous shales is unclear, they might have been derived from the Pieniny (Kysuca) or Šariš Unit (Tissalo or Kapuśnica and Wronine formations), but their origin from the Klape Unit (Nimnica Fm.) or another Fatric unit cannot be excluded either.

STOP A2

GPS: N49.266505°, E19.105575° – small quarry near the fieldroad

Grey Lower Cretaceous limestones with subvertical bedding show strongly developed anastomosing schistosity developed by pressure solution and shearing along the foliation planes that are enriched in insoluble dark matter. These marly limestones are used to be identified with the Pieniny Fm. (Pieniny Unit, Kysuca Succession), but the type of deformation is rather typical of Fatric units (Mráznica Fm.).

STOP A3

GPS: N49.264983°, E19.104127° – steep slope behind the restaurant

Thin-bedded pinkish and yellow-green marlstones are deformed by mesopenetrative disjunctive to crenulation cleavage (see Fig. 3.2 in chapter 3.1 below). Poorly preserved planktonic foraminifera indicate their Campanian–Maastrichtian age.

Together with Upper Cretaceous variegated marlstones exposed at stops A1 and A9, these rocks are affiliated with the Subpieniny (Czorsztyn) Unit. In the scree above the outcrop, fragments of calcareous sandstones similar to the Jarmuta Fm. occur.

STOP A4

GPS: N49.268415°, E19.104633° – small outcrop at the bifurcating field road junction

This is an interesting and potentially very important locality (Fig. 2.22c, d). Steeply N-dipping schistous Lower Cretaceous marly limestones are overlain by fine-grained polymict conglomerates and calcareous sandstones. The contact resembles a transgressive base of the Pupov Fm. (cf. next stop) overlapping tilted and eroded Cretaceous limestones that might belong to the Klape of analogous Fatric unit. If so, the Pupov Formation would be a representant of the Gosau-type sediments deposited above the frontal Fatric nappes incorporated into the PKB structure. This concept, though tentative and potentially erroneous, is adopted throughout this work.

STOP A5

GPS: N49.268749°, E19.104633° – small outcrops in the field road

A few tens of metres uphill, yellow and willow-greenish marls are cropping out along the abandoned field road, occasionally with thin sandstone beds (Fig. 2.22e). The impoverished planktonic foraminiferal

Figure 2.22 Photodocumentation of the Rovná hora section (photos a, c, d, g and h by D. Plašienka, b, e and f by P. Gedl): a – presently covered defile behind the Syrex restaurant building (stop A1); b – detail from the same outcrop – tectonic contact of the mid-Cretaceous dark shales to the left (sample Z43) and Senonian variegated marls on the right side of the picture (sample Z44); c – schistous Lower Cretaceous limestones on the right side (lmstK1) are overlain by fine-grained

assemblage containing mostly small globular chambered morphotypes (*Heterohelix* sp. and *Muricohedbergella* sp.) and scarce *Globotruncana arca* (Cushman) (samples D and RH4) suggest the ?late Santonian–Campanian–Maastrichtian age.

Sample Z46 yielded palynofacies composed entirely of black, opaque phytoclasts associated with very rare dinoflagellate cysts (Fig. 2.23). Their uppermost Albian–Campanian assemblage is dominated by Palaeohystrichophora infusorioides and characterized by bimodal preservation: *P. infusorioides* is pale-colured and well preserved, whereas remaining taxa, gonyaulacoids (*Spiniferites*, *Odontochitina costata*, and *Pterodinium*) are dark-brown and commonly worse preserved (resedimented?). Lithology and age of these marls are compatible with the Pupov Formation.

STOP A6

GPS: N49.270096°, E19.104649° – nowadays mostly destroyed outcrops around and above the unfinished cottage resort.

Various, tightly imbricated Jurassic and Cretaceous were (2013) appearing in small weathered exposures along the abandoned road cut, but presently are badly exposed.

The sample Z47 taken from black shale with sphaerosideritic concretions exposed some 25 metres behind the last cottage (Fig. 2.22f) yielded palynofacies composed of black, opaque phytoclasts and highly altered cuticles. Altered aquatic palynomorphs include foraminifera organic linings and dinoflagellate cysts (Fig. 2.23). Presence of *Phallocysta* and *Nannoceratopsis* among the latter suggests Aalenian age of strata in question. They may belong to the Skrzypny Shale Formation or the Szlachtowa Formation. The micaceous sandstones of the latter unit occur some tens metres up the road, where highly weathered black shale crop out (barren sample Z48 with recent contamination).

Sample RH6 (Š. Józsa) from black shales provided microfauna commonly found in the ?Early–Middle Jurassic calcareous benthic assemblages with dominant ophthalmidiids and nodosarids. Similar assemblages are reported from the Pieniny and Šariš sectors of the Pieniny Klippen Belt (Tyszka, 1999; Gedl & Józsa, 2015). On the other hand, the red siliceous shales (sample RH5) cropping amidst black shales contain deep water agglutinated foraminifera (DWAF). Scarce *Bulbobaculites problematicus* (Neagu) was present in the assemblage. Without any other index taxa, the presence of this species suggests the Cenomanian age in the PKB (Geroch & Nowak, 1984; Bąk, 2000).

Structural association of Jurassic black shales and micaceous sandstones (Szlachtowa Fm.) and Upper Cretaceous red pelagic shales (Malinowa Fm.) is characteristic of the Šariš (Grajcarek) Unit (e.g. Birkenmajer et al., 2008; Gedl & Józsa, 2015; Birkenmajer & Gedl, 2017).

STOP A7

GPS: N49.272318°, E19.105216° – washout grooves in the forest road climbing the southern slope of Pupov Hill above Miškovci settlement (Zázrivá district).

Gently NW-dipping fine-grained laminated calcareous sandstones with plant debris on the bedding planes are typical rocks of the Pupov Formation, S_0 295/10.

STOP A8

GPS: N49.266852°, E19.100657° – roadcut near Podkopec settlement (Terchová)

Subvertical Lower Cretaceous, dark grey marly limestones with anastomozing schistosity might belong, similarly as at stops A2 and A3, either to the Pieniny or Mráznica formations.

STOP A9

GPS: N49.265288°, E19.101056° – rock cliff below the road from Rovná hora Pass to Podkopec settlement, about 250 m WNW of the Syrex restaurant

Returning back to the southernmost rock unit of the examined profile, Upper Cretaceous variegated marlstones are exposed again in a large forested rock cliff. The upper part of the outcrop is formed by greenish-grey marlstones alternating with beds of fine-grained calcareous sandstones to siltstones. Bedding planes are steeply NNW-dipping, slightly refracted cleavage is flatly lying. The southern wall of the cliff exposes almost massive marlstones with unusually large Zoophycos ichnofossils (Plate 2.22g). Badly preserved planktonic foraminifers like Globotruncana arca (Cushman) and Globotruncana spp. indicate their late Santonian–Maastrichtian age. We assign these marlstones to the Subpieniny (Czorsztyn) Unit, together with similar variegated

conglomerates and sandstones (csK2; stop A4); d – detail of this contact; e – Campanian–Maastrichtian calcareous shales belonging presumably to the Pupov Fm. (stop A5, samples Z46 and RH4); f – Middle Jurassic black shales of Skrzypny or Szlachtowa Fm. (stop A6; samples Z47, RH6) exposed in an abandoned field road scarp; g – cliffy exposure of upper Senonian variegated marly limestones (stop A9) with ichnofossils *Zoophycos*; h – folded Paleogene flysch strata of the CCPB near the contact with PKB, Demkovská (Zázrivá district).

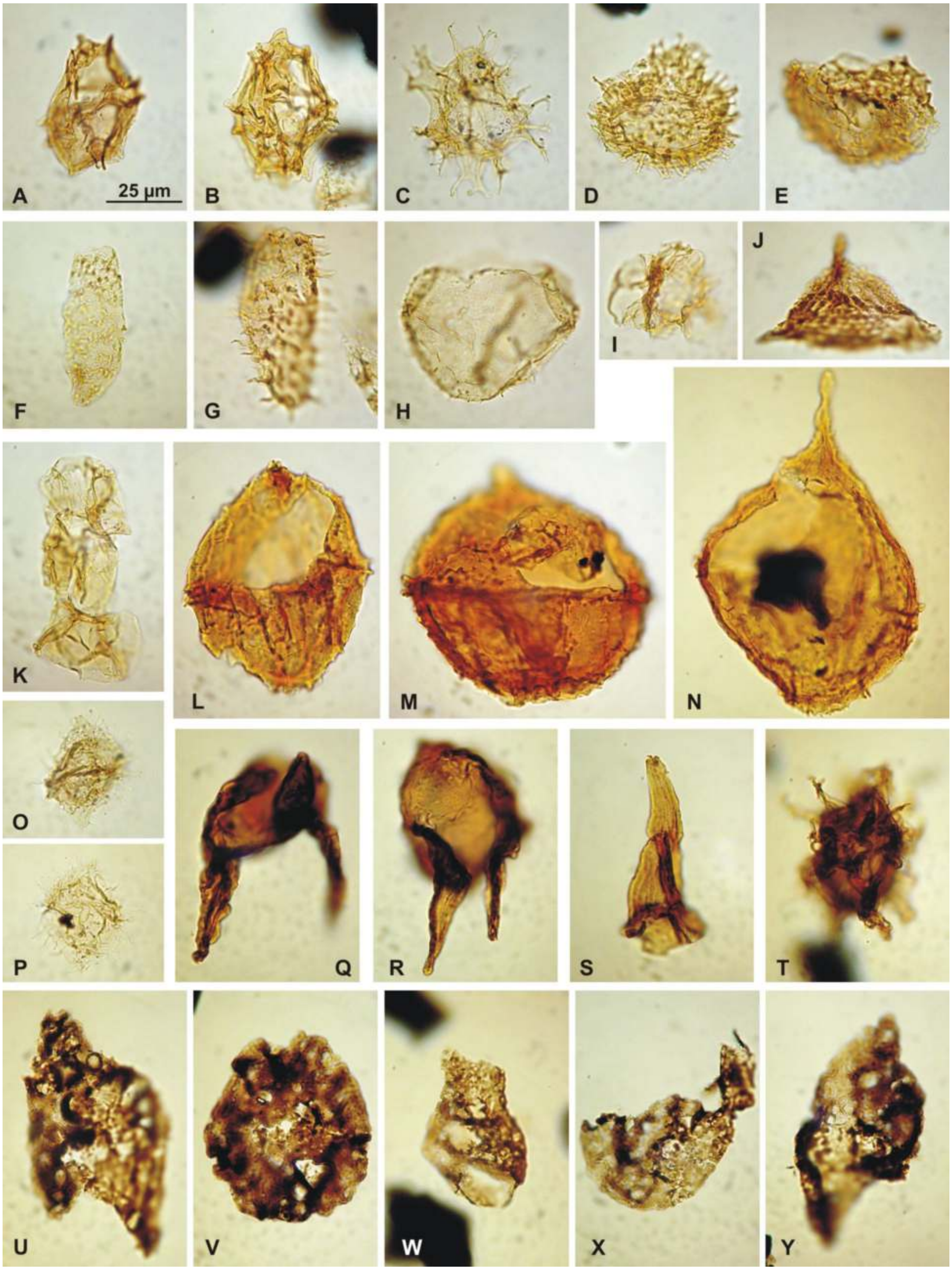


Figure 2.23 Palynology of the Rovná hora section (samples Z43–48; photo: P. Gedl). Scale bar in A refers to all photomicrographs. A, B: *Pterodinium* spp. (43); C: *Spiniferites* sp. (43); D: *Chlamydophorella* sp. (43); E: *Cassiculosphaeridia reticulate* (43); F: *Prolixosphaeiridium inequiornatum* (43); G: *Prolixosphaeridium parvispinum* (43), H: *Tenua hystrix* (43); I: *Heslertonia*? sp. (43); J: spore (43); K: *Codoniella campanulata* (43); L, M: *Cribroperidinium edwardsii*? (L: 45; M: 43); N: *Cribroperidinium orthoceras* (43); O, P: *Palaeohystrichophora infusorioides* (46); Q–S: *Odontochitina costata* (46); T: *Spiniferites* sp. (46); U: *Nannoceratopsis* sp. (47); V: spore (47); W: *Phallocysta elongata* (47); X: *Kallosphaeridium* sp. (47); Y: *Nannoceratopsis* sp. (47).

marlstones appearing at the nearby stops A1 and A3.

Down the valley about 500 m east of the Rovná hora Pass, at the entrance to village Zázrivá (Demkovská settlement) on the right bank of Petrovský potok Brook, there are outcrops in the Paleogene sediments of the CCPB (GPS N49.266065°, E19.113956°; but presently the access is difficult). Immediately at the contact with the PKB, flysch strata of the Huty Fm. are strongly disturbed by mesoscopic tight to isoclinal folds with steeply N-dipping axial planes (Fig. 2.22h). The next stop B1 exhibits similar S-vergent fold-thrust structures in the CCPB flysch deposits.

<u>(B) The Zázrivka–Končitá bedrock section</u>

The section starts at the road crossing at the entrance to Zázrivá-Centre, follows the Zázrivka stream bedrock exposures in the WSW–ENE direction up to the confluence with the Kozinský potok stream, and then turns NW to the Končitá Valley. It is an integrated section through all three PKB zones in the Zázrivá area, which runs across the Paleogene sediments of the CCPB, cuts its contact with the PKB formations and then transects the Plešivá Zone. The following long part is located in the Pupov Zone. At the end of the Zázrivka bedrock section, a tightly imbricated part represents the Ráztoky Fault dividing the Pupov and Havrania zones. Finally, outcrops of Jurassic black shales indicate presence of the Šariš Unit within the Havrania Zone. Biostratigraphic data were gathered by P. Gedl (organic-walled dinoflagellate cysts), M. Jamrich and E. Halásová (nannoplankton), J. Soták and Š. Józsa (foraminifers), J. Soták and M. Molčan Matejová (radiolarians).

STOP B1

GPS: N49.265643°, E19.151090° – crossing of the main road Terchová–Párnica with turning to Zázrivá-Centre (familiarly known as the "Satan´s crossing")

Outcrop is composed of alternation of grey, brownish-weathered fine-grained sandstones and grey shales. They belong to the Upper Eocene–Oligocene Zuberec flysch formation of the Central Carpathian Paleogene Basin. Conspicuous south-vergent fold and thrust structures (Fig. 2.24) are developed about 500 m south of the contact with the PKB. Based on analysis of fault-slip data, Marko et al. (2005) ascribed these deformation elements to the post-Oligocene backthrusting under the NNW–SSE oriented compression axis. Contractional deformation was partitioned into dominating dextral transpression in the PKB and south-vergent backthrusting in the adjacent CCPB sedimentary formations.

STOP B2

GPS: N49.268280°, E19.150748° – bedrock of the

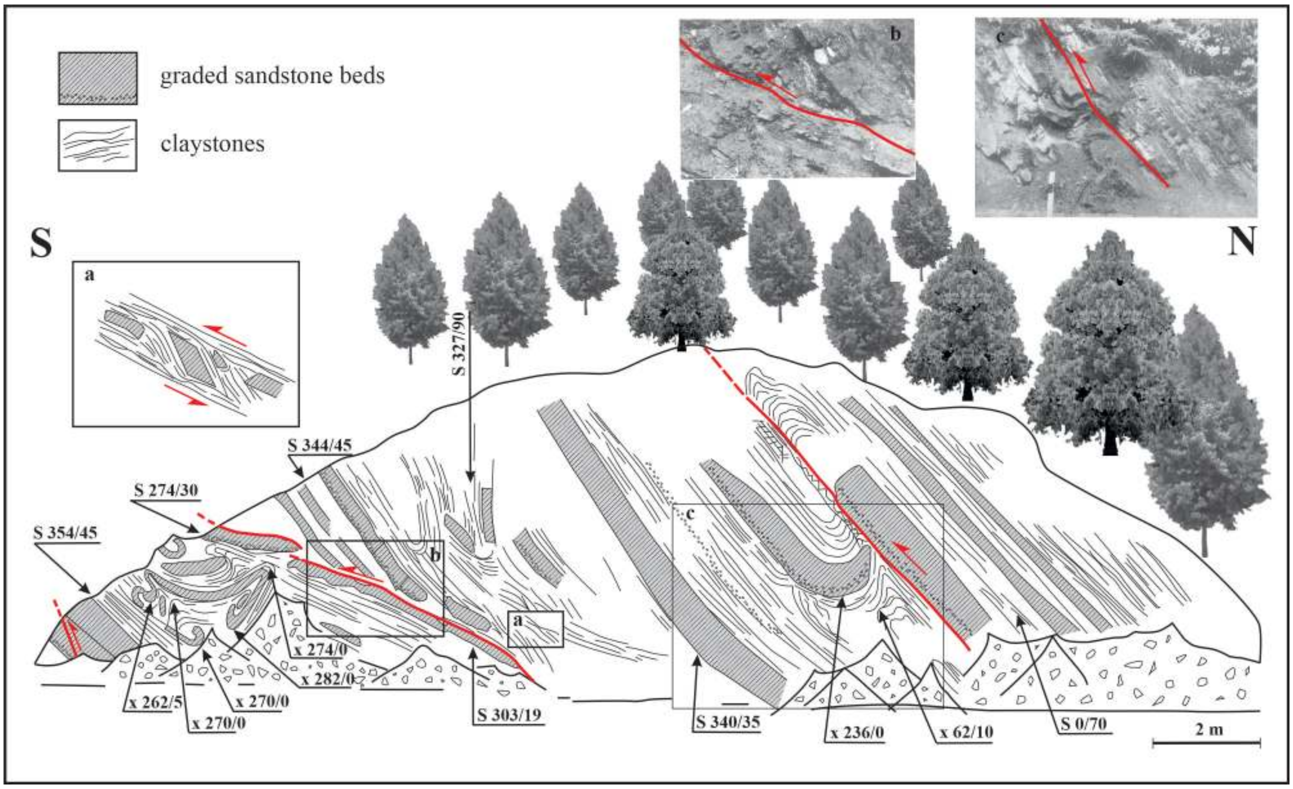


Figure 2.24 South-vergent fold and thrust structures in the Paleogene sediments adjacent to the PKB ("Satan´s crossing" site). Irregular minute folds in the left part of the outcrop were interpreted as synsedimentary slump folds. Adopted from Marko et al. (2005), slightly modified. S – bedding attitudes; x – fold axes.

Zázrivka stream below the foot-bridge

Lithology: thick-bedded calcareous sandstones and grey shales

Structure: bedding in a normal position is moderately dipping towards the NE, S_0 45/32, 53/40

Biostratigraphy: calcareous nannoplankton indicates late Priabonian–Oligocene age; foraminiferal assemblage of the Globigerinatheca index Zone indicate the Late Eocene (Priabonian) age of these sediments (sample A1; J. Soták), but recycled Paleocene agglutinated foraminifera are a characteristic feature.

Unit: Central Carpathian Paleogene Basin (CCPB), Huty Fm.

STOP B3

GPS: N49.270738°, E19.151453° – about 80 m upstream from the junction of the Zázrivka and Ráztoky brooks below the iron foot-bridge, house No 71-73 (Fig. 2.25a)

Lithology: grey shales with layers of graded sandstones to conglomerates

Structure: bedding in a normal position; S0 20/35, traces of cleavage 28/90, 200/75

Biostratigraphy: foraminiferal association of the Globigerinatheca index Zone are mixed with redeposited Cenomanian species (sample GZ2; Š. Józsa)

Analyzed samples Z1 and Z2 (P. Gedl) yielded typical flysch palynofacies composed of terrestrial elements: black and dark-brown phytoclasts, cuticles and sporomorphs (mainly pollen grains). Dinoflagellate cysts are infrequent and moderately preserved. Sample Z1 yielded, i.a., Areosphaeridium diktyoplokum, Operculodinium spp., Deflandrea and questionably determined Rhombodinium perforatum suggesting the Late Eocene (Priabonian) age. The same age can be concluded for sample Z2, which yielded Areosphaeridium diktyoplokum, Reticulatospahera actinocoronata, Deflandrea spp., and Thalassiphora.

Sample ZN23 (M. Jamrich) taken a dozen metres upstream from the foot-bridge yielded calcareous nannoplankton indicating the Late Eocene age (?NP16–NP17: Coccolithus pelagicus, C. eopelagicus, Cyclicargolithus floridanus, Reticulofenestra bisecta, R. stavensis, R. umbilicus).

Unit: Huty Fm. (CCPB)

STOP B4

GPS: N49.271009°, E19.151600° – 30 m north of stop B3, bedrock of the Zázrivka stream

Lithology: variegated marlstones

Biostratigraphy: sample 3.5 (J. Soták; Fig. 2.30) provided an impoverished assemblage of ?Coniacian–Santonian–Maastrichtian foraminifers Globotruncana arca (Cushman), G. lapparenti Brotzen, G. stuartiformis (Dalbiez), Contusotruncana sp. and ?Costellagerina lybica.

Unit: Púchov or Jaworki Fm., presumably the Subpieniny Unit)

Note: Accordingly, the rather abrupt principal tectonic boundary between the CCPB sediments and Oravic units of the PKB Plešivá Zone should be present between stops B3 and B4.

STOPS B5+B6

GPS: from N49.271505°, E19.152201° to N49.272306°, E19.152633° – a defile upstream from stop B4 up to the concrete road bridge, near houses Nos 74, 80, 87

Lithology, biostratigraphy and structure: grey spotted marlstones yielded Cenomanian foraminifers of the Rotalipora cushmani Zone (sample Z3.6, J. Soták: e.g. Rotalipora cf. globotruncanoides), they occur as pebbles and blocks in an olistostrome body (Figs 2.25b, 2.30) emplaced within Upper Cretaceous variegated marlstones – S0 335/40; variegated marlstones exposed upstream are rich in late Campanian Globotruncanas – Globotruncana ventricosa (White), G. arca (Cushman), G. falsostuarti Sigal (sample Z5, Š. Józsa) – S0 320/53; overlying marlstones (samples 3.7 and 4.7 of J. Soták; Fig. 2.30) belong to the lower–middle Turonian with planktonic foraminifera Dicarinella hagni Scheibnerová and Praeglobotruncana oraviensis Scheibnerová; below the concrete bridge, alternation of beds of fine-grained sandstones up to 40 cm thick and dark calcareous shales is cropping out; foraminiferal abundance zone of marginotruncanids (sample 5, J. Soták: Marginotruncana pseudolinneiana, M. tarfayensis, probably the middle–upper Turonian Snežnica Fm.) – S0 30/50; 2–3 m upstream bedding is overturned, weak cleavage 340/55.

Age: the whole, internally imbricated sequence is of the Late Cretaceous (Cenomanian–Turonian–Campanian) age

Unit: there are no decisive features allowing a direct affiliation; olistostrome bodies with Albian–Cenomanian marlstone clasts amidst younger variegated marls resemble the Záskalie breccia known from the Orava sector – if so, the lower part of the

and Kozinská streams, stop B21: f – Upper Cretaceous dark calcareous shales, samples Z5 on the left side and Z6 just right from the hammer; g – Aalenian black shales (sample Z7) some 3 m right from Z5 and Z6; h – Paleogene greenish-grey calcareous shales a few metres upstream from samples Z5–7.

Figure 2.25 Lower part of the Zázrivka section (photos a–e by D. Plašienka, f–h by P. Gedl): a – Paleogene shales of the CCPB at stop B3; b – olistostrome body with clasts of Cenomanian marlstones, stop B5+B6; c – waterfall outcrop B7, dark mudstones and calcarenites observed by R. Aubrecht; d – the same rocks exposed behind house Nr 102; e – medium-bedded turbidites of the Pupov Fm. (Maastrichtian–Danian Zázrivka beds), stop B15; f–h section at the confluence of Zázrivka

section probably belongs to the Subpieniny Unit, whereas the upper part (Snežnica flysch) might represent the Kysuca (Pieniny) Unit (Figs 2.30, 2.31)

STOP B7

GPS: N49.273417°, E19.153374° – small waterfall bellow iron foot-bridge (Fig. 2.25c)

Lithology: compact grey siliceous mudstones and fine-grained calcarenites contain microfauna very rich in sphaerical radiolarians and lithistid sponge spicules (samples 7 and 7.5, J. Soták); S_0 323/50

STOP B8

GPS: N49.273445°, E19.154032°; outcrop at the slope foot behind the house Nr 102 on the opposite side shows the same lithology as stop B7 (Fig. 2.25d)

Microfauna of dark silty claystones from both localities B7 and B8 (samples Z153–156; J. Soták and M. Molčan Matejová) contain radiolarians and scarce foraminifers (Fig. 2.26). Nasselarian radiolarians comprise of species *Pseudodictyomitrella* aff. *hexagonata* (Heitzer), *Archaeodictyomicra* aff. *rigida* Pessagno, *Parahsuum* cf. *carpathicus* Widz and De Wever, and *Cinguloturris* aff. *carpathica* Dumitrica. Rare sphaerical spumellarians are represented by *Zhamoidellum* aff. *ovum* Dumitrica. Radiolarian microfauna is completed by protoglobigerinid foraminifers (*Globigerina bathoniana* – *helvetojurassica* group) and large nodosariid foraminifers such as *Lenticulina muensteri* (Roemer) and *Lenticulina*

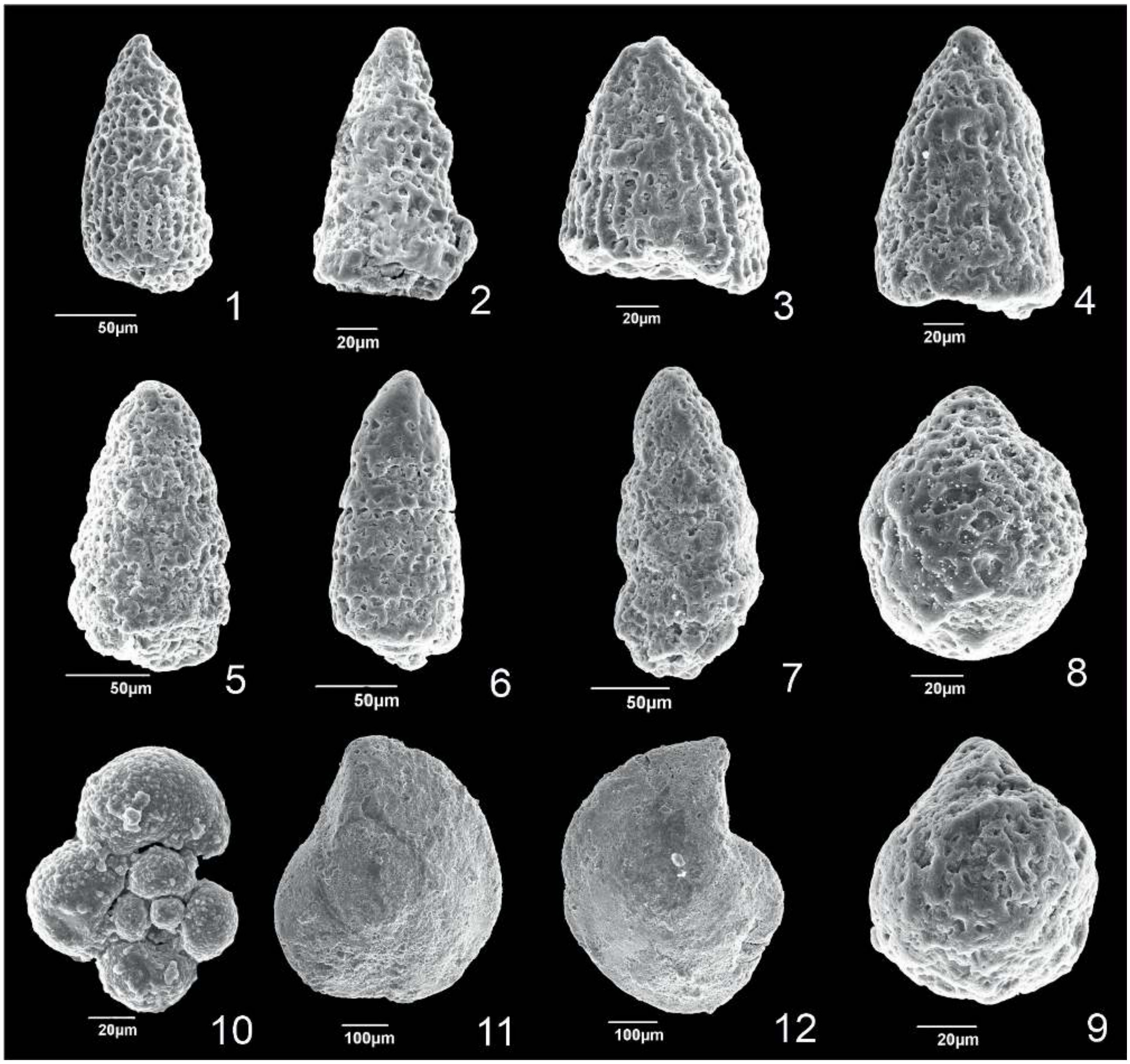


Figure 2.26 Radiolarian and foraminiferal microfauna from the dark shale formation (Szlachtowa Fm.?) in Zázrivá village (samples 153–156): 1, 2- *Pseudodictyomitrella* aff. *hexagonata* (Heitzer); 3, 4 – *Archaeodictyomicra* aff. *rigida* Pessagno; 5, 6 – *Parahsuum* cf. *carpathicus* Widz and De Wever; 7 – *Cinguloturris* aff. *carpathica* Dumitrica; 8, 9 – *Zhamoidellum* aff. *ovum* Dumitrica; 10 – *Globigerina* gr. *bathoniana*; 11 – *Lenticulina muensteri* (Roemer); 12 – *Lenticulina* cf. *toarcense* Payard.

cf. *toarcense* Payard. The assemblage of radiolarian species provides stratigraphic data for the Middle Jurassic age of the formation (cf. Ožvoldová, 1988, 1998; Rakús & Ožvoldová, 1999; Ožvoldová & Frantová, 1997; O'Dogherty et al., 2017). This is also confirmed by the presence of bathoniana group of planktonic foraminifera and nodosariid species of benthic foraminifera (Hart et al., 2012; Gedl & Józsa, 2015; Tyszka, 1994; Hendriques & Canales, 2013). Aalenian–Bajocian age of the dark claystones corre-

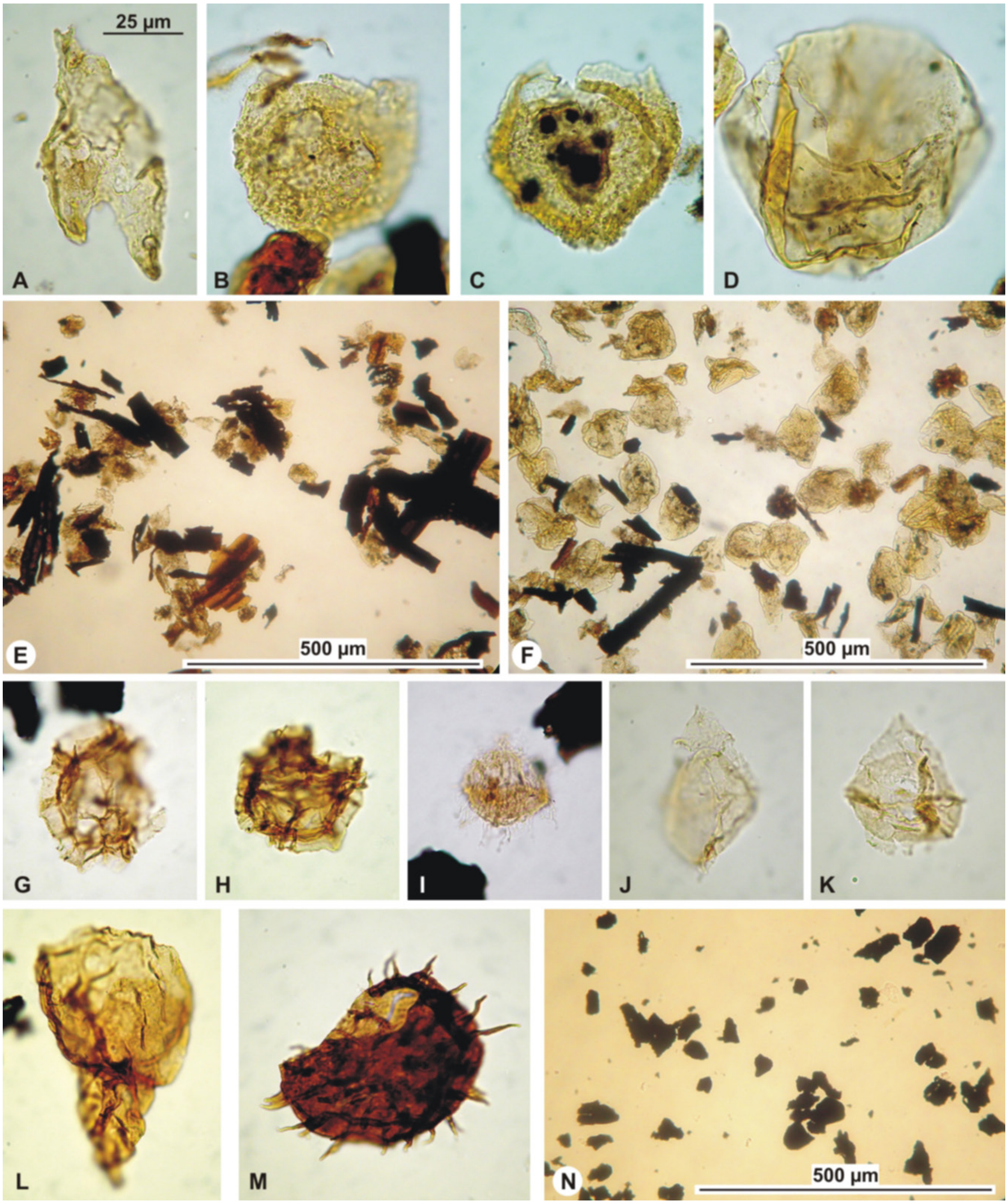


Figure 2.27 Palynology of samples from house 102 in Zázriva (samples Z153–157; photo: P. Gedl). Scale bar in A refers to all photomicrographs except for E, F and N. A: *Nannoceratopsis* sp. (156); B, C: *Batiacasphaera* sp. (156); D: *Dissiliodinium giganteum* (156); E: palynofacies of sample 154; F: palynofacies of sample 153; G, H: *Pterodinium cingulatum* (157); I: *Palaeohystrichophora infusorioides* (157); J, K: *Subtilisphaera*? spp. (157); L: *Odontochitina* sp. cf. *rhakodes*; M: *Pervosphaeridium* sp. (157); N: palynofacies of sample 157.

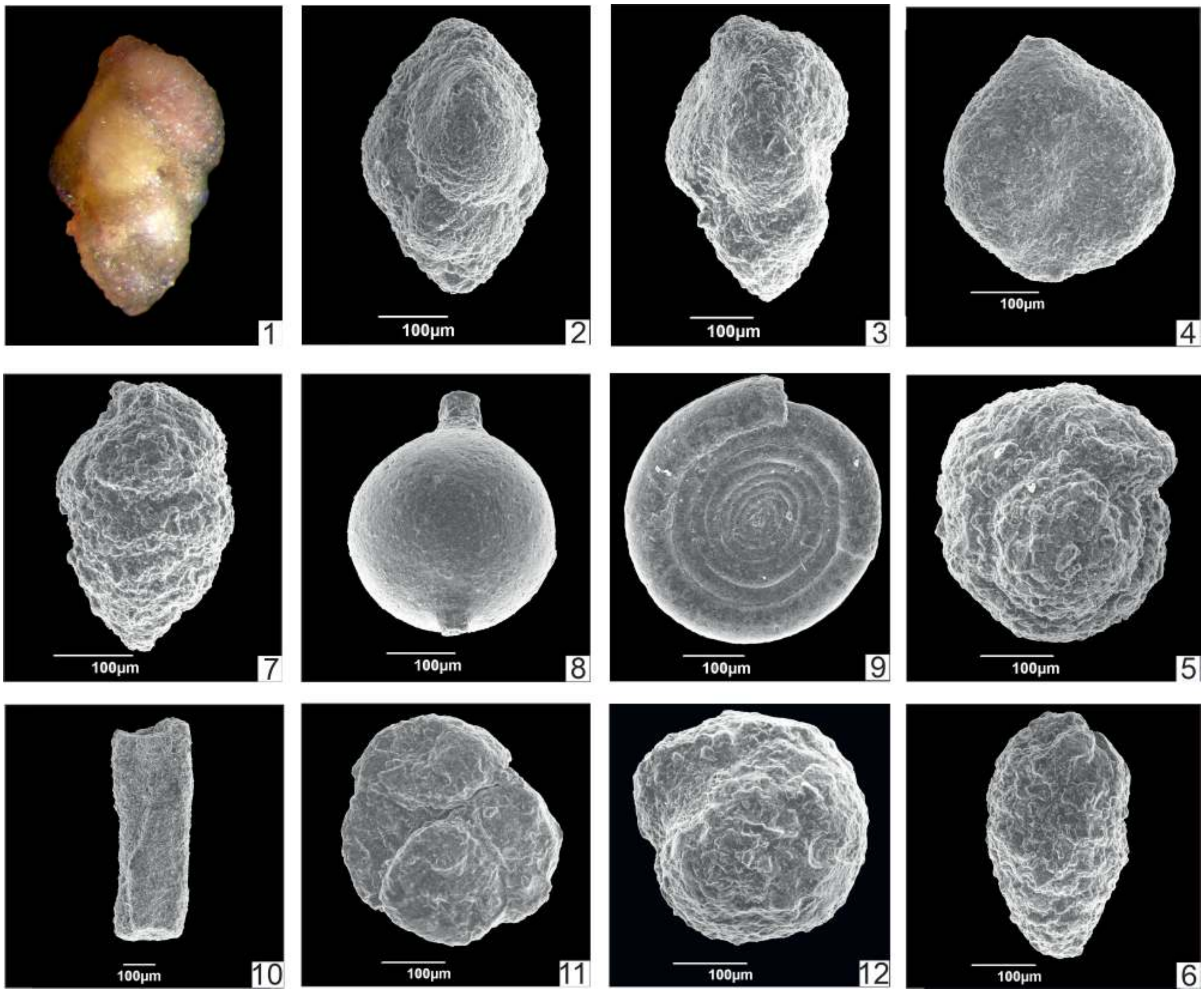


Figure 2.28 1–6 Foraminiferal microfauna of variegated claystones of the Malinowa Fm. from stop B9 in the Zázrivka section (sample Z143a): 1–3: *Uvigerammina jankoi* (Majzon); 4: *Caudammina gigantea* (Geroch); 5: *Recurvoides* cf. *nucleolus* (Grzybowski); 6: *Karrerulina coniformis* (Grzybowski). 7–9 Upper Cretaceous microfauna of the Malinowa Fm. from stop B10 the Zázrivka section (sample Z148): 7: *Uvigerammina jankoi* (Majzon); 8: *Caudammina ovulum* (Grzybowski); 9: *Ammodiscus glabratus* Cushman & Jarvis. 10–12 Agglutinated foraminifera from grey marlstones of the flysch sequence from stop B10 (sample Z145): 10: *Bathysiphon gerochi* Myatlyuk; 11: *Haplophragmoides walteri* (Grzybowski); 12: *Recurvoides* cf. *nucleolus* (Grzybowski).

sponds to the Szlachtowa Formation, presumably its upper part.

Benthic foraminiferal association from samples Z-7 and Z-9 (Š. Józsa) contains rather non-indicative, but likely Middle Jurassic assemblage *Lenticulina* spp., *Nodosaria* sp., *Prodentalina* ? spp., *Rhabdammina* sp., *Hyperammina* ? sp., *Planularia* sp., *Ichtyolaria* ? sp., *Spirillina* sp. and/or *Cornuspira* sp., *Saccammina* sp., *Rhabdammina* sp., *Trochammina* sp., *Ammodiscus* sp., *Glomospira charoides*, *Glomospira gordialis* (Jones & Parker) and cores of biserial agglutinated foraminifera (*Textularia* ? *agglutinans* d'Orbigny).

Samples Z153–156 contain dinoflagellate cysts of the early Bajocian age (Fig. 2.27), based on the presence of *Dissiliodinium giganteum*. Although all samples yielded large amounts of palynological organic matter, their composition differs from sample to sample. Sample 156 yielded frequent cuticles and dark palynodebris, frequently in a form of elongated phytoclasts, and common dinoflagellate cysts represented mainly by Batiacasphaera. Palynofacies of sample 155 is characterized by increased proportion of black, opaque phytoclasts and higher ratio of dinoflagellate cysts represented by *Dissiliodinium giganteum*. Sample 154 yielded, in turn, increased proportion of cuticles and less frequent dinoflagellate cysts, which appear to be a dominant element in sample 153. In the latter sample, predominating dinoflagellate cysts are represented by mass-occurrence (an acme) of *Dissiliodinium giganteum*.

The Middle Jurassic age is supported by nannoplankton samples ZN21 and 22 (M. Jamrich). These yielded *Watznaueria fossacincta*, *W*. *barnesiae*, *W*. *contracta*/*Lotharingius*, *Carinolithus magharensis*, *Cyclagelosphaera margerelii*, and *Discorhabdus striatus*. The assemblage indicates most likely the Bajocian age.

Unit: although the lithology is not typical, presumably these rocks represent the upper part of the Szlachtowa Fm. of the Šariš Unit.

STOP B9

GPS: N49.275028°, E19.154948°; small oucrop at the left bank of the Zázrivka stream opposite to house Nr 129 exposes alternation of red and black shales

The soft red claystones (sample Z143a; J. Soták) contain rich microfauna of agglutinated foraminifera with *Uvigerammina jankoi* (Majzon; Figs. 2.28, 2.30), which is a marker species of the Turonian formations (Morgiel & Olszewska, 1981; Bubík, 1995; Olszewska, 1997; Neagu, 2011). The association of *Uvigerammina*-bearing claystones is completed by species *Caudammina gigantea* (Geroch), *Karrerulina coniformis* (Grzybowski), *Hormosina crassa* Geroch, *Recurvoides* cf. *nucleolus* (Grzybowski) and *Ammovertelina* aff. *irregularis* (Grzybowski). Considering such microfauna, the variegared Turonian claystones belong to the Malinowa Fm. Of the Šariš Unit.

Sample Z143b (P. Gedl) was taken from very soft, black intercalations within the red shale. Sample yielded large amounts of palynological organic matter composed of very well preserved, immature particles including both terrestrial (i.a., sporomorphs) and marine palynomorphs (Fig. 2.29). The latter are dinoflagellate cysts and foraminifera organic linings. Assemblage of the former is dominated by *Dissiliodinium* specimens with subordinate *Nannoceratopsis* (incl. *N. dictyambonis*) and rare *Phallocysta elongata*. The age of this assemblage is likely late Aalenian. The age of the sample and its lithology corresponds to the Skrzypny Shale Formation.

STOP B10

GPS: N49.275777°, E19.156487°; slope cut along the asphalt field road from Zázrivá-centre towards SE towards the Dudová ridge, behind the bridge opposite the church; this outcrop was added after this road cut was cleaned in summer 2020 and exposed previously unrecognized rocks

Lithology: the lower part of the section shows a steeply N-dipping (S_0 350/72) flysch sequence of bedded sandstones with fine mica flakes and thin seams of black shales are exposed; higher up behind the road curve cherry-red shales and greenish siliciclasic sandstones are cropping out in the washed-out groove

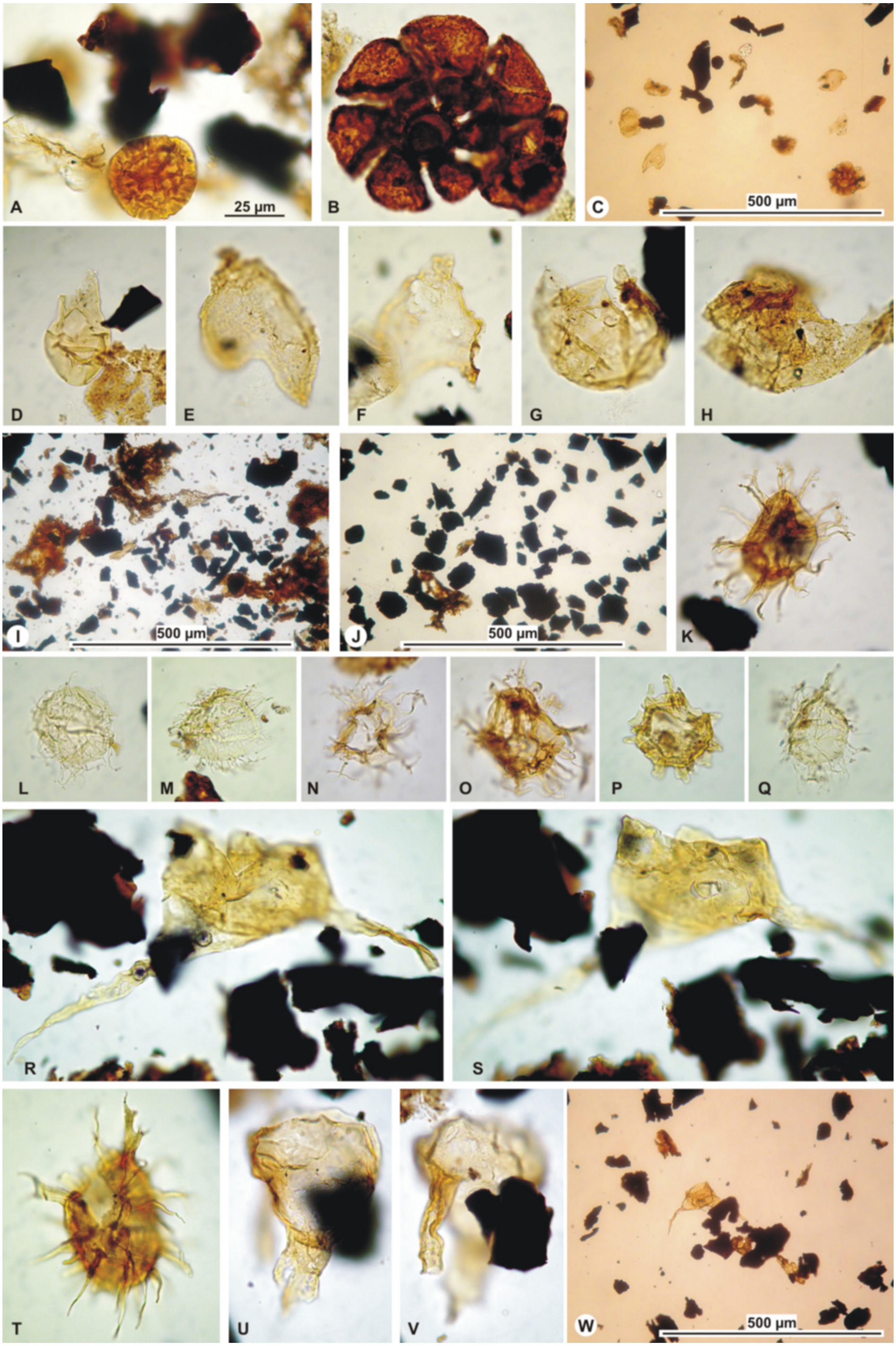
Sample Z145 (J. Soták, Fig. 2.28) from the flysch sequence yielded the Upper Cretaceous foraminiferal association comprising species *Haplophragmoides watersi* (Grzybowski), *Bathysiphon geochi* and *Recurvoides* cf. *nucleosus* (Grzybowski).

Samples Z144–147 (P. Gedl) were taken from very thin shale intercalations that occasionally occur among the sandstone beds. These are soft, dark shale, some with frequent mica flakes. Sample 144 (taken from southernmost part of the exposure), which contain very frequent mica flakes yielded palynofacies composed entirely of large amount of terrestrial elements, including large-sized cuticles. A terrestrial palynofacies (mainly black phytoclasts) was found in sample 145, but this sample yielded also very rare dinoflagellate cysts including very well preserved specimen of *Palaeohystrichophora infusorioides*. The third sample from the northern part of the exposure studied (Z146) yielded a similar palynofacies and more frequent dinoflagellate cysts. The latter show variable preservation stage ranging from very well preserved to highly damaged. Among determinable forms *Odontochitina dilatata*? (*O. diducta*?), *Spiniferites* sp., *Palaeohystrichophora infusorioides*, *Pervosphaeridium* sp., *Litosphaeridium conispinum*, *Odontochitina porifera*?, and a few *Dissiliodinium* specimens, which are likely reworked from Jurassic. Sample Z147 from the northernmost part of the exposure of the flysch sequence yielded very low amounts of palynological organic matter with no dinoflagellate cysts. Dinoflagellate cysts found in samples Z145 and Z146 clearly show the Upper Cretaceous age of the strata exposed. Presence of both Odontochitina species, if properly determined, suggest Coniacian–Santonian age. An older, uppermost Albian–Cenomanian dating can be based on the presence of *Litosphaeridium conispinum* (together with *P. infusorioides*).

The variegated claystones with thin greenish sandstone intercalations (sample Z148, J. Soták; Fig. 2.28) are poor in agglutinated foraminifera, which involve species *Uvigerammina jankoi* (Majzon), *Ammodiscus glabratus* Cushman & Jarvis, *Caudammina ovulum* (Grzybowski), *Recurvoides* cf. *nucleolus* (Grzybowski) and *Karrerulina* sp. The bulinimiform morphology of *Uvigerammina indicates* the Upper Turonian–Coniacian age of the Malinowa Formation at this locality.

Red pelagic shales with thin beds of greenish-grey quartzose sandstones occur also in a debris higher up along the road and then widely aroun Pavláškova skala Hill (GPS N49.275471°, E19.190677°).

Unit: lithology and age of the flysch sequence in the lower part of the section would indicate its possible assignemet to the Haluszowa Formation, while variegated shales correspond to the Malinowa Formation, both representing typical members of the Šariš Unit.


A
25 µm
B
C
500 µm
D
E
F
G
H
I
500 µm
J
500 µm
K
L
M
N
O
P
Q
R
S
T
U
V
W
500 µm

STOP B11

GPS: N49.277974°, E19.157460°; Zázrivka bedrock ca 200 m upstream from the Zázrivá centre (north from the bridge opposite the church)

Lithology: grey claystones

Structure: monoclinal strata S_0 340/75

Biostratigraphy: Nannoplankton samples ZN9 and ZN10 (M. Jamrich) provided taxa pointing to the latest Cretaceous to earliest Paleocene age (?*Prinsius* sp., *Cribrocorona gallica*, *Calculites obscurus*); foraminiferal sample (J. Soták; Figs 2.30, 2.32) contains planktonic and lower bathyal to abyssal benthic foraminiferal assemblage indicating the Paleocene age (*Morozovella subbotinae*, *Acarinina soldadoensis*, *Subrheophax pseudoscalaris*, *Nuttallides trumpyii*).

Unit: Pupov Fm. (Zázrivka beds)

STOP B12

GPS: N49.278556°, E19.157861°; Zázrivá – Zázrivka bedrock, 30 m upstream from stop B11

Lithology: prevalence of grey claystones and mudstones, thin beds (1–3 cm) of fine-grained distal turbiditic sandstones

Structure: monoclinal strata S0 345/80 with normal succession, metric fold with limbs 310/63 vs. 190/80, fold axis 270/80; farther upstream S_0 18/36, 330/65 (cf. Fig. 3.3 below)

Unit: Pupov Fm. (Zázrivka beds)

STOP B13

GPS: N49.278778°, E19.158389°; Zázrivka left bank, bedrock ca 25 m above from stop B12

Lithology: grey claystones, thin distal turbiditic sandstones

Structure: strata are folded – overturned, S0 generally 350/60, weak cleavage 20/85; two fold systems – 1) axes SW–NE with steep axial planes and 2) with axes NW–SE (cf. Fig. 3.3).

Biostratigraphy: Samples 9, 11 and 13 (J. Soták) taken between stops B9 and B12 provided Campanian–Maastrichtian planktonic foraminifers *Globotruncana ventricosa*, *Globotruncana* cf. *arca*, *G. linneiana*, *G. lapparenti*, *Globotruncanita elevata* (Figs 2.30, 2.32)

Unit: Pupov Fm. (Zázrivka beds)

STOP B14

GPS: N49.279518°, E19.159183°; Zázrivka left bank, bedrock downstream of red/yellow metal road bridge, wooden house No 239

Lithology: grey claystones, thin distal turbiditic sandstones; S_0 20/50

Biostratigraphy: only agglutinated foraminifera without any stratigraphical importance were washed out from the sample GZ3 (Š. Józsa). Sample ZN7 (below the bridge; M. Jamrich) yielded, i.a. the Lower Paleocene forms ?*Prinsius* sp. and *P. martini*, and sample ZN8 (wooden house) the uppermost Cretaceous species *Lithraphidites quadratus* (CC25–CC26).

Unit: Pupov Fm. (Zázrivka beds)

STOP B15

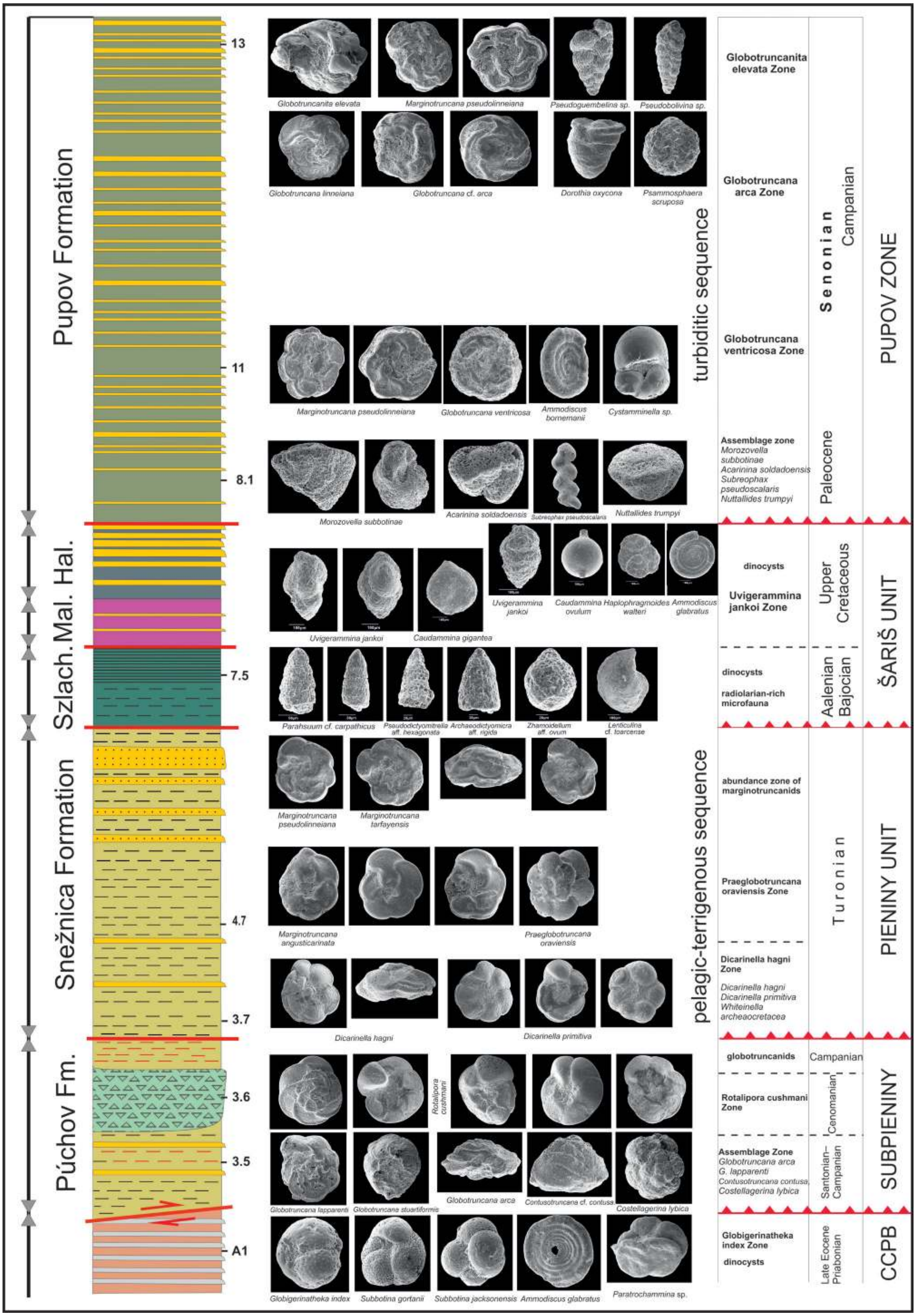
GPS: N49.27975°, E19.159472°; Zázrivka bedrock below and 20 m above the red/yellow metal road bridge (Fig. 2.25e)

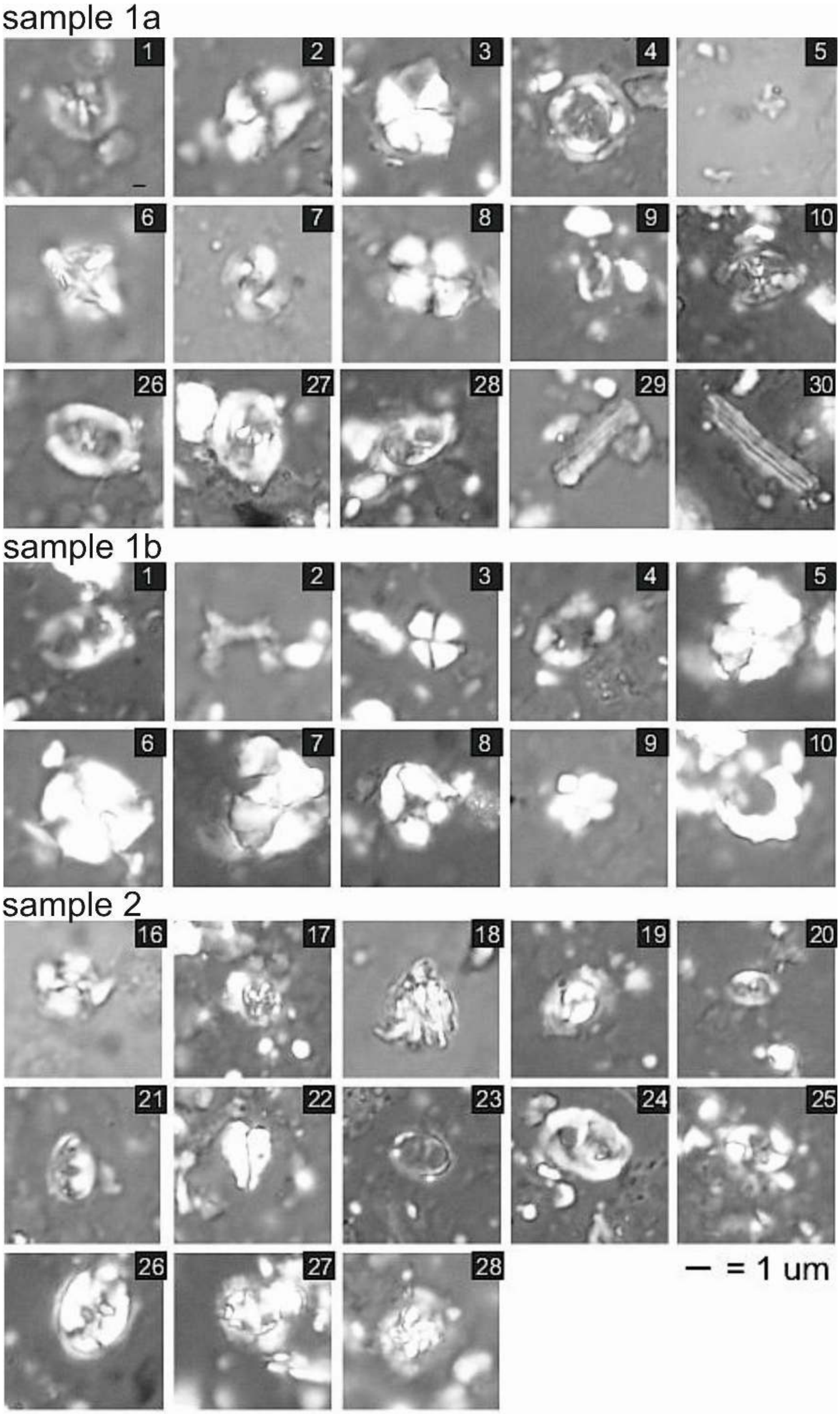
Lithology: distal flysch – grey slightly calcareous claystones, thin turbidite sandstone beds to 25 cm

Figure 2.29 Palynology of the localities B9 and B10 (samples Z143–147; photo: P. Gedl). Scale bar in A refers to all photomicrographs except for I, J and W. A: palynofacies of sample 143; B: foraminifera organic lining (143); C: palynofacies of sample 143; D: *Phallocysta elongata* (143); E: *Nannoceratopsis gracilis* (143); F: *Nannoceratopsis dictyambonis* (143); G: *Dissiliodinium psilatum* (143); H: *Dissiliodinium lichenoides* (143); I: palynofacies of sample 144; J: palynofacies of sample 145; K: *Spiniferites ramosus* (146); L, M: *Palaeohystrichophora infusorioides* (L: 145; M: 146); N, O: *Spiniferites* spp. (146); P: *Litosphaeridium conispinum* (146); Q: *Palaeohystrichophora infusorioides* (146); R, S: *Odontochitina dilatata*? (*O. diducta*?) – the same specimen, various foci (146); *Pervosphaeridium* sp. (146); U, V: *Odontochitina porifera*? (the same specimen, various foci; 146); W: palynofacies of sample 146 with a specimen of *Odontochitina dilatata*? (*O. diducta*?) in the centre.

Figure 2.30 (next page) Stratigraphic subdivision of the lower part of the Zázrivka bedrock section based on lithological logging and high-resolution biozonation (mainly after J. Soták). Not to scale, the column represents the lower, ca 1.5 km long part of the Zázrivka bedrock section. Szlach. – Szlachtowa Fm.; Mal. – Malinowa Fm.; Hal. – Haluszowa Fm.

Figure 2.31 (next page) Selected Upper Cretaceous and Paleogene nannoplankton species from the Zázrivka beds (stops B15 and B17; reproduced from Rapánová, 2006). Sample 1a: 1 – *Ahmuellerella octoradiata*; 2 – *Watznaueria barnesae*; 3 – *Braarudosphaera bigelowii*; 4 – *Cylindralithus biarcus*; 5 – *Micula* sp.; 6 – *Micula staurophora*; 7 – *Cyclicargolithus floridanus*; 8 – *Watznaueria barnesae*; 9 – *Neocrepidolithus* sp.; 10 – *Chiastozygus* sp.; 26–27 – *Reinhardithes anthophorus*; 28 – *Placozygus sigmoides*; 29–30 – *Litraphidi tesquadratus*. Sample 1b: 5 – *Biantholithus sparsus*; 6 – *Watznaueria barnesae*; 7 – *Biantholithus sparsus*; 8 – *Neocrepidolithus* sp.; 9 – *Hexalithus gardetae*; 10 – *Ceratolithoides aculeus*. Sample 2: 16 – *Watznaueria barnesae*; 17 – *Prediscosphaera cretacea*; 18 – *Nannoconus* sp.; 19 – *Prinsius bisulcus*; 20 – *Tranolithus gabalus*; 21 – *Tranolithus orionatus*; 22 – *Fasciculithus* sp.; 23 – *Neochiastozygus junctus*; 24 – *Zeugrhabdotus* sp.; 25–26 – *Eiffelithus gorkae*; 27–28 – *Prediscosphaera cretacea*.


Pupov Formation
Szlach.Mal. Hal.
Snežnica Formation
Púchov Fm.
13
11
8.1
7.5
4.7
3.7
3.6
3.5
A1
Globotruncanita elevata
Marginotruncana pseudolinneiana
Pseudoguembelina sp.
Pseudobolivina sp.
Globotruncana linneiana
Globotruncana cf. arca
Dorothia oxycona
Psammosphaera scruposa
Marginotruncana pseudolinneiana
Globotruncana ventricosa
Ammodiscus bornemanii
Cystamminella sp.
Morozovella subbotinae
Acarinina soldadoensis
Subreophax pseudoscalaris
Nuttallides trumpyi
Uvigerammina jankoi
Caudammina gigantea
Uvigerammina jankoi
Caudammina ovulum
Haplophragmoides walteri
Ammodiscus glabratus
Parahsuum cf. carpathicus
Pseudodictyomitrella aff. hexagonata
Archaeodictyomicra aff. rigida
Zhamoidellum aff. ovum
Lenticulina cf. toarcense
Marginotruncana pseudolinneiana
Marginotruncana tarfayensis
Marginotruncana angusticarinata
Praeglobotruncana oraviensis
Dicarinella hagni
Dicarinella primitiva
Rotalipora cushmani
Globotruncana lapparenti
Globotruncana stuartiformis
Globotruncana arca
Contusotruncana cf. contusa
Costellagerina lybica
Globigerinatheka index
Subbotina gortanii
Subbotina jacksonensis
Ammodiscus glabratus
Paratrochammina sp.
turbiditic sequence
pelagic-terrigenous sequence
Globotruncanita elevata Zone
Globotruncana arca Zone
Globotruncana ventricosa Zone
Assemblage zone
Morozovella subbotinae
Acarinina soldadoensis
Subreophax pseudoscalaris
Nuttallides trumpyi
dinocysts
Uvigerammina jankoi Zone
dinocysts
radiolarian-rich microfauna
abundance zone of marginotruncanids
Praeglobotruncana oraviensis Zone
Dicarinella hagni Zone
Dicarinella hagni
Dicarinella primitiva
Whiteinella archeaocretacea
globotruncanids
Rotalipora cushmani Zone
Assemblage Zone
Globotruncana arca
G. lapparenti
Contusotruncana contusa
Costellagerina lybica
Globigerinatheka index Zone
dinocysts
Senonian
Campanian
Paleocene
Upper Cretaceous
Aalenian Bajocian
Turonian
Campanian
Cenomanian
Santonian–Campanian
Late Eocene Priabonian
PUPOV ZONE
ŠARIŠ UNIT
PIENINY UNIT
SUBPIENINY
CCPB


sample 1a
1
2
3
4
5
6
7
8
9
10
26
27
28
29
30
sample 1b
1
2
3
4
5
6
7
8
9
10
sample 2
16
17
18
19
20
21
22
23
24
25
26
27
28
— = 1 um

thick at some 5 m thickness distance

Structure: overturned bedding, lower part S0 5/40, 20/70, upper part S0 330/80 with mesopenetrative disjunctive cleavage 270/90

Biostratigraphy: Two samples Z3 and Z4 (P. Gedl) taken from the Pupov Fm. yielded similar palynofacies typical for the Late Cretaceous composed of black, opaque phytoclasts. Rarely, highly altered dinoflagellate cysts occur; *Spiniferites* and reworked *Nannoceratopsis* were found in sample Z3.

Poorly preserved planktonic forams occurring in sample GZ4 (Š. Józsa) indicate the ?late Santonian–Maastrichtian age based on the occurrence of *Globotruncana linneiana* (d'Orbigny) and *Globotruncana arca* (Cushman). The benthic assemblage yielded *Rectoprotomarsonella rugosa* (Hanzlíková).

Calcareous nannoplankton from this locality points to the Late Cretaceous (Campanian – Maastrichtian) age either, but some forms indicate reaching the Paleocene (e.g. *Cyclicargolithus floridanus*, *Neocrepidolithus* sp.). The K/T boundary interval NP1 was detected by *Biantholithus sparsus* Bramlette & Martini (determined by E. Halásová, presented in the Master thesis of Rapánová, 2006; Fig. 2.31, samples 1a, 1b). New samples ZN1–ZN6 (M. Jamrich) were taken each ca 5 m o thickness and confirmed the presence of Campanian species (zone CC22 or younger – *Eiffellithus eximius*, *Lithastrinus grillii*, *Prediscosphaera cretacea*, *Watznaueria barnesiae*) and earliest Paleocene forms (zones NP1–NP2: *Biantholithus sparsus*, *Cruciplacolithus primus*, *Prinsius dimorphosus*, *Prinsius* sp., *P. martini*).

Unit: Pupov Fm. (Zázrivka beds).

STOP B16

GPS: N49.280361°, E19.160833°; Zázrivka bedrock upstream

Lithology: alternation of packets with prevalence of claystones and thin-bedded flysch with sandstones and sandy limestones (beds 1–10 cm) vs. claystones 1:1

Structure: overturned succession (hieroglyphs on northern sufaces) S_0 358/85, 8/80, 0/50 .

Biostratigraphy: Only agglutinated foraminifera without any stratigraphical importance were washed out from the samples.

Unit: Pupov Fm.

STOP B17

GPS: N49.280833°, E19.161222°; Zázrivka bedrock below two foot-bridges near houses 262–264.

Lithology: overturned distal flysch, upstream prevalence of sandstones over claystones, S0 335/75

Biostratigraphy: Foraminifers of the *Abatomphalus mayaroensis* Zone indicate late Maastrichtian; nannoplankton consists of 95% of the Upper Cretaceous and 5% of the Paleocene forms (*Fasciculithus* sp., *Neochiastozygus junctus*, *Prinsius bisulcus* – Halásová in Rapánová, 2006; Fig. 2.31, sample 2); new samples ZN11–15 for nannoplankton (M. Jamrich) were taken each 5 m of thickness and provided upper Senonian taxa of zones CC22 to CC25 (e.g. *Cribrocorona gallica*, *Calculites obscurus*, *Reinhardtites levis*, *Eiffellithus eximius*).

Unit: Pupov Fm. (Zázrivka beds)

STOP B18

GPS: N49.281917°, E19.165194°; Zázrivka bedrock near the road-bridge with red/white handrails

Lithology: prevalence of claystones over sandstones 2:1, beds of sandy limestones with trace fossil *Paleodictyon*

Structure: overturned bedding S_0 340/85

Biostratigraphy: Only agglutinated foraminifera without any stratigraphical importance were washed out from the samples.

STOP B19

GPS: N49.281724°, E19.165345°; Zázrivka bedrock ca 150 m above stop B18

Lithology: prevalence of sandstones (20–30 cm) over claystones 5:1, S_0 315/55, 5/80

Age: Late Cretaceous

STOP B20

GPS: N49.281917°, E19.168056°; right bank of Zázrivka some 50 m below the confluence of Havranský and Kozinský streams, opposite a house on the other side of the stream (Fig. 2.33)

Lithology: predominance of sandstones and then claystones in the upper part, S_0 333/59, 0/75

Biostratigraphy: Sample ZN19 (M. Jamrich) yielded Campanian (zone CC22) nannoplankton forms *Eiffellithus eximius*, *Uniplanarius trifidus*.

Unit: Pupov Fm.

STOP B21

GPS: around N49.282111°, E19.168667°; defile at the right bank of Zázrivka at the confluence with Kozinský potok stream – the "mélange zone"

Lithology and biostratigraphy: This outcrop is located at a very vulnerable place exposed to frequent changes due to water erosion during the river highstands. At the same time, it is located in a structurally extremely complicated position (even in frame of the PKB); just within a wide shear zone at the junction of the WNW–ESE trending Ráztoky Fault with its branching feathers striking NNW–SSE (Fig. 1.16). We have visited and documented this about

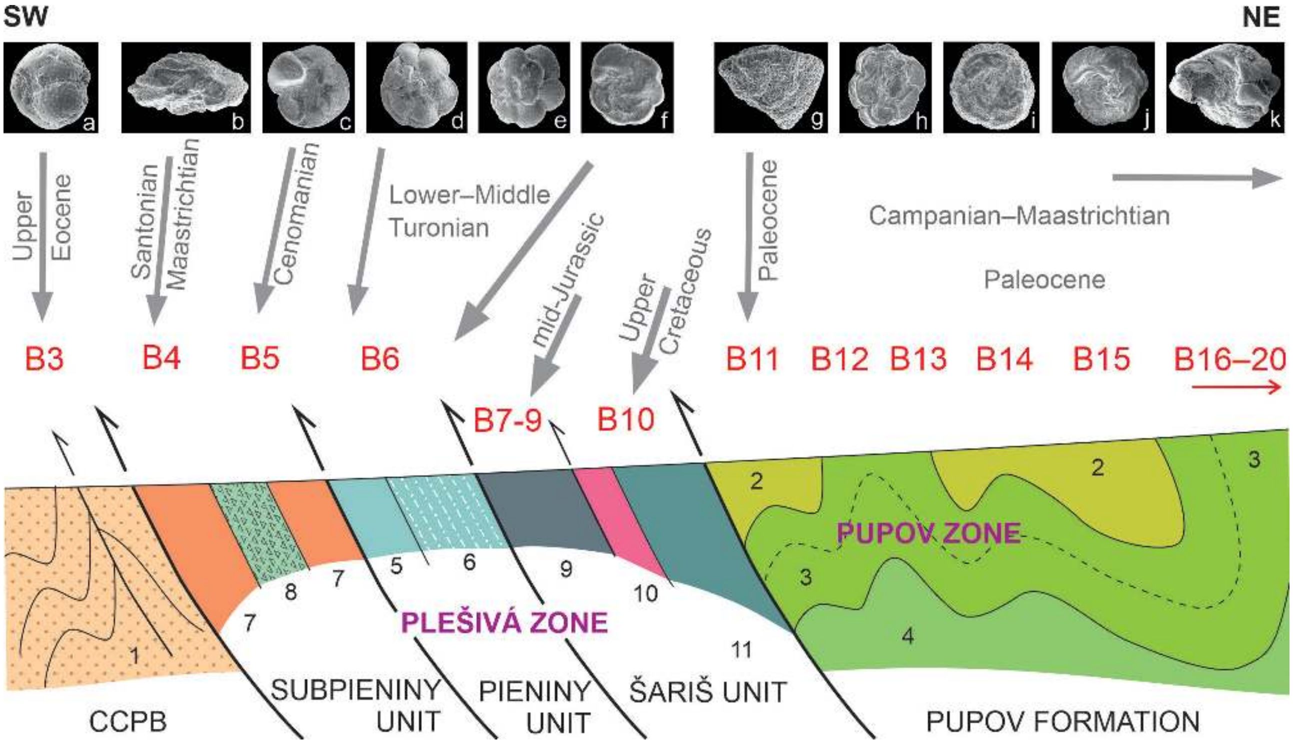


Figure 2.32 Sketchy cross-section through the junction zone of the CCPB and PKB units near Zázrivá village with characteristic foraminiferal species (J. Soták). The SW–NE trending section along the Zázrivka stream follows stops of the excursion B route (red marks) and some documentation points aside (green) where there are no outcrops in the Zázrivka bedrock. Not to scale. The section is about 1 km long. Legend: 1 – turbidite sequence of medium-bedded sandstones and mudstones of the Central Carpathian Paleogene Basin; 2–4 Pupov Formation: 2 – grey mudstones and distal turbiditic sandstones (Maastrichtian–Danian, Zázrivka beds), 3 – fine-grained turbidites with laminated claystones and thin-bedded sandstones (Campanian–Maastrichtian), 4 – medium- to thick-bedded calcareous turbidites (Coniacian–Santonian) and variegated marlstones (Campanian); 5–6 Pieniny Unit : 5 – variegated hemipelagic marlstones (lower Turonian, Kysuce Fm.), 6 – marly sequence with medium- to thick-bedded turbiditic sandstones (middle Turonian, Snežnica Fm.); 7–10 Subpieniny Unit (Jaworki or Púchov Fm.): 7 – variegated marlstones (Santonian–Maastrichtian), 8 – calcareous olistostrome body with fragments of Cenomanian marlstones (Záskalie breccias); 9–11 – Šariš Unit: 9 – dark siliceous marlstones, mudstones and fine-grained calcarenites (early Middle Jurassic, Szlachtowa Fm.), 10 – red pelagic shales (Upper Cretaceous, Malinowa Fm.), 11 – calcareous sandstones and black shales (Upper Cretaceous, Haluszowa Fm.). Fossil images: a – *Globigerinatheka index*; b – *Globotruncana arca*; c – *Rotalipora globotruncanoides*; d – *Dicarinella hagni*; e – *Praeglobotruncana oraviensis*; f – *Marginotruncana angusticarenata*; g – *Morozovella subbotinae*; h – *Globotruncana linneiana*; i – *Globotruncana ventricosa*; j – *Globotruncana lapparenti*; k – *Globotruncanita elevata*.

15–20 metres long section repeatedly during several years and each year it looked differently – some rock units disappeared and others have cropped out. A mixture of slices and chips of sedimentary rock formations of diverse lithologies and ages reminds a tectonic mélange that was likely formed by recurring along-strike slipping within the Ráztoky and related fault zones. The general situation is sketched in Fig. 2.33. Unfortunately, the last inspection in July 2020 revealed that most of rock units described below are no more exposed.

Detailed description (integration of different states of the outcrop during years 2004, 2006, 2013, 2014) from the SW towards the NE:

(i) Bedrock outcrops of red radiolarites (abbreviated as "rr" in Fig. 2.33), which pass to lenses of black radiolarites towards upstream. Sample Z51 (dark greyish-black, poorly calcareous shales) collected from the black radiolarites "br" yielded palynofacies composed of black, opaque phytoclasts and poorly preserved, dark-brown dinoflagellate cysts (Fig. 2.34). Among the latter *Ctenidodinium* sp. and *Compositosphaeridium polonicum* could be determined suggesting Callovian–Oxfordian age. Thus the black radiolarites represent the Sokolica Radiolarite Formation, the red ones may represent the Czajakowa Fm. Black radiolarites are coated by soft, weathered, greenish-black calcareous shales (Z52). These yielded, in turn, very rare dinoflagellate cysts represented by *Nannoceratopsis* spp. and associated by an acritarch *Veryhachium* and frequent spores. Their presence suggests the late Early – early Middle Jurassic age of the assemblage being comparable to the one from sample Z7.

(ii) About 5 metres thick body or layer of brownish-black, fine-grained sandstones rich in tiny mica flakes underlain by black shales resemble sediments of the "Black Flysch" ("bf"), i.e. the Szlachtowa Formation. However, the underlying dark grey calcareous shales (sample ZN17, M. Jamrich) yielded Paleocene taxa *Coccolithus pelagicus*, *Sphenolithus* sp., ?*Fasciculithus* sp., ?*Markalius apertus*, ?*Biantholithus sparsus*.

(iii) Body of firmly lithified pebbly conglomerate (1–2 m) with perfectly rounded exotic pebbles (granitoids, rhyolites) up to 5 cm in diameter ("ec").

(iv) Samples Z5 and Z6 (P. Gedl) were collected from marlstones and calcareous shales ("uc"). Sample Z5 (pale-grey-greenish, spotty, calcareous shale) yielded palynofacies characteristic for pelagic/hemipelagic rocks composed almost entirely of black, opaque phytoclasts. Dinoflagellate cysts are rare, less than 1%, the most frequent are *Pterodinium* and *Spiniferites*. Neighbouring sample Z6 30 cm apart (black, hard, poorly calcareous shale) yielded palynofacies that differs by almost 50% ratio of pollen grains and higher frequency of dinoflagellate cysts. Among the latter *Pterodinium* is most frequent (with subordinate *Spiniferites* and other gonyaulacoids like *Florentinia*). Both samples represent Upper Cretaceous hemipelagic deposits. Presence of *Litosphaeridium siphoniphorum* in sample Z5 indicates the late Albian – earliest Turonian age of its assemblage. A similar palynofacies, but with much rarer dinoflagellate cysts, was found in the Pupov Beds exposed a few hundred metres down the Zázrivka Stream (samples Z3 and Z4; stops B11–13).

Impoverished foraminiferal assemblage containing

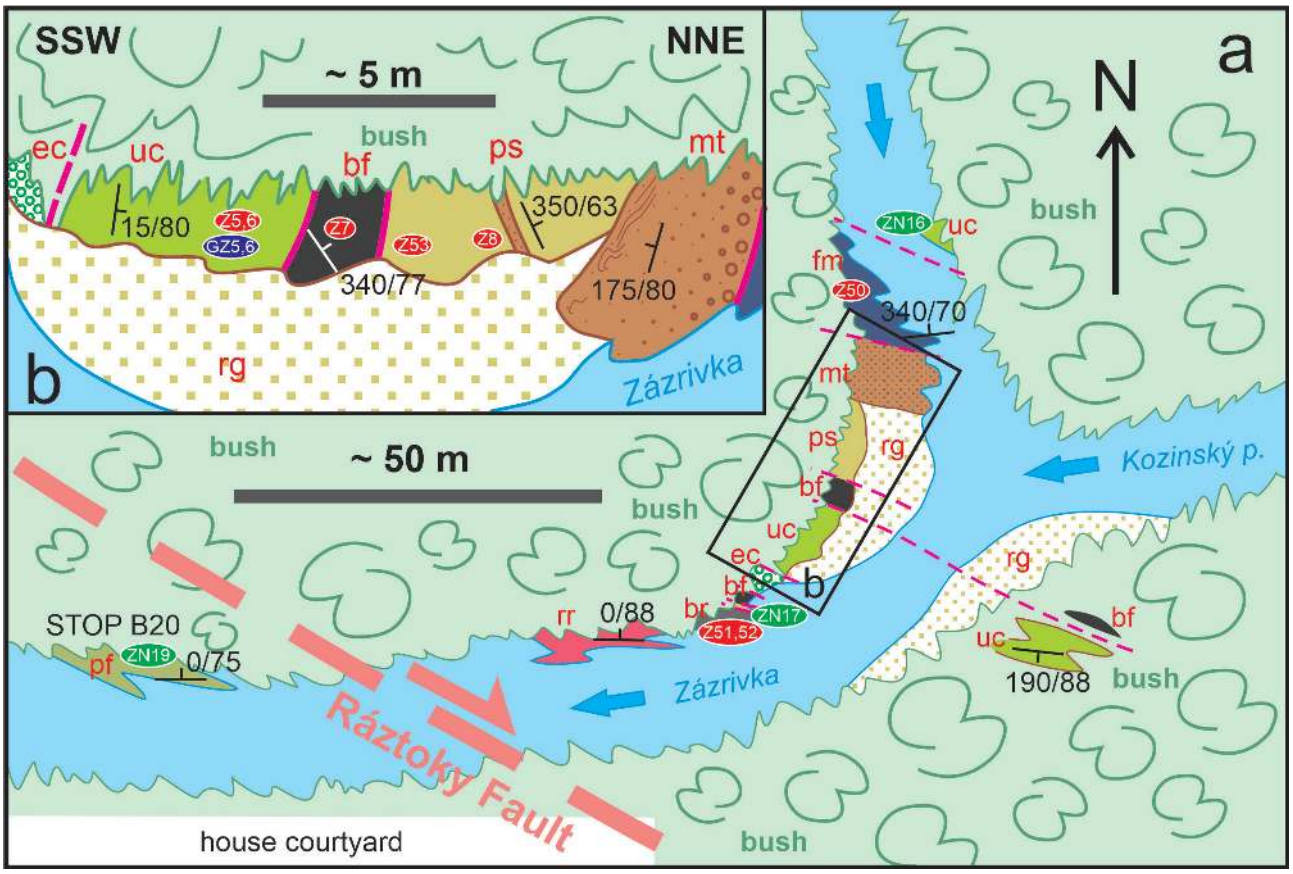
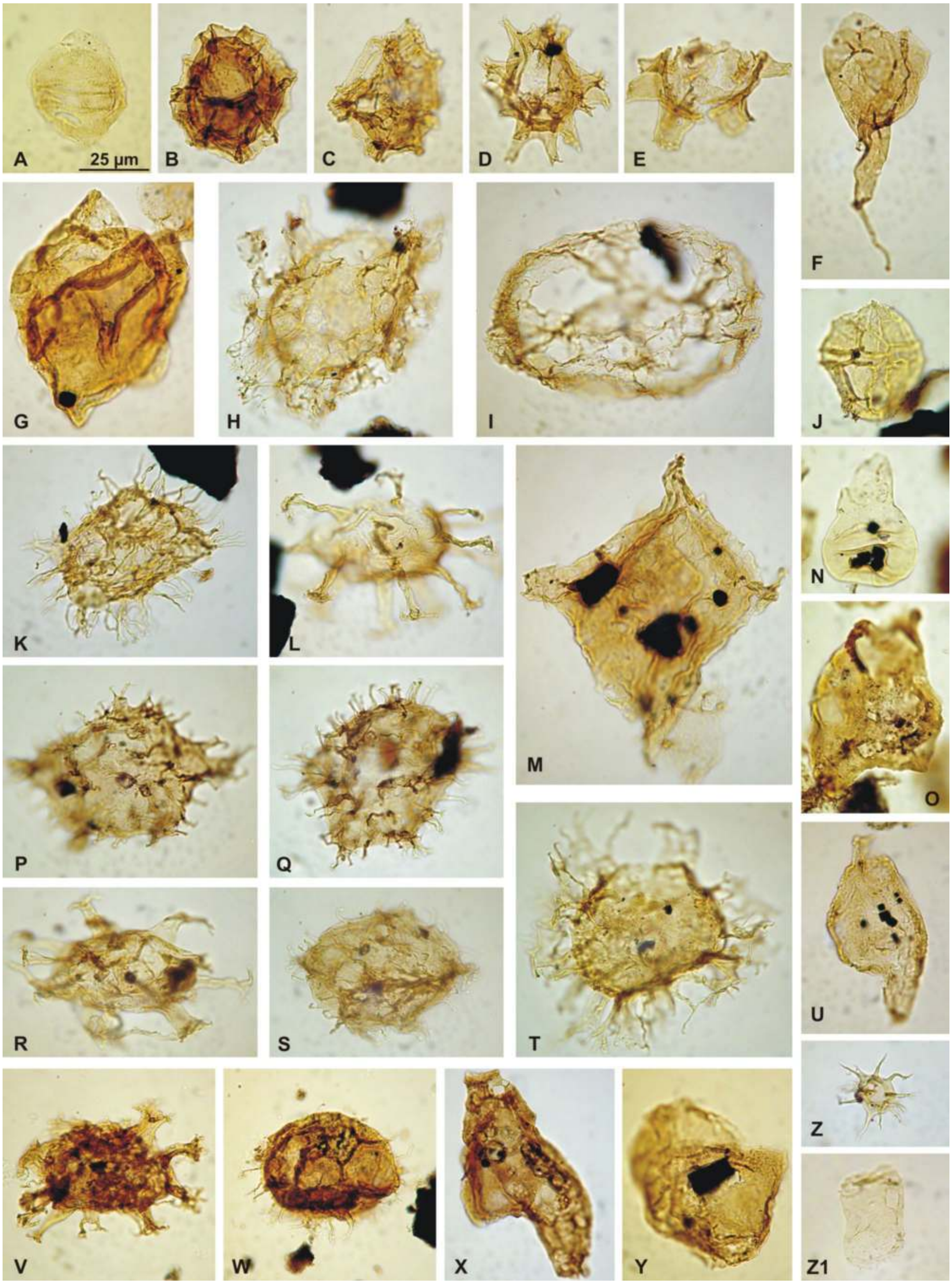


Figure 2.33 Schematic depiction of the defile at stops B20 and B21: a – bird-eye view of the situation at the Zázrivka – Kozinský potok streams junction; b – idealized sketch of the defile (stop B21) with the bedding attitudes and sample locations (red elipses for positive dinocyst samples, blue for foraminiferal and green for nannoplankton samples). The scale is approximate. Abbreviaitons: pf – Pupov Formation; rr – red radiolarites (Upper Jurassic Czajakowa Fm.); br – black radiolarites (Middle–Upper Jurassic Sokolica Fm.); uc – dark grey calcareous shales (Upper Cretaceous); bf – black shales (lower Middle Jurassic Szlachtowa or Skrzypny Fm.); ps – Paleocene–Eocene dark grey shales and sandstones; mt – megaturbidite bed; fm – dark grey spotted marlstones and limestones (Fleckenmergel, Lower Jurassic Allgäu Fm.); rg – river gravels.

Figure 2.34 Palynology of the "mélange zone" at the confluence of the Zázrivka and Kozinská streams (samples Z5–8, Z50–53; photo: P. Gedl). Scale bar in A refers to all photomicrographs. A: *Subtilisphaera* sp. (5); B, C: *Pterodinium* spp. (5); D: *Spiniferites* sp. (5); E: *Litosphaeridium siphoniphorum* (5); F: *Odontochitina operculata* (5); G: *Deflandrea* sp. (53); H: *Glaphyrocysta* sp. (53); I: *Thalassiphora delicata* (53); J: *Carpathodinium* sp. A (=? *Evansia eschachensis*; 7); K: *Apectodini-*



um sp. (53); L: *Homotryblium* sp. (53); M: *Rhombodinium* sp. (53); N: *Phallocysta elongata* (7); O: *Nannoceratopsis* sp. (7); P: *Apectodinium paniculatum* (8); Q: *Apectodinium hyperacanthum* (8); R: *Homotryblium* sp. (8); S: *Apectodinium* sp. (8); T: *Areoligera* sp. (8); U: *Nannoceratopsis* sp. (50); V: *Compositosphaeridium polonicum* (51); W: *Ctenidodinium*? sp. (51); X: *Nannoceratopsis* sp. (52); Y: *Scriniocassis* sp. (50); Z: *Veryhachium* sp. (52); Z1: *Valvaeodinium* sp. (50).

scarce and poorly preserved planktonic foraminifera resembling *Globotruncana* spp. or *Marginotrincana* spp. in samples GZ5 and GZ6 (Š. Józsa) indicate their ?middle Turonian – late Santonian – Maastrichtian age. A more precise age might be suggested by the presence of *Caudammina gigantea* (Geroch) among the agglutinated foraminifera, which is typical for the early Campanian in the PKB (Bąk, 2000), but occurrs up to the Maastrichtian in the External Carpathians (Geroch & Nowak, 1984).

(v) Black to dark-grey-greenish, calcareous shale (sample Z7) exposed 3 metres up the stream from samples Z5 and Z6 (and below sample Z53) yielded an Aalenian (presumably late Aalenian) dinoflagellate cysts assemblage including, i.a., *Nannoceratopsis evae*, *Phallocysta elongata* and *Carpathodinium* sp. A. Its palynofacies is dominated by altered phytoclasts; excellently preserved aquatic palynomorphs are represented by dinoflagellate cysts dominated by *Phallocysta* (acme) and organic foraminifera linings. These shales represent most likely the Szlachtowa Formation (“bf”).

(vi) A different age is suggested for soft, dark-grey-greenish, calcareous shale (Z53; “ps”) exposed a few metres above samples Z5-6 and Z7. Sample Z53 yielded palynofacies composed almost entirely of terrestrial palynodebris with high ratio of cuticles. Among them occur rare and moderately preserved dinoflagellate cysts representing, i.a., *Rhombodinium*, *Thalassiphora delicata*, *Polysphaeridium*, and *Areoligera* (Fig. 2.34). Their presence suggests most likely the Early Eocene age of these shales. Reworked Jurassic genus *Nannoceratopsis* was also found there.

(vii) The following sample Z8 was collected some metres upstream, above the confluence of the Zázrivka and Kozinská streams. Dark-grey, calcareous shale collected below a 20-cm thick sandstone layer yielded a latest Paleocene – earliest Eocene dinoflagellate cyst assemblage including, i.a., *Apectodinium paniculatum*, *A. quinquelatum*, and *A. hyperacanthum*. Palynofacies of this sample is dominated by black, opaque and dark-brown phytoclasts (up to 80%) and cuticles. Dinoflagellate cysts are poorly preserved, among them *Apectodinium* spp., *Areoligera*, *Deflandrea*, *Glaphyrocysta* and *Homotryblium* could be determined (Fig. 2.34).

(viii) A 3.5–4 m thick subvertical megaturbidite layer with graded bedding (“mt”) – the base in the north contains limestone clasts, fining upward upper part shows convolute bedding and frequent plant remnants; S_0 175/80.

(ix) The northern part of the profile upstream Zázrivka (Fig. 2.33) beyond the megaturbidite bed is composed of dark-grey marlstones and limestones with black spots of the Felckenmergel facies (“fm”). The sample Z50 collected some 12 metres up the stream from sample Z8 yielded rare dinoflagellate cysts and palynofacies composed almost entirely of black, opaque phytoclasts. Dinoflagellate cysts present (*Nannoceratopsis*, *Valvaeodinium*? sp., *Scriniocassis* sp.), and lack of *Phallocysta* suggest the Toarcian age. However, sample ZN16 a few metres upstream provided Upper Cretaceous nannoplankton species *Calculites obscurus*, ?*Marthasterites furcatus*, *Quadrum gartneri*. It is possible that lithologically similar Jurassic and Cretaceous sediments are imbricated here again.

Unit: tectonic mixture of various rock units – except of the block of exotic conglomerates and the Paleogene rocks in the middle part of the section, both of unknown provenance, the other imbricated Jurassic and Cretaceous formations probably belong to the Šariš Unit.

STOP B22

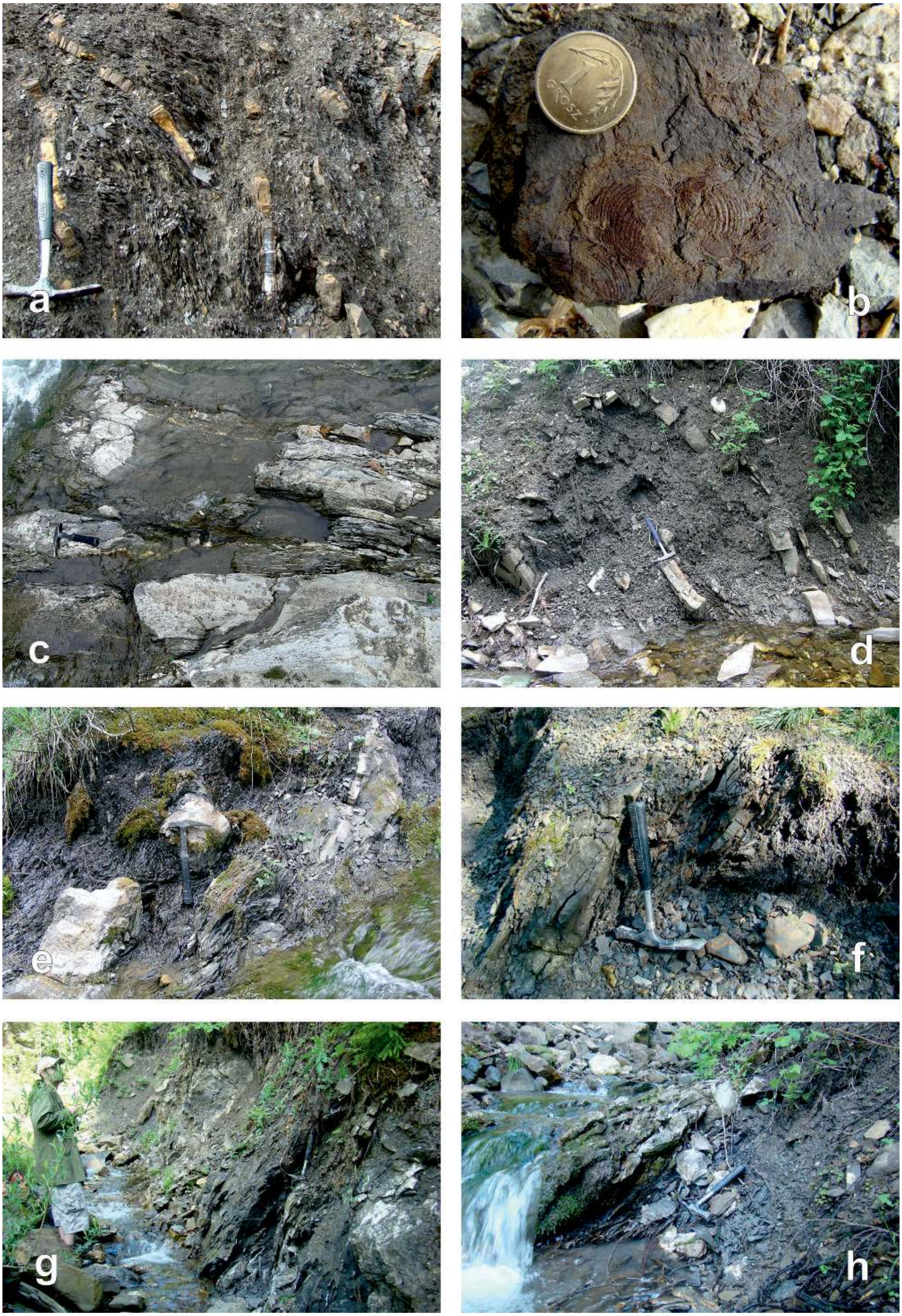
GPS: N49.283874°, E19.169101°; slope cut behind the house No 314 at the road crossing – turning to Končitá Valley

Lithology: brownish-black calcareous shales with sphaerosiderite concretions and “posidonia” (*Bositra buchi*) imprints (Fig. 2.35a, b); S_0 220/70

Biostratigraphy: Samples Z9–Z11 yielded palynofacies dominated by black, opaque phytoclasts (70–90%), cuticles, sporomorphs, phytoclasts, and aquatic palynomorphs. The latter are represented mainly by dinoflagellate cysts – *Nannoceratopsis* spp., *Phallocysta elongata* and *Kallosphaeridium* spp. Presence of, i.a., *Nannoceratopsis evae* in sample Z10 suggest middle–upper Aalenian age of the exposed strata (Fig. 2.36).

Unit: Skrzypne or Szlachtowa Fm., most probably the Šariš Unit

Figure 2.35 Upper part of the Zázrivka–Končitá bedrock section (photos a, b and f–h by P. Gedl, c–e by D. Plašienka): a – black shales with pelocarbonate concretions and layers, Aalenian Srzypny Fm., stop B22; b – “posidonias” (*Bositra buchi*) at stop B22; c – mid-Cretaceous spotted marlstones (samples Z12, ZN20), stop B23; d – black shales with micaceous sandstone beds (samples Z13-14), Szlachtowa Fm., stop B24; e – “Zázrivá beds” type locality (stop B26), black shales with limestone blocks, Skrzypny Fm.; f – black shales with asphaltite coatings (sample Z16), Skrzypny Fm.; g – Middle Jurassic succession of dark spotted siliceous marlstones and radiolarites (sample Z19, stop B27); h – mid-Cretaceous dark calcareous mudstones (sample Z20, stop B28).


a
1 GROSZ
b
c
d
e
f
g
h

STOP B22x

GPS: N49.284615°, E19.169487°; small klippe above the road to Končitá settlement, ca 70 m north of stop B22

Lithology: Lower part of the klippe is composed of reddish nodular limestones overlain by platy limestones with black cherts; S_0 208/25.

Age: Late Jurassic–Early Cretaceous.

Unit: Czorsztyn and Pieniny fms of the ?Pieniny-Kysuca, ?Orava, or ?Šariš Unit

STOP B23

GPS: N49.285077°, E19.169413°; bedrock at the Končitá and Havrania streams junction

Lithology: dark grey spotted limestones and marls (Fig. 2.35c); S_0 75/90

Biostratigraphy: Sample Z12 (P. Gedl) yielded small amount of palynological organic matter and palynofacies characteristic for pelagic deposits: predominance of black, opaque phytoclasts and subordinate amounts of pollen grains and dinoflagellate cysts (Fig. 2.36). The latter are moderately preserved; they include *Oligosphaeridium* spp., *Odontochitina operculata*, *Subtilisphaera* and *Pterodinium*. The presence of *Protoellipsodinium spinocristatum* suggests the Aptian–Albian age (but not uppermost Albian as there is no P. infusorioides), whereas the presence of *Pterodinium* suggests the offshore sedimentary setting.

Trochospiral many-chambered planktonic foraminiferal morphotypes with bad preservation, similar to *Ticinella rohri* (Bolli), *Hedbergella trocoidea* (Gandolfi) or *Ticinella roberti* (Gandolfi) indicate the latest Aptian or late early Albian age (sample GZ12, Š. Józsa).

The nannoplankton sample ZN20 (M. Jamrich) is dominated by abundant Watznaueria barnesiae. Other species, like *Eprolithus floralis*, *Assipetra terebrodentarius*, *Sollasites* sp., *Tetrapodorhabdus decorus*, *Watznaueria fossacincta*, are wide age-range forms, but do not exclude the mid-Cretaceous age.

Unit: Tissalo (Kapuśnica) Fm. of the Šariš Unit?

STOP B24

GPS: N49.285359°, E19.168862°; Končitá stream cut above a small bridge (Končitá street, house No 3, Fig. 2.35d)

Lithology: black shales and micaceous sandstones, overturned bedding S_0 300/70

Biostratigraphy: sample Z13 (P. Gedl) was taken from black, hard shale with calcite veins exposed near micaceous sandstones (Szlachtowa Fm.). Its terrestrial palynofacies is composed of black, opaque phytoclasts and highly altered cuticles; no dinoflagellate cysts were found. Rare, poorly preserved *Nannoceratopsis* and more common *Batiacasphaera* specimens were found in sample Z14 collected 50 metres upstream from a similar exposure of weathered black shale and micaceous sandstone layer. No precise age can be given, although the presence of *Dissiliodinium lichenoides* may indicate late Aalenian age of this sample (Fig. 2.36).

Unit: Szlachtowa Formation, Šariš Unit

STOP B25

GPS: N49.286193°, E19.167379°; left side of the Končitá Valley, small abandoned quarry in the bush

Lithology: thick-bedded micaceous sandstones with overturned graded bedding S_0 270/55; load casts, other sole marks 210/38 indicate palaeocurrents from north towards south

Age: Early Jurassic?

Unit: probably the Šariš Unit

STOP B26

GPS: N49.288472°, E19.163083°; Končitá stream cut and erosional gully below the steep wooden slope of Končitá Hill (right bank); type locality of the "Zázrivá Beds" (Fig. 2.35e, f)

Lithology: black shales and dark laminated limestone and sandstone beds, bedding S_0 53/90

Biostratigraphy: Two samples Z15 and Z16 were taken from lower part of the "Zázrivá Beds" section, from shales interlayered with black, hyaline lenses (asphaltite?). Both samples yielded large amounts of palynological organic matter, which palynofacies consists of terrestrial elements only – black and brown phytoclasts, cuticles and very rich spores. General composition of this palynofacies and its preservation resembles the one from Skrzypny Shale Formation (as for example from samples Z9–Z11, stop B22), except for lack of aquatic palynomorphs (mainly dinoflagellate cysts). This suggests that exposed in this place Skrzypny Shale Formation may represent a "continental" (lagoonal?) facies. Presently this locality is not exposed.

A typical "marine" palynofacies of the Skrzypny Shale Formation was found in sample Z17 from an exposure of this unit in the western bank some 150–200 metres upstream. This sample yielded rich dinoflagellate cyst assemblage (associated by foraminifera organic linings) and black, opaque phytoclasts and small-sized cuticles (Fig. 2.36). This assemblage is similar to the ones from samples Z9–Z11 (including *Nannoceratopsis evae*) and may suggest a similar age – lower–middle Aalenian.

The sample GZ17 (Š. Józsa) is dominated by ophthalmidiids and spirillinids. Nodosarids and trochamminids are subordinate. Such assemblages are bound to the the ?Lower – Middle Jurassic facies in the Pieniny Klippen Belt (Tyszka, 1994, 1999; Gedl & Józsa, 2015).

Unit: Skrzypny Formation, Kysuca or Šariš Unit.

STOP B27

GPS: N49.290868°, E19.159683°; end of the asphalt road in Končitá settlement, terminal bus stop; large erosional gully (Fig. 2.35g).

Lithology: schistous marly limestones with boudi-

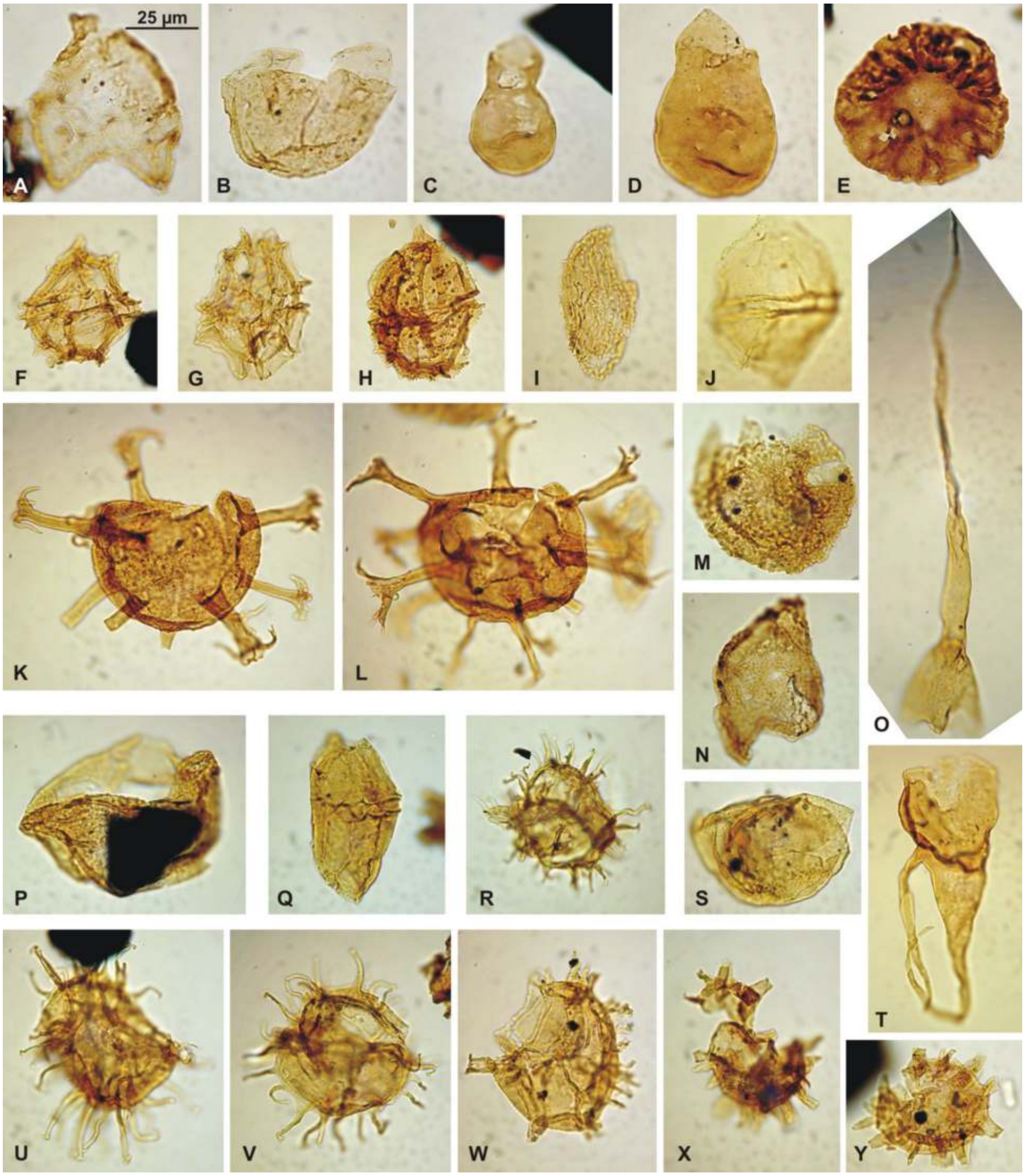


Figure 2.36 Palynology of the Končitá Valley profile (samples Z9-17, Z18-21; photo: P. Gedl). Scale bar in A refers to all photomicrographs. A: *Nannoceratopsis* sp. (10); B: *Kallosphaeridium*? sp. (10); C, D: *Phallocysta elongata* (10); E: spore (10); F: *Pterodinium* spp. (12); H: *Gonyaulacysta diutina*? (12); I: *Protoellipsodinium spinocristatum* (12); J: *Subtilisphaera* sp. (12); K, L: *Oligosphaeridium complex* (12); M: *Batiacasphaera* sp. (14); N: *Nannoceratopsis* sp. (14); O: *Odontochitina operculata* (12); P: *Dissiliodinium lichenoides* (14); Q: *Carpathodinium predae* (18); R: *Ctenidodinium cornigerum* (18); S: *Mendicodinium* sp. (18); T: *Odontochitina operculata* (12); U, V: *Ctenidodinium cornigerum* (18); W: *Pterodinium* sp. (19); X, Y: *Litosphaeridium arundum* (20).

nated layers of spotted limestones; anastomozing S_{01} 210/60, 260/80.

Biostratigraphy: First sample (Z18) stems from a huge exposure in the eastern stream bank, just above the terminus. There exposed are hard, spotty (dark greenish with blackish spots) limestones cut by calcite veins and interlayered with thin layers of greenish-black shale layers. Sample Z18 was taken from these shale intercalations. It yielded black, opaque phytoclasts and moderately preserved dinoflagellate cysts with frequent *Mendicodinium* and *Ctenidodinium cornigerum* (Fig. 2.36). Precise dating of this sample is difficult; presence of *Carpathodinium predae* suggest the upper Bajocian–lower Bathonian age.

Precise age of thin-layered limestones exposed some 50 metres upstream (the limestones are thinner-layered and contain less shales compared to the previous exposure). Sample Z19 taken from a thin shale intercalation yielded very poorly preserved, mainly undeterminable dinoflagellate cyst assemblage (Fig. 2.36). Presence of ?*Ctenidodinium* and ?*Nannoceratopsis* could indicate its Middle Jurassic age. But the presence of very rare *Pterodinium* and undetermined peridinioids would suggest the Late Cretaceous age and reworking of the Jurassic taxa.

Unit: presumably imbricated Cretaceous and Jurassic formations of the Šariš Unit

STOP B28

GPS: N49.291851°, E19.158949°; exposures along a small creek about 100 metres north of the bus terminal in the Končitá Valley (Fig. 2.35g)

Lithology and biostratigraphy: Dinoflagellate cysts found in sample Z20 collected from an exposure of thin-layered marl and limestone on the eastern stream bank are equally poorly preserved. Palynofacies of this sample is composed almost entirely of black, opaque phytoclasts associated by rare, highly altered dinoflagellate cysts. However, the age of this sample can be relatively precisely established as the Albian–lowermost Cenomanian based on the presence of *Litosphaeridium arundum*. Additionally, *Spiniferites* and *Pterodinium* occur in this sample (Fig. 2.36).

Unit: probably the Šariš Unit

Other important localities in the Plešivá zone

On the northern slopes of the Plešivá Valley and settlement (Zázrivá district), eastward of the lower part of the Zázrivka section (B), several other remarkable outcrops occur. A small klippe on the Plešivský Žiar ridge (GPS N49.271770°, E19.167973°) is composed of the Jurassic–Lower Cretaceous formations assigned to the Czertezik Succession by Haško (1976), i.e. belonging to the Subpieniny Unit in our conception. Position of this klippe is not very clear – towards the west it seems to be related to variegated Upper Cretaceous marlstones (Púchov Fm.) as the southernmost PKB strip adjacent to the deformed Paleogene deposits of the CCPB. From the south it is juxtaposed to Upper Cretaceous flysch sandstones and exotic conglomerates of probably the Pieniny Unit (Snežnica and Sromowce fms), but the northen boundary is unclear due to landsliding.

In the easternmost part of the Plešivá Zone, on the Dudová – Pavláškova skala ridge, rocks assigned to the Šariš Unit appear (Fig. 1.16). Medium- to coarse-grained calcareous sandstones are tentatively classified as the Jarmuta-Proč Formation (Črchle settlement). Further east (Dubovské lúky meadows; GPS N49.276227°, E19.208101°), a slice of Jurassic quartzites (Dutkov vrch Fm.) and black shales (Szlachtowa Fm.) is present – already arbitrarily ranged to the Havrania Zone, however (see above).

In August 2020, we sampled a temporary outcrop

Figure 2.37 Temporary outcrop in Zázrivá-Dolina, Upper Creatceous strata of the Šariš Unit: a – general view, variegated shales of the Malinowa Fm. to the left and grey-brown shales of the ?Haluszowa Fm. to the right; b – detail of the Malinowa Fm.

– excavation for a new house in Dolina settlement (Zázrivá district, GPS N49.274159° E19.137054°). There, the about 25 metres long cutting on the slope foot exposed the contact of CORB-type variegated pelagic shales on the left (eastern) side of the section with dark grey calcareous shales and sandstones to the right (Fig. 2.37). The slightly calcareous shales are cherry-red to yellowish-green and contain siliciclastic turbiditic sandstone beds 10–15 cm thick. Their lithology corresponds to the Malinowa Formation. Its contact with the overlying strata (bedding is nearly vertical, ca 83/82, but sole marks indicate overturned bedding) does not show any features of tectonic contact, thus it appears to be sedimentary.

Samples Z69A and Z69B (Š. Józsa) provided the lowermost Turonian planktonic foraminifers of the Whiteinella archeocretacea Biozone: *Muricohedbergella*? *planispira* (Tappan), *Whiteinella aumalensis* (Sigal), *Whiteinella baltica* Douglas & Rankin, *Whiteinella aprica* (Loeblich & Tappan), *Whiteinella archeocretacea* Pessagno, *Whiteinella brittonensis* (Loeblich & Tappan), *Praeglobotruncana gibba* (Klaus), *Praeglobotruncana*? cf. *stephani* (Gandolfi), *Dicarinella algeriana* (Caron), *Dicarinella imbricata* (Mornod), *Dicarinella hagni* Scheibnerová, *Bollitruncana carpathica* (Scheibnerová).

The overlying strata are composed of brownish-weathered dark grey marlstones and calcareous turbiditic sandstones. We suppose that the calcareous flysch sequence belongs to the Haluszowa Formation of the Šariš Unit. Samples for foraminifers were barren, but sample Z157 (P. Gedl, Fig. 2.27) yielded very rare dinoflagellate cysts dispersed in predominating small-sized, black, opaque phytoclasts. Dinoflagellate cysts show various preservations: from well preserved but dark-coloured to pale-coloured but poorly preserved. Determinable forms represent mainly *Pterodinium cingulatum*, *Subtilisphaera* sp., *Spiniferites* sp., *Pervosphaeridium* sp., *Palaeohystrichophora infusorioides*, and *Odontochitina* ?*rhakodes*. The age of dinoflagellate cyst assemblage from the sample Z157 is Late Cretaceous. Reworked Early-Middle Jurassic taxa occur, too (*Dissiliodinium*, *Nannoceratopsis*).

In the map view, this outcrop provides a connection between occurrences of the Šariš Unit exposed east of the Zázrivka stream (Dudová – Pavláškova skala ridge) and in the middle part of the Zázrivka section (stops B7–10) with the northern part of the Rovná hora section (stop A4), which is otherwise unclear due to a thick Quaternary cover and landsliding (see Fig. 1.16).

2.5 Istebné Zone (Zázrivá–Párnica sigmoid)

This N–S trending, about 5 km long and 1–2 km wide zone connects the W–E striking eastern part of the Varín and similarly oriented western part of the Orava PKB sectors (Fig. 2.1). For a long time, this only transversal structure affecting the PKB was considered as a 10 km long dextral strike-slip offset along a lateral ramp (e.g. Haško & Polák, 1979; Nemčok & Nemčok, 1998), despite that already Andrusov (1926, 1938) remarked that no N–S faults prolong northwards into the Flysch Belt. He supposed that the sigmoid originated during the post-Paleogene backthrusting of the Klippen and Flysch belts and was shaped by the northward submerging rigid Malá Fatra core – i.e. the sigmoid was formed as a transversal or oblique ramp during backthrusting. This view we can share, since it is indicated by strata dips along the zone. The PKB formations plunge moderately to the north-east or east under the thick flysch complexes of the EWC Magura (Krynica) Unit – e.g. going up the slope east of Opálené Hill (Figs 1.16, 1.17 and 2.1). Nevertheless, the N–S trending faults are present within the Istebné Zone, especially along its western margin along the contact with the Mesozoic sedimentary complexes of the Krížna Nappe (designated as the Istebné faults in Figs 1.16 and 1.17). These faults may have formed as oblique normal faults during the Lower Miocene dextral transtension (Gaži & Marko, 2006; see chapter 3.2 bellow).

Deciphering of the structure of PKB units in the Istebné Zone is complicated by poor outcropping. The area is mostly affected by extensive landslides of various ages and by a thick cover of debris of Magura sandstones occurring in topographically higher position. It seems that also many klippen present in this area are loose blocks transported downslope by landslides, both recent and older. The latter are not so well identifiable nowadays, especially in forested areas. Lithology of these scattered exposures is variable and indicates that probably all units that occur in the Havrania and Plešivá zones are present also here: Jurassic quartz sandstones, black shales and Upper Cretaceous variegated shales (Šariš Unit?), rather thick complexes of spotted marly Jurassic? and Cretaceous? limestones (Fleckenkalk) and Lower Cretaceous limestones (presumably Kysuca Unit), a few blocks of red crinoidal and nodular limestones (Czorsztyn Succession), and mid-Cretaceous variegated marls (Kysuca Unit). Recently, the latter were nicely exposed, but not studied yet, along a new timber road south of Opálené Hill.

The bedding strikes and structural trend of the Istebné Zone vary from N–S to NW–SE. As can be seen from the excellent map of Andrusov (1938), the transition from this direction to the overall WSW–ENE to SW–NE trend of the next Kubín Zone of the Orava PKB sector is gradual for the distance of approximately 1–2 km (Fig. 2.1).

2.6 Kubín Zone

The Kubín Zone occupies the westernmost part of the Orava PKB sector adjacent to the Zázrivá sigmoid area (Istebné Zone; Fig. 2.1). The following description is based on the recent investigations of M. Molčan Matejová in cooperation with R. Aubrecht, P. Gedl, Š. Józsa, E. Halásová and D. Plašienka in the area east of town Dolný Kubín (Fig. 1.16). Molčan Matejová (2019) developed updated geological and tectonic maps of the area and studied in detail several litho-biostratigraphic sections (Fig. 2.38). From these, the section Revišné 2 was already published (Molčan Matejová et al., 2019) details from the other sections are in preparation to be published in independent papers soon. Hereafter, only a brief description of these sections is presented.

In general, rock formations of all three Oravic units (Pieniny, Subpieniny and Šariš) are present in the Kubín Zone. However, only fragments of sedimentary successions occur in a strongly imbricated and poorly outcropped area. At some localities, e.g. sections Revišné 2 and Beňova lehota 2, formations of very different age and possibly of different tectonic units are intimately imbricated, even if they are lithologically almost identical (Lower/Middle Jurassic vs. mid-Cretaceous black shales in section Beňova Lehota 2). Bedding is dominantly moderately NW to N-dipping, but strong deviations occur locally.

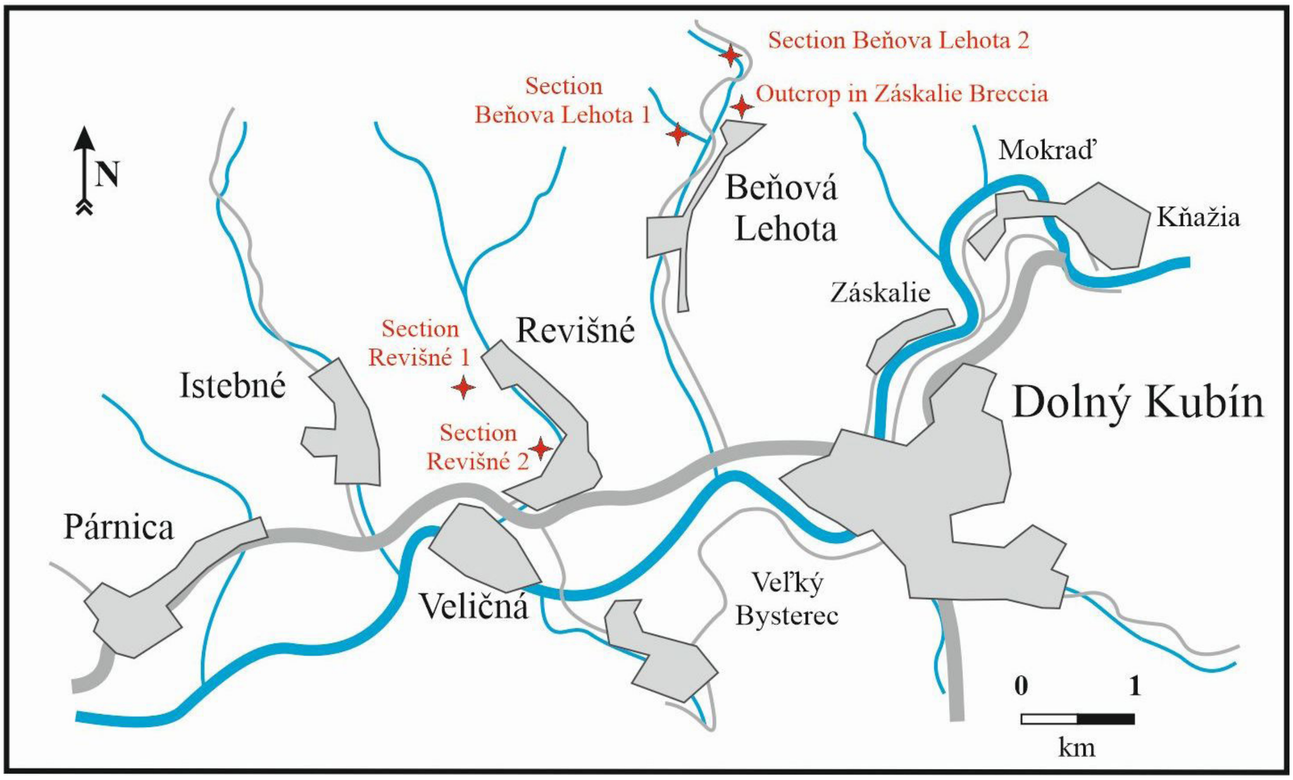


Figure 2.38 Location map of litho-biostratigraphic sections in the Kubín Zone (Molčan Matejová, 2019).

Concerning the distribution of Oravic units, three subparallel belts can be roughly distinguished. The northern belt, adjacent to the Magura (Krynica) Unit, is feebly exposed due to thick debris of Magura sandstones and numerous landslides. On the N–S trending ridge Pikula–Repiská (ski resort Kubínska hoľa – Koliesko), there occur several large klippen of the Pieniny Fm. (also with Jurassic radiolarites and nodular limestones in places) near the contact. These klippen remind olistoliths, because they seem to be embedded in dark grey marly shales (Pikula), or in calcareous sandstones and limestone breccias (Repiská), all underlain by Púchov-type variegated marlstones. Sandstones contain large foraminifers *Pseudosiderolites vidali* (Douvillé) indicating Campanian to Maastrichtian age. As such, these sediments resemble the Gregorianka breccias (sensu Plašienka & Mikuš, 2010) of the Jarmuta Formation and thus are tentatively assigned to the Subpieniny (Czorsztyn) Unit. A possibly similar situation occurs to the north-east on the Vtáčnik ridge. However, Záskalie-type carbonatic breccias form only a narrow strip there at the contact with the Magura rocks, so indicating a rapid eastward wedging-out of the northern belt (Fig. 1.16). Large Vtáčnik klippen to the south are dominantly composed of the Pieniny Fm. and some radiolarites and likely belong to the Pieniny Unit.

The Záskalie breccias, which are somehow analogous to the Gregorianka breccias, were described in the nearby valley eastward (section Beňova Lehota 1; Molčan Matejová, 2019). The monomictic breccias are composed of sharp-edged clasts of grey marly limestones, partialy spotted, accompanied by Jarmuta-type sandstones. Marchalko et al. (1979) described *Globotruncana arca* (Gushman), *Stensioeina pommerana* Brotzen as the youngest identified fossils found in the matrix of the Záskalie Breccia. These microfossils limit the origin of the breccia to the Campanian, less likely Campanian–Maastrichtian. Our study identified presence of *Pseudosiderolites vidali* (Douvillé) in the matrix of the breccia, assigning it to the Campanian–Maastrichtian age. Interestingly, presence of sandstone with *Discocyclina* sp. was noted in the Beňova Lehota 1 Section. The determined foraminifera would reflect the Paleocene–Eocene age of the beds. The sandstones in question could belong to the Paleogene Proč Formation, which was in the eastern part of PKB merged with Jarmuta Formation into the Jarmuta-Proč Formation (Plašienka & Mikuš, 2010). However, position of these sandstones in the section is not clear.

The northern belt of the Kubín PKB Zone is marked also by presence of sedimentary formations that most probably represent the Šariš (Grajcarek) Unit. In the Beňova Lehota 2 section (Molčan Matejová, 2019; Molčan Matejová et al., in preparation), a long profile in bedrock of the Lehotský potok stream exposes the Lower–Middle Jurassic (Sinemurian, Toarcian–Aalenian) black shales with turbiditic, slightly micaceous sandstone intercalations (Fig. 2.39a). They are akin to the Skrzypny, but mostly to the Szlachtowa Fm., but imbricated with macroscopically indistinguishable Cretaceous black shales (dated by dinocysts and foraminifers). The Upper Jurassic–Lower Cretaceous siliceous limestones in the upper part of the section also remind rock of the Šariš Unit. Possibly some klippen in the Pikula area also belong to the Šariš Unit.

Figure 2.39 Outcrops in the Kubín Zone: a – folded Middle Jurassic black shales in the Beňova Lehota 2 section. Marína Molčan Matejová for scale; b – the view of the Revišné 1 section, Roman Aubrecht and Marína Molčan Matejová sampling.

The central part of the Kubín Zone is dominated by the Pieniny Unit (Kysuca Succession; Figs 1.16 and 1.20). In the studied area, the Kysuca klippen are formed by radiolarites to radiolarian limestones of the Czajakowa Formation (Callovian–Oxfordian) and nodular limestones of Czorsztyn Formation (Kimmeridgian). However, most of the klippen are represented by the Pieniny Limestone Formation (Tithonian–Barremian). In the section Revišné 1, the Pieniny Fm. is formed by grey, often spotted marly limestones with occassional presence of cherts. Typical light grey “Biancone” limestone with brown cherts was found sporadically. Radiolarian and radiolarian-spiculitic microfacies prevail. Usual Calpionella microfacies of the Tithonian–Berriassian age is scarce and several zones and subzones were not detected – neither in the Revišné 1 section (Fig. 2.39b), nor in any other samples from the area. In the section Revišné 1, it is questionable whether it is a tectonic reduction of the beds with missing calpionellid zones, or the outcropping limestone sequence was deposited in an environment poor in calpionellids. Alternatively, the Pieniny Fm. in this section might belong to a different unit, presumably the Šariš (Grajcarek) Unit, in which the stratigraphic condensation and strongly reduced thickness of the Lower Cretaceous succession are typical (Birkenmajer & Gedl, 2017).

Large klippen formed by the Pieniny limestones occur mostly at ridges (e.g. the conspicuous Tŕniny klippe between Beňova Lehota and Záskalie), whereas they are surrounded or underlain by some mid-Cretaceous marly formations, but mostly by flysch deposits of the Snežnica Formation. This situation indicates the overall overturned succession modified by the SE-vergent fold-thrust structures. The Snežnica Formation consists of dark grey marly shales alternating with steel-grey fine-grained calcareous turbiditic sandstones, which in places pass into microconglomerates predominantly with carbonate cement. The Snežnica Fm. is macroscopically similar to the Jarmuta Formation. Especially in the field with minimal rock exposure, differentiation in the weathered debris is impossible. In general, the Snežnica Fm. (Turonian) shows thickening- and coarsening-upward and pass gradually into the Sromowce Formation (Coniacian–Santonian). Bodies of pebbly mudstones and conglomerates often contain well-rounded pebbles and cobbles of various rocks, in part designated as “exotic” (e.g. Triassic carbonates of various facies, shallow-water Upper Jurassic limestones, granitoids, probably Permian clastic and volcanic rocks etc. – cf. Mišík et al., 1977; Mišík & Sýkora, 1981; Birkenmajer, 1988; Mišík & Marschalko, 1988).

The southern PKB belt of the Kubín Zone juxtaposes strongly disturbed sediments of the CCPB. Similarly like the northern belt, it is mostly composed of the Subpieniny and Šariš units (Fig. 1.16). As shown at the Revišné 2 section (Molčan Matejová et al., 2019), these two units are tighly imbricated. Analysis of the Revišné klippe showed that the upper and middle parts of the klippe consist of Middle Jurassic crinoidal limestones and the Krasín Breccia (Aubrecht & Szulc, 2006), which are typical members of the Czorsztyn Succession. By analogy, the crinoidal limestones (Smolegowa and Krupianka limestone formations) can be dated to Bajocian. Filling of interstitial spaces of the Krasín Breccia is represented by red mudstone; therefore, we suppose it originated later, starting from the uppermost Bajocian onward, during the relative sea-level rise and the change of the crinoidal facies to the Ammonitico Rosso facies (Czorsztyn Fm.). Occurrences of the Czorsztyn klippen in the Orava region are rare and the Revišné locality is its first record including the crinoidal limestones with neptunian dykes and the Krasín Breccia outside the Middle Váh Valley.

On the other hand, rocks outcropping in the bottom part of the klippe in Revišné are, by its composition, very close to the description of the Grajcarek Unit from the Polish part of the PKB (Birkenmajer, 1986; Birkenmajer & Gedl, 2017). In an overturned succession, the following formations were determined (Molčan Matejová et al., 2019): (1) Czorsztyn and Revišné limestone formations are stratigraphically oldest (Tithonian) and are composed of red to green biodetritic nodular limestones with *Saccocoma*-spiculitic and spiculitic microfacies; (2) light grey, partially spotted Pieniny Limestones provided biostratigraphic proofs for the Late Tithonian, Late Valanginian and the uppermost Barremian or Barremian/Aptian boundary interval ages; (3) the section continues with grey spotted marlstones (Kapuśnica and Wronine formations; Aptian–Albian) with planktonic foraminiferal and radiolarian microfacies.

Besides the upper klippe in the Revišné 2 section, rock formations that can be integrated in the Subpieniny Unit comprise Upper Cretaceous variegated marlstones (Púchov Fm.), and Jarmuta-type sandstones and conglomerates with bodies of Záskalie breccias, including their type locality in Dolný Kubín (Marschalko et al., 1979). In contrast, quartzitic sandstones of the same character as those from the Jedľovinka Hill above Zázrivá (Dutkov vrch Fm.), cropping out for instance at the ridge between Revišné and Beňova Lehota villages, point to the presence of various formations affiliated with the Šariš Unit also in the southern belt – possibly together with some small klippen of the Lower Cretaceous limestones, such as that in the lower part of section Revišné 2.

The overall structure of the Kubín Zone resembles a tight imbricated synclinorium, similarly as that of the eastern part of the Varín PKB part described above. The imbricated northern and southern limbs are built up by the Šariš and Subpieniny units in the lower structural postion, while the folded Pieniny Unit in a higher structural position forms the central belt of the Kubín Zone (Figs 1.16 and 1.17). However, the structurally even higher units known from the Varín sector (Kozinec and Klape units, Pupov Fm.) were not recognized with certainty here. Nevertheless, we presume that structural evolution of both PKB parts was analogous, though separated by the transversal Istebné Zone related to the Zázrivá sigmoid (see chapter 3.2 below).

Due to a scarce presence of semiductile structures like folds, the structural investigation on the Kubín Zone was focused on the kinematic and palaeostress analyses of brittle structures – mesoscopic faults and joints. Most of slickensides with recognizable kinematics were measured in limestone klippen composed of the Pieniny Fm., a part also in the CCPB sediments adjacent to the PKB. The palaeostress analysis revealed altogether six stages with different orientation and magnitudes of the stress axes. All these palaeostress fields are attributed to the Cenozoic evolution. However, their precise dating is impossible in the studied area owing to the absence of sediments younger than Oligocene. Moreover, concerning the klippen exposures, only Jurassic to Lower Cretaceous rocks could be investigated. Nevertheless, comparison and correlation of the palaeostress stages with other Western Carpathian areas with well-established age determination of the stages (e.g. Marko et al., 1995; Kováč & Hók, 1996; Vojtko et al., 2008, 2010; Pešková et al., 2009; Bučová et al., 2010; Šimonová & Plašienka, 2017; Pulišová et al., 2018), it was possible to tentatively reconstruct the palaeostress fields evolution also in the studied area.

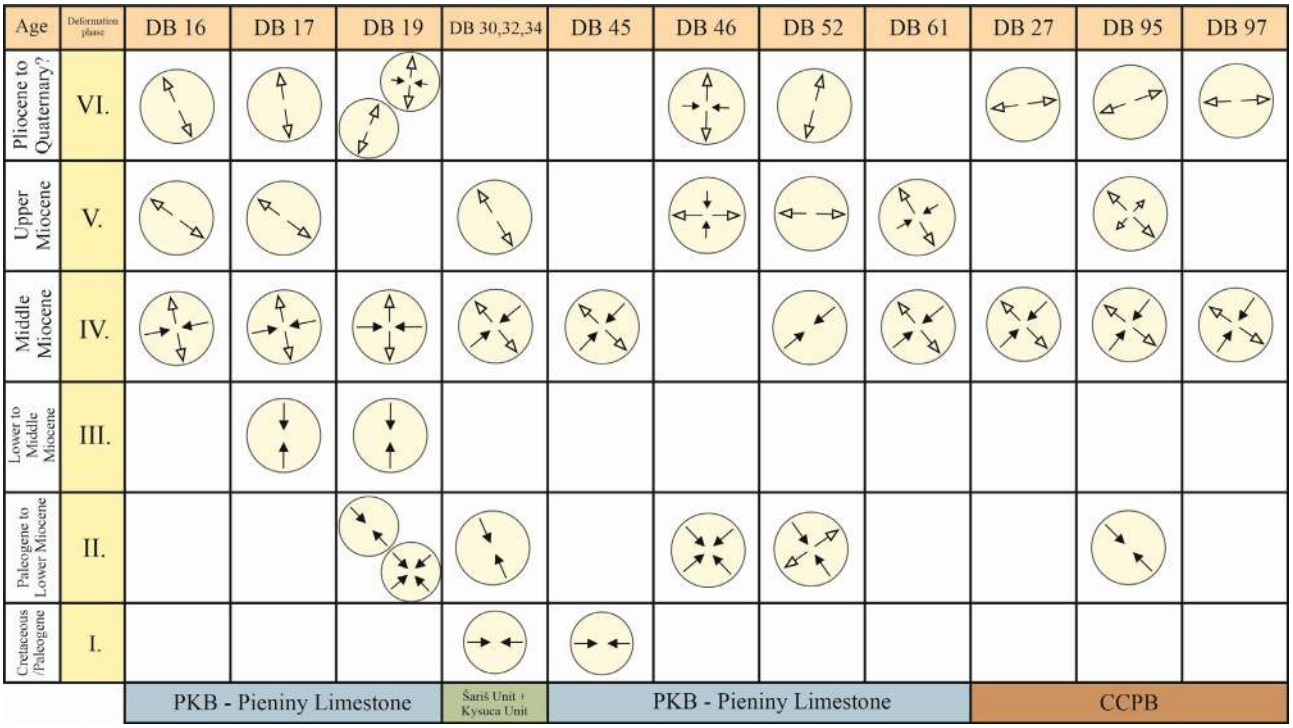


Figure 2.40 Summary of the palaeostress analysis of fault structures in the Kubín Zone and adjacent CCPB sediments. DB – documentation sites.

The resolved orientations of horizontal stress axes are grouped into six stages depicted in Figure 2.40. The oldest phase with W–E compression was sporadically recorded in the limestone klippen and might be correlated with the tectonic stage S3 (see chapter 3.4 below) marked by compression parallel to the PKB trend. The next stage is characterized by the overall NW–SE compression that probably took place during the whole Paleogene (Plašienka et al., 2020) up to the Lower Miocene, since it affected also the CCPB formations. The rotation of the compressional stress in a clockwise direction by approximately 45° defines the second distinct deformation phase. In the Middle Miocene, there was a change to a transpressional regime, which resulted in strike-slip and dip-slip faults oriented in the NW–SE and NE–SW directions. The beginning of NE–SW extension is most probably of the Late Miocene age. The last documented deformation took place in the Pliocene–Quaternary? and it is divided into two subgroups – extension in the W–E direction and extension in the NNW–SSE to NNE-SSW directions. The second subgroup was identified only within the PKB units.

3 Tectonics of the Pieniny Klippen Belt and adjacent zones in north-western Slovakia

The PKB sharply differs from the neighbouring zones by its composition, structure and tectonic evolution, as well as by the surface morphology and landscape. In spite of this, the PKB is not a kind of an "exotic terrane", but it shows close structural and evolutionary relationships with the neighbouring, although diversing zones. In this chapter, we provide: (i) some additional small-scale structural data to those already presented above; (ii) magnetotelluric profiles across the Zázrivá–Párnica sigmoid and palaeostress analysis and interpretation of brittle fault structures associated with this transversal zone; (iii) interpretations of two gravity profiles transecting the broader area of interest; and finally (iv) the evolutionary tectonic model of the PKB in this area.

The structural trend of the PKB units in the Varín (Kysuce) sector, as well as the the PKB/CWC and PKB/EWC contacts are generally W–E trending. By this trend, the Varín sector diverges from the neighrouring, generally SW–NE trending PKB sectors – Púchov in the weste and Orava in the east. The Púchov vs. Varín transition is characterized by necking and narrowing of the PKB due to dextral strike-slipping along the W–E striking Bytča–Žilina fault zone (Plašienka et al., 2020). The eastern contact with the Orava sector is characterized by an abrupt change of the structural trend from W–E to N–S strike along the Zázrivá sigmoid. Within the eastern Varín sector, all strata are steeply N- to NW-dipping in general. Hence the internal structural trends are slightly oblique to the overall W–E strike of bounding faults and different from the almost uniform SW–NE structural trend of the adjacent Púchov sector occurring southwestward (Fig. 3.1). Thus the Varín sector appears to be affected by several differently oriented shortening events as characterized in the Fig. 3.1 caption.

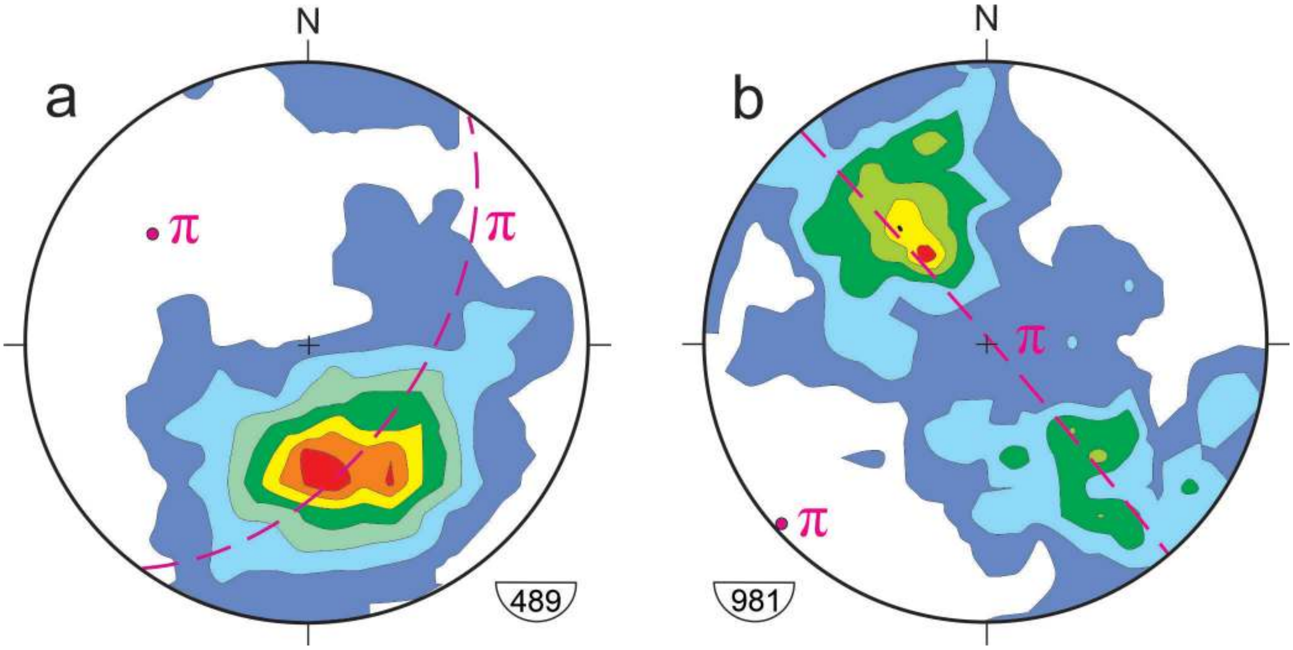


Figure 3.1 Left – the cumulative contour stereoplot (a) of poles to bedding from the eastern part of the Varín PKB sector (Havrania, Pupov and Plešivá zones). The complex pattern and position of the π-pole appears to be a result of interference of three superposed principal deformation stages with different shortening direction: (i) W–E compression with N–S structural trends (the least expressed; stage S3 – see below); (ii) NW–SE compression that generated SW–NE trending structures (stages S4–S6) followed by dextral transpression in the same stress field; (iii) N–S compression with backtilting and backthrusting (dominant in the Varín sector; stage S7). The right stereoplot (b) shows poles to bedding from the Púchov sector of the PKB (Middle Váh River Valley; Plašienka et al., 2020) for comparison. In that area, the structural pattern is dominated by the NW–SE compression, though W–E compression operated as well. However, the N–S contraction did not function.

3.1 Small-scale structural elements

The modern structural research has been performed in wider surroundings of the area under consideration, but only a few localities were described directly from it (Nemčok & Nemčok, 1998; Kováč & Hók, 1996; Marko et al., 2005; Gaži & Marko, 2006; Pešková et al., 2009, 2012; Beidinger et al., 2011; Bučová, 2013). Nevertheless, the works from outside, but still in the PKB contiguous zones, also provide important structural information that can be applied in the area concerned (e.g. Aleksandrowski, 1989; Nemčok, 1994; Nemčok & Nemčok, 1994; Marko et al., 1995; Decker & Peresson, 1996; Nemčok et al., 1998; Hrouda et al., 2009; Bučová et al., 2010; Beidinger & Decker, 2016; Šimonová & Plašienka, 2017; Soták et al., 2017; Pulišová et al., 2018; Plašienka et al., 2018, 2020). Concerning the eastern PKB branch (in Poland and eastern Slovakia), some results of detailed structural investigations were published by Ratschbacher et al. (1993), Jurewicz (1994, 1997), Plašienka et al. (1998, 2012, 2013), Jacko and Janočko (2000) Plašienka and Mikuš (2010), Plašienka (2012b) and Ludwiniak (2018). However, due to the considerably different post-Eocene tectonic evolution of the eastern PKB branch, only the pre-Oligocene deformation structures can be correlated with the western branch (cf. Plašienka et al., 2020). Regrettably, almost no structural data are available from the Ukrainian part of the PKB.

This chapter was compiled by D. Plašienka, M. Molčan Matejová, J. Bučová and V. Šimonová, relying mostly on their own research. Hereafter we present some mesoscopic field structural data, although scarce, which document the complex multistage structural evolution of the PKB units in the area concerned.

At an outcrop scale and dependent on the lithology, the PKB rocks were deformed by the ductile/brittle and purely brittle mechanisms. According to data compiled from the eastern PKB branch (Plašienka, 2012b and references therein), which can be applied also to the area under consideration, deformation paleotemperatures were in the range of the deep diagenesis and rarely exceeded 200°C. In accordance, the very low-grade deformation mechanisms included only a limited crystal-plastic deformation by twinning of coarse calcite grains (e.g. crinoids). However, the pressure solution mass transfer was much more effective process in accumulation of macroscopic deformation, especially in clay-rich carbonates like marls, marlstones and marly limestones.

A very weak semiductile deformational overprint of the PKB rocks can be revaled by the anisotropy of magnetic susceptibility (AMS) data. As reported by Márton et al. (2009) and Madzin et al. (2021), magnetic fabric of the turbidite deposits of large parts of the CCPB out of the PKB surroundings is dominantly sedimentary by origin. On the other hand, Hrouda and Potfaj (1993a, b) and Hrouda et al. (2009) reported a slightly higher degree of internal deformation in the Peri-Klippen Paleogene complexes, but still only with signs of incipient “pencil structure” stage (cf. Hrouda & Chadima, 2020). Sandstone samples from the Terchová-Zázrivá area (deformed Paleogene flysch deposits of the CCPB in contact with the PKB) show a magnetic fabric transitional between planar and linear with the magnetic foliation poles clustering in a NNW–SSE trending girdle, while the magnetic lineations are highly scattered. Hrouda and Potfaj (1993a, b) interpreted this fabric as largely deformational by origin, having been caused by the N–S oriented shortening. Concerning the proper PKB rocks, the AMS data were obtained from Upper Cretaceous red pelagic marls at several localities along the PKB (Márton et al., 2013). Magnetic ellipsoids are mostly oblate and parallel to bedding. Orientation of the magnetic lineation is variable and not well understood – it tends to be parallel to the PKB strike in the eastern segment, while subperpendicular to the trend of the western PKB branch. It is not to be excluded that the complex AMS patterns might have resulted from superposition of two or even three variously oriented shortening events – first general W–E compression, locally parallel to N–S trending mesoscopic cleavage, overprinted by NW–SE oriented shortening with large-scale buckle folding and imbrication in the western PKB branch (Plašienka et al., 2018) and by additional SW–NE compression restricted to the eastern PKB branch (Plašienka, 2012b; Plašienka et al., 2020). These three events are then recorded in different ways in various PKB domains. However, more detailed studies are required.

The primary stratification of clay-rich rocks is often amplified by early post-sedimentary, penecontemporaneous processes such as compaction due to the sediment loading and pressure solution producing a mesoscopically pervasive foliation parallel to the bedding. The compaction structures are a cumulative product of sediment dewatering, pore reduction and external rotation of phyllosilicate flakes towards the bedding planes. Pressure solution features are represented either by wriggling stylolites in pure pelagic, Biancone-type limestones, or by laminae enriched in clay minerals in marly deposits. Pressure solution of the soluble phase (predominantly calcite) led to the accumulation of an insoluble material composed mostly of phyllosilicates and opaque organic matter in bedding-parallel solution seams. Bedding-normal shortening is indicated also by e.g. flattened bioturbation spots in the "Fleckenmergel" facies marlstones, or by early diagenetic, discontinuous calcite veinlets subnormal to the bedding-parallel foliation, but confined to individual beds that eventually might have led to brittle boudinage of intercalated more competent layers, e.g. thin sandstone beds.

In place, reactivation of diagenetic stratification by simple shearing produced mesoscopic scaly fabric. Foliation planes are then anastomosing, often polished and sometimes with striae. This process was also fluid-assisted with pressure solution, additional flattening and precipitation of calcite in pressure shadows and fibrous veins (see e.g. Ratschbacher et al., 1993). Occasionally, shear sense indicators like C or C´ shears and asymmetric, lozenge-shaped objects (σ-clasts) were observed. The layer-parallel shearing is mostly restricted to the steeply dipping strata within the regional fault zones (e.g. the dextral Ráztoky fault). In the eastern PKB branch, similar shear zones are related to the along-strike dextral transpression (Ratschbacher et al., 1993; Plašienka, 2012b; Plašienka et al., 2020).

In the area concerned, the steep scaly fabric is limited to fault zones with important strike-slip component like the Ráztoky fault and related N–S trending antithetic sinistral shear zones (Končitá Valley fault zone). Both zones are accompanied by a few tens of metres wide damage zones that show complicated structure with fragments and blocks of various, often unrelated formations, scaly fabric and numerous slickensides. Examples are presented above – stops B21 to B27.

Cleavage planes transcutting at high angles the bedding-parallel foliation are relatively scarce, they were mostly observed in marly carbonates, especially in the Upper Cretaceous "couches

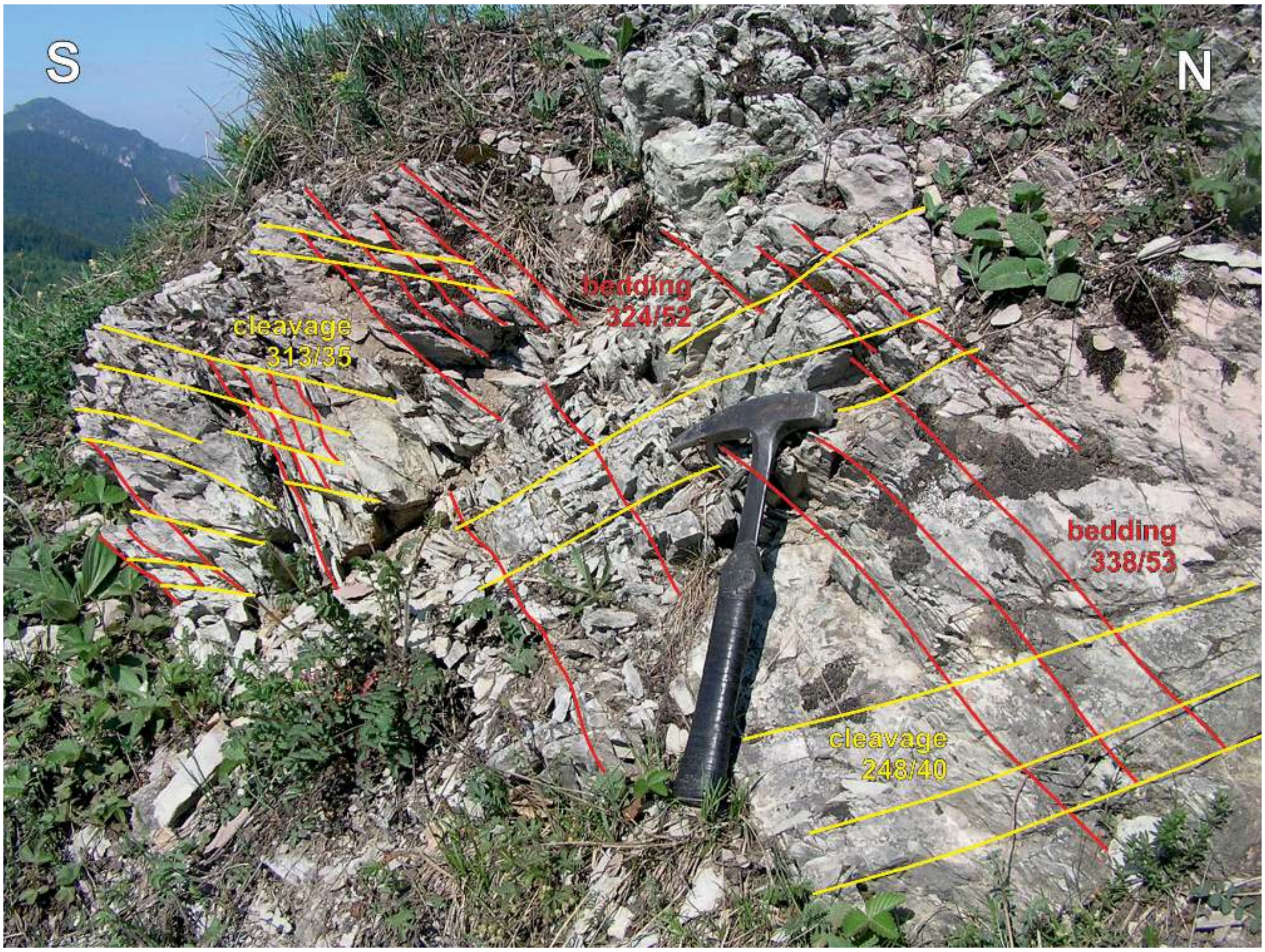


Figure 3.2 Bedding vs. cleavage relationships in the Upper Cretaceous variegated marlstones at the Rovná hora pass (stop A3).

rouges" variegated marlstones (see stop A3 Rovná Hora; Fig. 3.2). Bedding-normal cleavage sets were described also from the the Jurassic "ammonitico rosso" nodular limestones in the eastern PKB branch (Plašienka, 2012b). The cleavage was formed by the pressure solution mechanism with concentration of the insoluble clayey material along the new foliation surfaces at very low-grade temperature conditions, similarly as the bedding-parallel foliation. It indicates layer-parallel shortening, possibly connected with large-scale, upright buckle folding. However, the cleavage attitudes are varying; probably they were partly re-oriented by younger movements (as at stop A3).

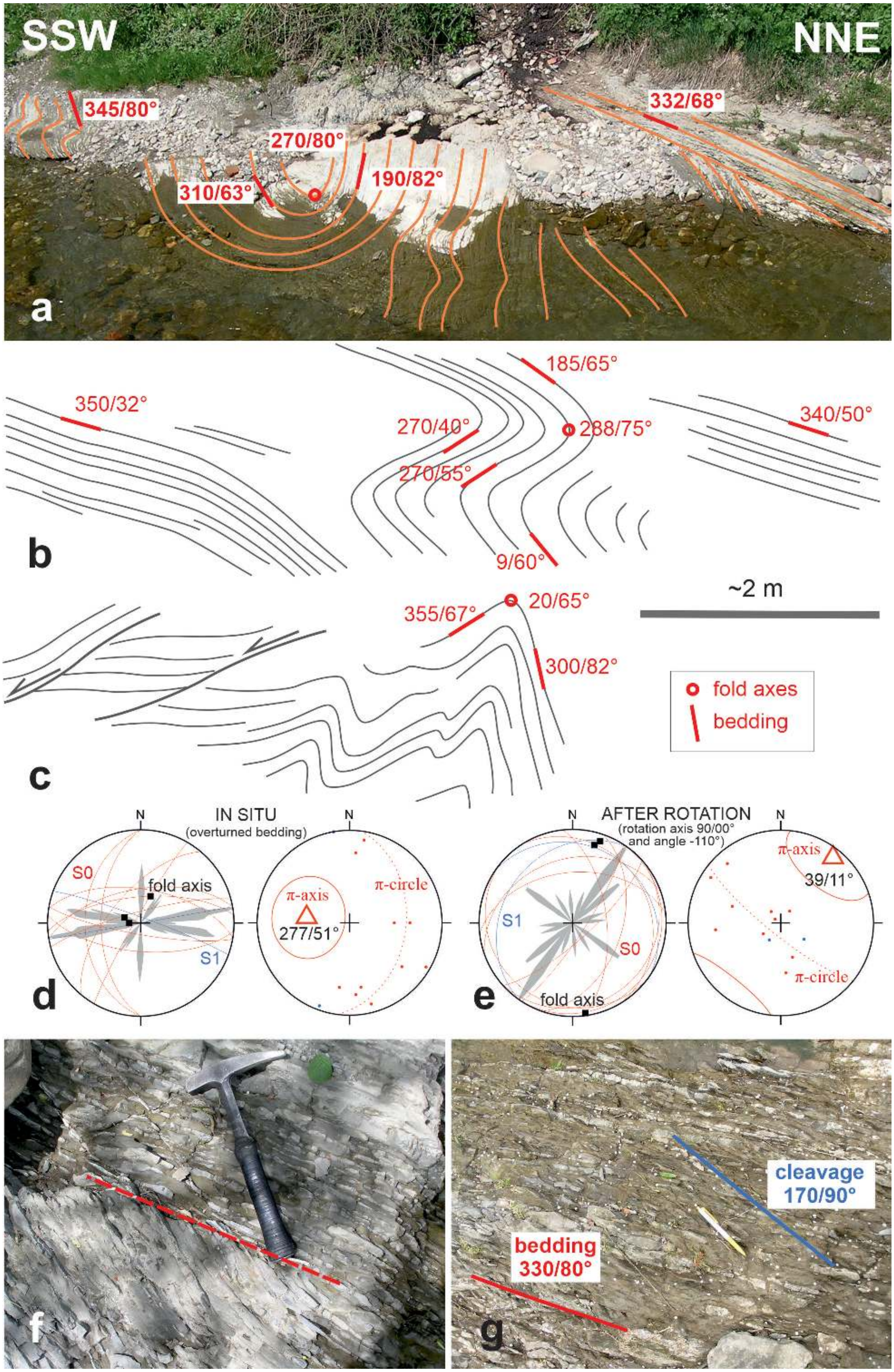
Worth mentioning is a quite common orientation of cleavage perpendicular to the PKB structural trend in both its eastern (Plašienka, 2012b) and western branch (Plašienka et al., 2018). Its kinematic meaning remains unclear, but possible relation to the transversal "cross folds" (see below) with axes normal to the PKB trend and to the oldest resolved paleostress field with W–E compression (originally in the pre-rotation position roughly NW–SE) may be suggested. Long axes of slightly oblate AMS strain ellipsoids in the western PKB branch (Márton et al., 2013) might be also related to an early deformation event related to the incipient oblique collision of the CWC block with the Oravic continental fragment during the latest Cretaceous – earliest Paleogene (see also Plašienka et al., 2018). Indications of a slight oroclinal bending of the PKB discussed by Márton et al. (2013) and Bučová (2013) might have also resulted from this event.

Surprisingly enough, the mesoscopic folds are less frequent as one would expect in such a highly deformed zone as the PKB is. In the area concerned, there are only two sites where outcrop-scale fold arrays are present. In suitable conditions (low water level), the mesoscopic folds of various orientation and fold shapes can be observed in the Zázrivka stream bedrock (cf. stops B10–12). Laminated grey calcareous mudstoned with infrequent thin beds of distal sandy turbidites of the Pupov Formation are contorted by a rather irregular fold set with steeply plunging axes (Fig. 3.3a–c). Metric folds occur in suites separated by long sections with homoclinal bedding. Folds are open to tight, close to the similar geometry, formed by a semiductile flow, since no bedding-parallel slip was observed. Most probably they originated by penecontemporaneous deformation of poorly indurated laminated marlstones, either by slumping or by layer-parallel shortening controlled by the regional stress field.

In either case, folding occurred before regional tilting of sedimentary succession up to subvertical to overturned position. In the more probable latter situation, compression would have been NW–SE to W–E oriented (Fig. 3.3f). As can be seen in some places, the fold arrays and the homoclinal intervals are separated by discrete semiductile extensional shear bands devoid of slickensides (Fig. 3.3d) that were probably formed during folding and accommodated the gravitational instability of sections thickened by folding. The locally developed, general W–E striking subvertical disjunctive cleavage is then obviously younger, having no geometrical relations to folds and formed in already lithified and tilted strata (Fig. 3.3e). Hence this cleavage is different – younger than the pre-tilting cleavage observed at stop A3.

Another outcrop with pervasive mesoscopic folds occurs at the steep south-western slope of Končitá Hill (GPS N49.285033°, E19.158647°). Well-bedded Jurassic radiolarites of (probably) the Šariš Unit are deformed by dm-scale chevron-type folds. Folds are tight, slightly asymmetric with steeply westward dipping axial planes and moderately N-plunging axes (Fig. 3.4). Once again, these folds belong to the category of the so-called "cross folds" oriented perpendicularly to the principal PKB structural trend, which were generated by W–E compression early in the tectonic development of the PKB. As such, thay should be completely overturned, since the whole Šariš Unit succession is overturned in this area.

There are also some other indications that the N–S structural trend is an important phenomenon in the PKB, although mostly suppressed by younger deformation. Cross-sections labelled "g" and "h" in Figure 1.17 indicate presence of regional gentle to open symmetric macrofolds with the km-scale vawelengths and N–S trending axes. The Zázrivá sigmoid is the surface expression of a transversal monocline that also belongs to this system. Furthermore, some other transversal zones can be recognized by field mapping all around the area. They are distinguished by an abrupt change of bedding strikes in rather narrow (few tens metres) N–S trending belts. There the bedding attitudes depart from the general W–E to SW–NE strikes and moderate to steep NW–N directed dips by the NNW–SSE to N–S strikes and steep westward dips (which would become east-dipping after the tilt correction of overturned successions). As such, these transversal zones look like macroscopic kink bands that contribute to the general eastward axial plunge of the PKB in a staircase-like manner. Apparently, the transversal structures and "cross folds" originated before the regional backthrusting and tilting of sedimentary formations into steep positions. Consequently, they seem to represent the oldest deformation stage recording the W–E oriented contraction, as revealed also by the


SSW
NNE
345/80°
332/68°
270/80°
190/82°
310/63°
a
185/65°
350/32°
270/40°
288/75°
340/50°
270/55°
b
9/60°
~2 m
355/67°
20/65°
300/82°
fold axes
bedding
c
N
IN SITU
(overturned bedding)
S0
fold axis
S1
π-axis
277/51°
π-circle
d
N
AFTER ROTATION
(rotation axis 90/00° and angle -110°)
S1
S0
fold axis
π-axis
39/11°
π-circle
e
f
cleavage
170/90°
bedding
330/80°
g

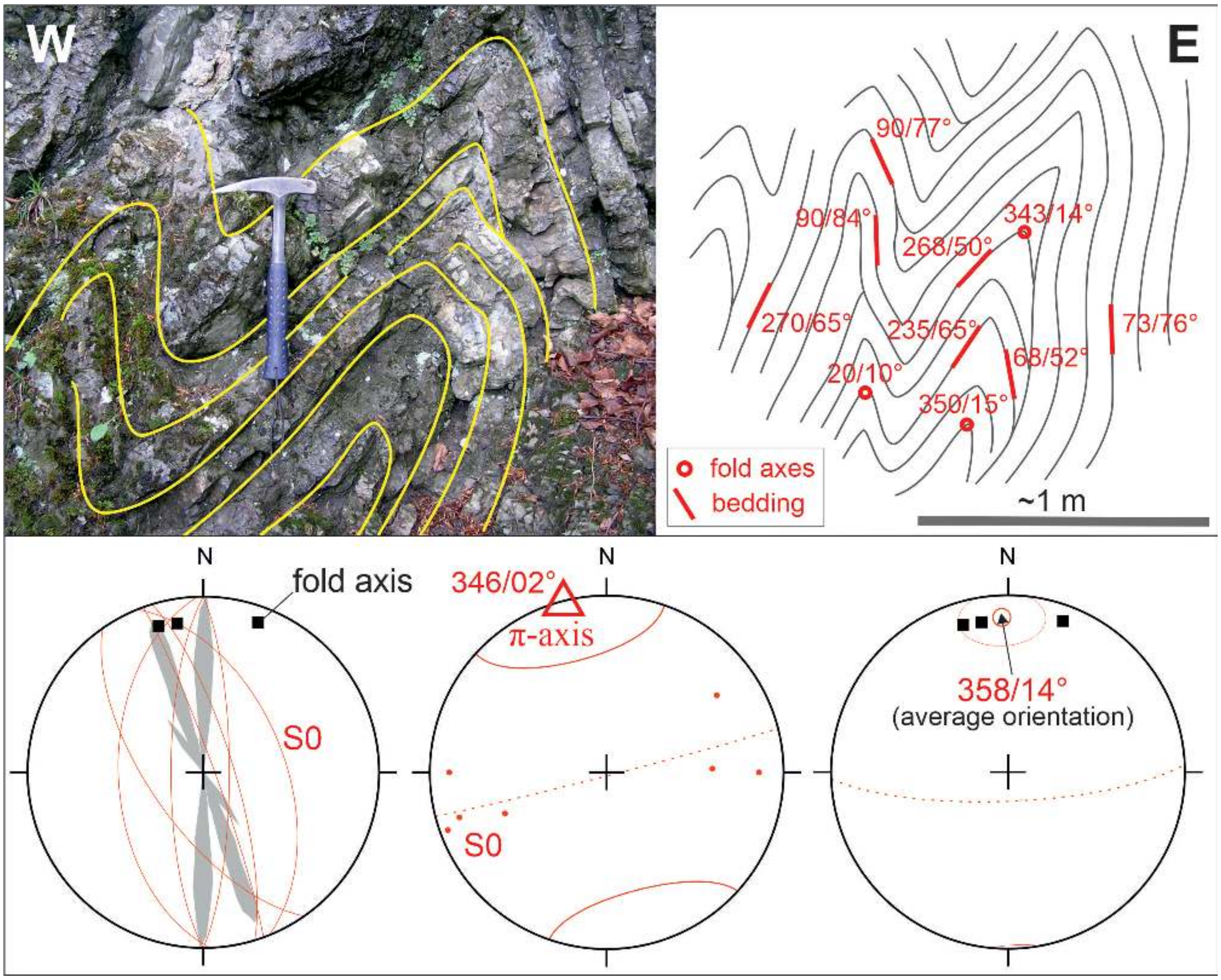


Figure 3.4 Photo, line drawing and structural diagrams of the fold array in radiolarites at Končitá Hill.

oldest resolved palaeostress field reconstructed from the brittle faults with a similarly oriented principal compression axis (e.g. Šimonová & Plašienka, 2017). A folding event with moderate contraction parallel to the PKB trend was assumed by Plašienka et al. (2018) for development of macroscopic periclinal folds of the Manín Unit in the Middle Váh River Valley. Timing of this event likely falls within the latest Cretaceous – earliest Paleogene interval.

To summarize, all the conspicuous deformation of the PKB units occurred in the brittle field at very low-grade conditions. Thick layers of massive limestones embedded in less competent marly or shaley matrix were often truncated by brittle fractures and individualized as separate blocks – the variously shaped tectonic klippen and their groupings (e.g. Uhlig, 1890; Andrusov & Scheibner, 1968; Andrusov, 1974; Plašienka, 2012b, 2018b). The klippen have been usually considered as stiff tectonic blocks floating in soft matrix, i.e. the “klippen mantle”. This leading feature of the PKB structure has led many authors to look on PKB as the megabreccia, block-in-matrix mélange, or “raisins in cake” analogue. However, as pointed out by Plašienka (2018b), many of such isolated klippen blocks are primary olistoliths, or are secondarily affected by surface processses of selective erosion and downslope sliding.

Kinematic and palaeostress interpretation of common disjunctive brittle structures, such as faults, joints, slickensides or mineralized fractures, has been published by a range of authors in various PKB parts (for the partial reviews see Šimonová & Plašienka, 2017; Plašienka et al., 2020). In general, these studies indicate a gradual clockwise rotation of the palaeostress field from W–E, NW–SE to N–S oriented maximum compression axis (latest Cretaceous?–Early Miocene) up to its SW–NE position during the Late Miocene overall extension. Similar palae-

Figure 3.3 (previous page) Photos and line drawings of folds and other structural elements in the Pupov Formation exposed in the Zázrivka stream bedrock (stops B10–12). a–c – bird-eye views on fold tracks; d – stereographic projections of fold elements; e – the same back-rotated; f – semiductile fault separating packets of strata with oblique bedding; g – disjunctive cleavage traces.

ostress history was documented also in the Zázrivá surroundings by Bučová (2013). The stress field rotation is in part an effect of the Middle Miocene CCW block rotation of the whole Western Carpathian domain, however (e.g. Marko et al., 1995).

3.2 On the origin of the Zázrivá sigmoid in the Western Carpathian Pieniny Klippen Belt

This chapter was elaborated by F. Marko, V. Bezák, P. Gaži, D. Majcin, J. Vozár, J. Madarás and R. Klanica based on their own original data. These include structural measurements along the Zázrivá sigmoid and magnetotelluric investigations along two profiles transcutting the PKB and adjacent zones.

The Pieniny Klippen belt (PKB) is interrupted and offset only at its western branch nearby village Zázrivá. This distinctive structure was noticed and described as the Zázrivá sigmoid already by Uhlig (1902). Along this structure, the Orava segment of the PKB is shifted 7 km towards the south in relation to Varín segment of PKB (Fig. 3.5). This remarkable morphotectonic phenomenon has attracted attention of generations of geologists. Andrusov (1926, 1931b, 1938, 1945) mapped the PKB near Zázrivá and presented a classical definition of this structure as a “complicated horizontal flexure” due to collision of the Inner Western Carpathians with the foreland and adaptation of the PKB shape to the shape of foreland margin that was accomodated by a ductile flexure. The role of faults during this Miocene process was minor, and he did not expect northern continuation of the N–S trending Zázrivá fault following Zázrivá sigmoid into the Outer flysch unit (Andrusov, 1938). On the other hand, the works of followers (Scheibner, 1968b; Maheľ et al., 1967; Haško & Polák, 1979), and later works based on structural analysis of faults (Nemčok, 1993, 1994; Nemčok & Nemčok, 1994, 1998; Kováč & Hók, 1993; Kováč, 1995; Marko, 2003; Gaži, 2006) and geophysical research (e.g. Kadlečík et al., 1988) emphasized the role of faulting in development of the Zázrivá sigmoid. The Zázrivá sigmoid is currently considered as a record of the significant horizontal shift along the Zázrivá fault, which is the N–S trending discontinuity cutting the Pieniny Klippen Belt. The Zázrivá fault belongs to the first order Zázrivá–Budapest fault zone affecting

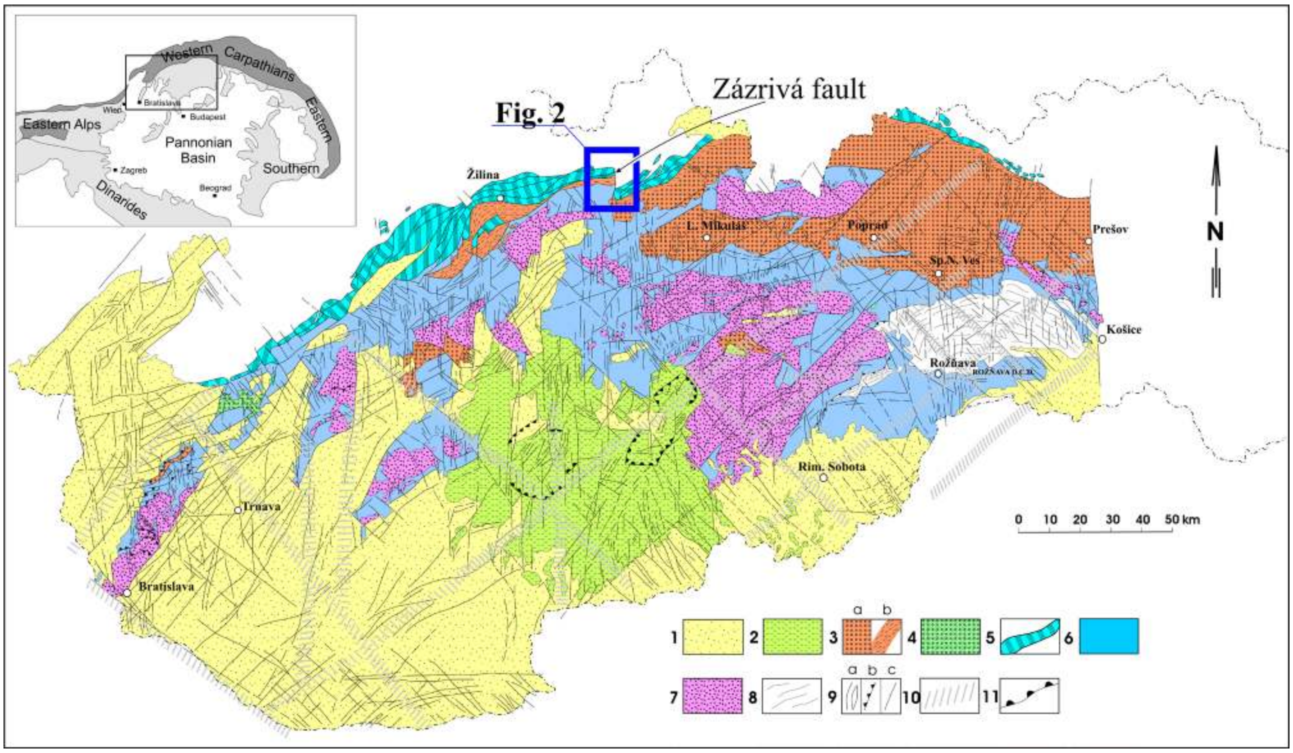


Figure 3.5 Faults of the Inner Western Carpathians and the Vienna basin (Marko et al., 2017). 1 – Neogene sediments; 2 – products of Neogene volcanism; 3 – Paleogene sediments; 4 – Upper Cretaceous sediments (Gosau group); 5 – PKB units; 6 – undivided Mesozoic nappe and cover units including Late Paleozoic cover; 7 – crystalline basement; 8 – Gemeric unit; 9 – faults: a) not specified, b) reverse, c) normal; 10 – geophysically detected deep crustal dislocations; 11 – boundary faults of volcanic calderas.

the whole structure of the Western Carpathians and represents the eastern boundary fault of the Central Slovakian fault system (sensu Kováč & Hók, 1993) and possible continuation to Ružomberok–Staré Hory N–S fault system.

Up to-date we have several "pin points" as the age of fault activity, map distribution and attitudes of units, knowledge about geophysically detected tectonic style and dips of units at the contact zone of the Inner and Outer Western Carpathians and context of regional tectonic evolution, which are the constraints for all explanations of the Zázrivá

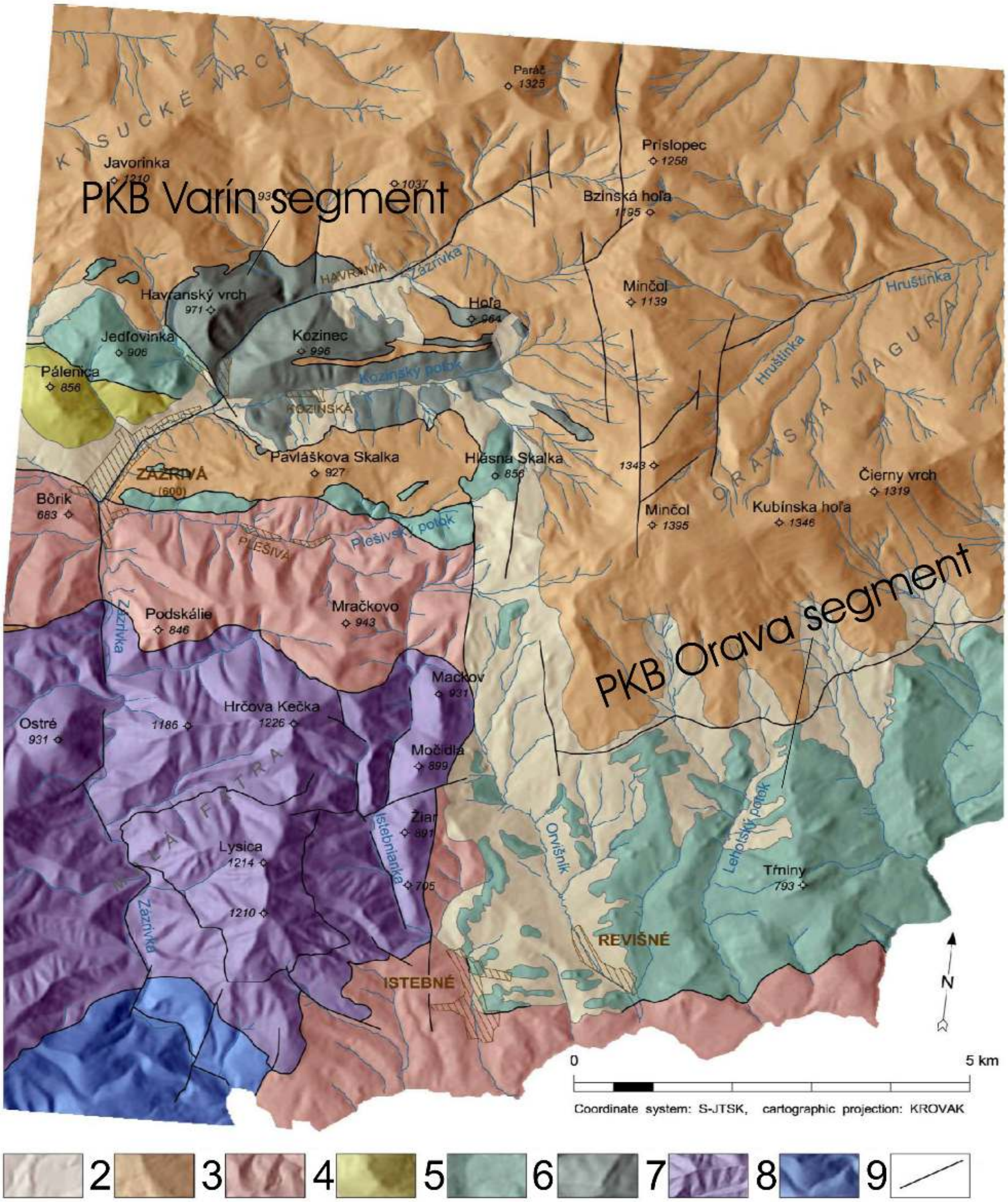


Figure 3.6 Tectonic map of the Zázrivá sigmoid area (modified after Andrusov, 1931a, 1938; Haško & Polák, 1978; Gross et al., 1993). 1 – Gravitational slides, Quaternary sediments; 2 – Magura Unit; 3 – Central Carpathian Paleogene; 4 – Manín (Klape) Unit; 5 – Kysuce Unit; 6 – Orava (Kozinec) Unit; 7 – Fatric nappe unit; 8 – Tatric cover unit; 9 – faults and tectonic boundaries.

sigmoid origin. Nevertheless, we can calculate with various rheologies, parameters of tectonic structures (as physical, dimensions, depth reach, kinematics, tectonic regime) and MT models of deep crustal architecture, all allowing to consider with more variants – models of the Zázrivá sigmoid origin, which are discussed below.

3.2.1 Models of the Zázrivá sigmoid evolution

Configuration of geological units in the area of the Zázrivá sigmoid can be explained by several ways.

The **Model M1** considers the sigmoid as the N–S oriented flexural bend. Ductile bending – flexure is a classical Andrusov´s (1926, 1938) description of the Zázrivá sigmoid, which is regarded to be a result of different progress of the western (Varín) segment and eastern (Orava) segment of PKB towards the north due to complex shape of Inner Western Carpathians (IWC) frontal ramp, during the Neo-Alpine convergence. The PKB zone was not interrupted; only bended, Varín and Orava segments are connected by narrowed and stretched N–S oriented segment of PKB (Fig. 3.6). The process of bending was brittle-ductile, while the role of faults is minor in this model. This development of the offset between the Varín and Orava PKB segments was coeval with the Inner Carpathians vs. foreland collision at this part of the Western Carpathians.

The **Model M2** (Fig. 3.7) interprets the sigmoid as the dextral strike-slip along NE–SW to NNE–SSW oriented brittle shear zone. This model is similar like the bending model, but considers movement along the dextral strike-slip shear zone (sensu Twiss & Moores, 1992) in brittle conditions (Fig. 3.7). It explains the structural style of transition zone between the Varín and Orava segments created by relics of sheared PKB units. This model could operate in conditions of NE–SW oriented compression of the Badenian–Sarmatian stress field after collision of the IWC with the foreland in this part of Carpathians. Nevertheless, occurrence of this NNE–SSW shear zone was not confirmed in the Outer, nor in Inner Western Carpathians, so it retains as a hypothetical solution. This model does not explain as well the uplift of the western (Varín) block, resp. downthrown of the eastern (Orava) block.

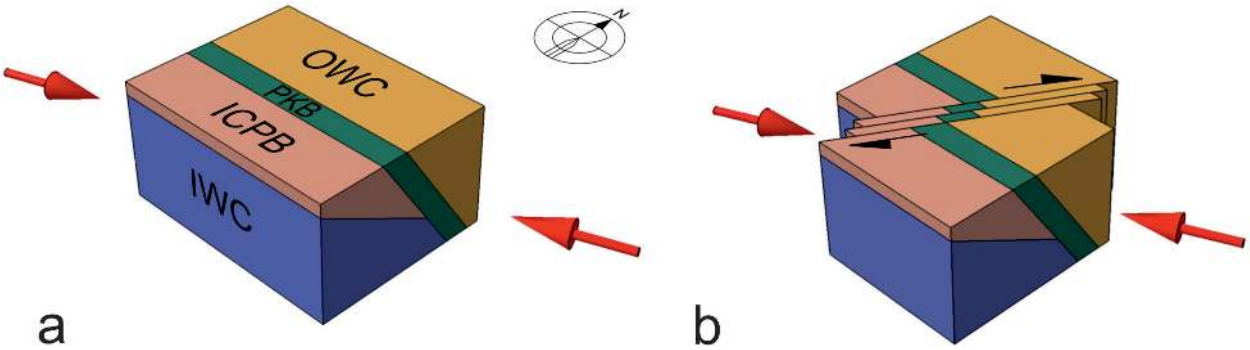


Figure 3.7 Model M2 of the NNE–SSW oriented dextral transpressional brittle shear zone operating in conditions of ENE–WSW compression: a – starting situation; b – dextral shearing. OWC – Outer Western Carpathians; PKB – Pieniny Klippen Belt; IWC – Inner (Central) Western Carpathians; ICPB – Inner (Central) Carpathian Paleogene Basin.

Model M3 (Fig. 3.8) – dextral strike-slip along the single N–S oriented Zázrivá fault. Particularly in the large-scale geological maps (Fig. 3.5), it seems to be evident that the dextral offset of the PKB should be a result of right lateral strike-slip movement along a single Zázrivá fault (Fig. 3.8), which is drawn as a single line in modern geological maps. Zázrivá fault could operate as a dextral strike-slip under the NE–SW oriented compression after the Inner Carpathians collision with the Outer Carpathians during the Badenian–Sarmatian. Dextral strike-slip along the Zázrivá fault is expected from structural analysis of meso-scale brittle faults in the wider area (Kováč, 1995; Kováč & Hók, 1993; Nemčok, 1994; Nemčok & Nemčok, 1998; Potfaj et al., 1991). The weak point of this single fault model is that it can not explain origin and structural style of the transition PKB zone connecting the Varín and Orava segments of PKB (Istebné Zone, see above) and it cannot explain differences in uplift/erosional levels of the Varín and Orava blocks of the IWC.

Model M4 (Fig. 3.9) – dip-slip along the single N–S oriented and eastward dipping Zázrivá normal fault. If the PKB is affected by south-vergent backthrusting (e.g. Haško & Polák, 1979; Marko et al., 2005;

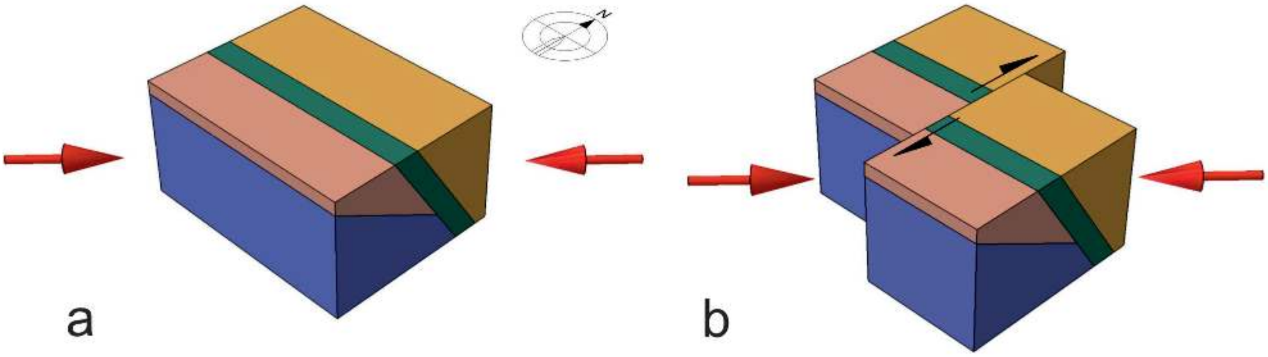


Figure 3.8 Model M3 of the N–S oriented single dextral strike-slip operating under conditions of NE–SW compression resp. NW–SE extension: a – starting situation; b – dextral strike-slipping.

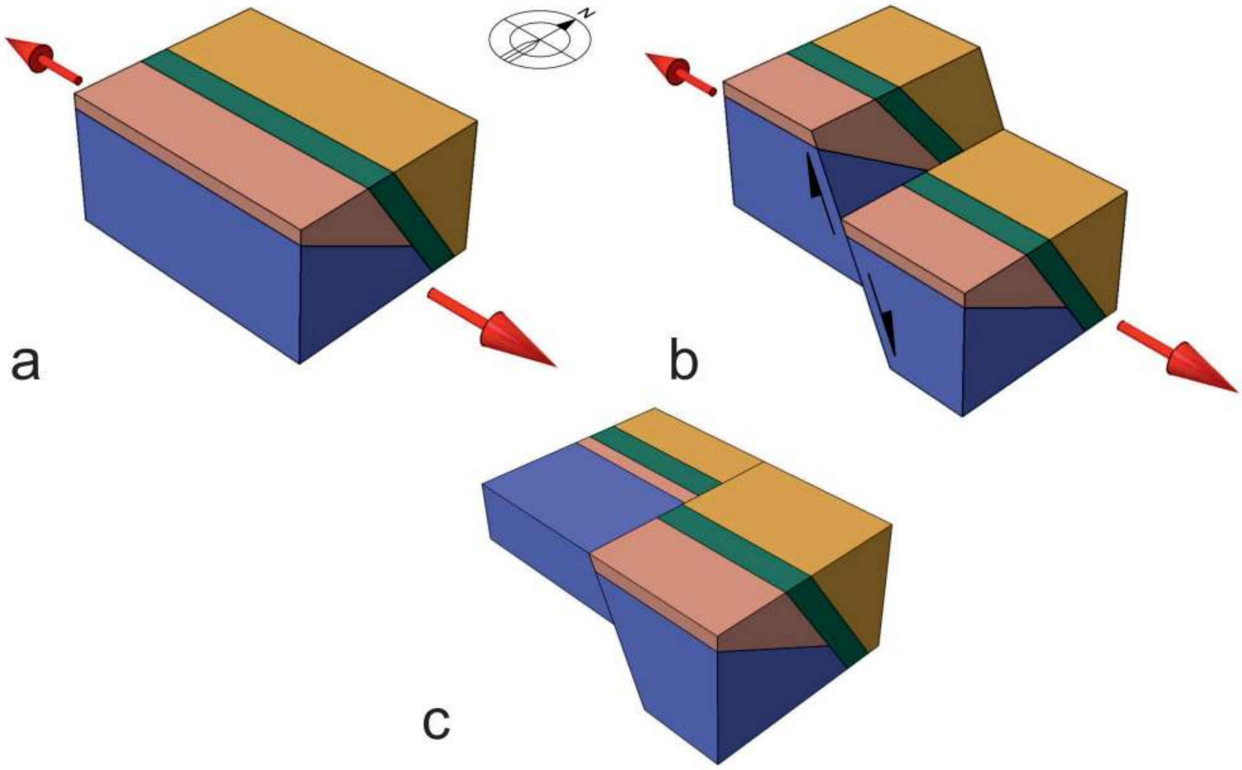


Figure 3.9 Model M4 of the N–S oriented, steeply east-dipping normal fault operating in conditions of E–W tension: a – starting state; b – normal faulting; c – resulting situation after erosion.

Plašienka et al., 2020), it is inclined to the north as it is seen in the deep reflection seismic profile (Tomek et al., 1989) and interpreted in geological cross sections (Haško & Polák, 1978; Pešková et al., 2012). In this case we can calculate even with a model of normal faulting to explain the Zázrivá sigmoid structure. Also, the map geometry of a contact of the northern PKB margin with the OFC units points to the northward dip of the PKB (Fig. 3.6). Under these conditions the right lateral separation of the Varín and Orava segment of the PKB could be created by downthrown of the eastern Orava block and/or uplift of the western Varín block along the Zázrivá fault (Fig. 3.9). This model generally fits the observed distribution of geological units, but it cannot explain origin and structural style of the transition PKB zone connecting Varín and Orava segment. Process of vertical block movements could operate in conditions of E–W tension, complementary to N–S compression, that means it could be coeval with the IWC collision with the foreland. Vertical movements along the N–S Zázrivá fault are clear. Contrary to the eastern block, units of the lower structural level are exhumed by erosion in the western block. The Central Carpathians Paleogene sediments of the Podtatranská Group (Gross et al., 1993) occur in the eastern block in a wide belt between the PKB and Chočské vrchy Mts, while in the western block these sediments form a narrow, deeply eroded zone.

If the apparent strike-slip offset of PKB in the Zázrivá sigmoid was really caused only by vertical block movements along the Zázrivá fault, we can estimate that the western block with Malá Fatra Mts. should has been uplifted at least 7 km (for 45o dip of PKB zone), what is too extreme value. That´s why we have to calculate with the strike-slip activity of the Zázrivá fault to create this offset as well.

Model M5 (Fig. 3.10) – dextral transtension along the Zázrivá fault zone. Every of the above discussed models of the Zázrivá sigmoid origin explains some aspects of this structure, but not all of them. We gathered relevant mechanisms from single models and combined these to comprehensive model corresponding with the known geological data.

The most real process of the Zázrivá sigmoid origin could be a combination of the dextral strike-slip and the vertical block movements along the N–S fault zone (Fig. 3.10) what is typical for transtesional and transpressional regime. The negative flower structure in reflection seismic profile 315/85 (Kadlečík et al., 1988) crossing the Zázrivá fault points to transtesional character of the Zázrivá fault. This model fits perfectly with the observed surface geological architecture and it does not need so extreme values of fault shifts like the above discussed models. The western Varín block is surely uplifted in relation to the eastern Orava block. Contrast in vertical movements of both blocks and their horizontal offset is a result of the Inner Carpathians frontal ramp shape, which is not planar in this area, but undulated. We expect that the frontal ramp of northwardly propagating Inner Western Carpathians is low-angle dipping under the

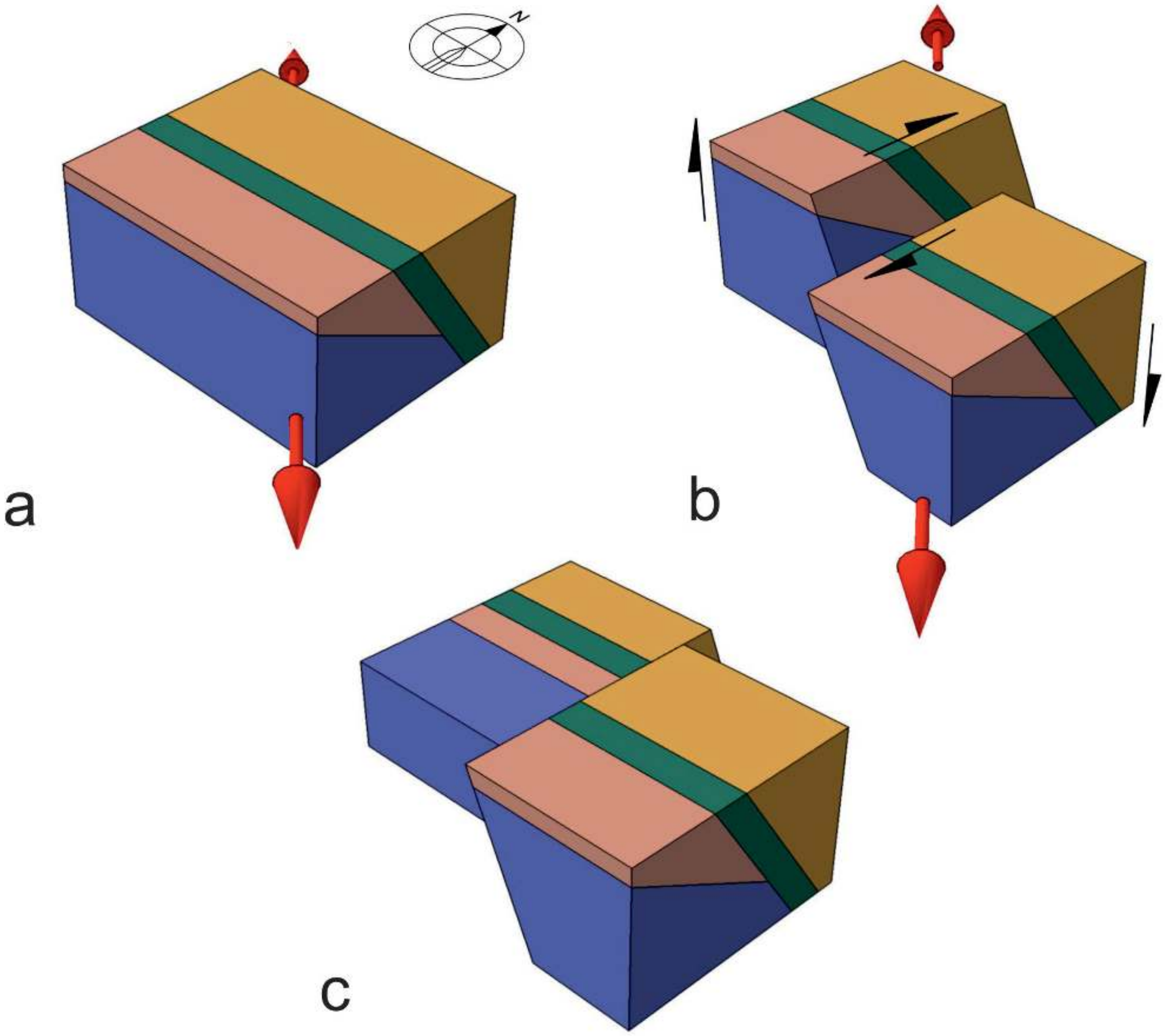


Figure 3.10 A combined Model M5 of coeval normal dip-slip and dextral strike-slip along the N–S oriented, steeply eastward dipping single fault operating in conditions of dextral transtensional regime: a – starting situation; b – oblique dextral transtension; c – final state after erosion.

Varín block and is high-angle dipping under the Orava block. This resulted in separation of overriding IWC to the western Varín and the eastern Orava blocks and more northward progress and coeval uplift of the Varín block than Orava block, which was not uplifted, or it even relatively subsided. The different movements of these two blocks was accommodated and controlled by the Zázrivá fault, which operated as a tear fault of the Inner Western Carpathians thrust.

The Zázrivá fault is not a single fault, but ca 3.5 km wide fault zone of subparallel N–S trending faults (Fig. 3.6). It follows the boundary (maybe deep seated fault in the foreland) between low-angle and high-angle part of frontal ramp of the IWC thrust. The central damage zone of the fault is ca 0.8 km thick, it is created by narrowed, stretched and sheared PKB units connecting the Varín and Orava segment. Due to intense strike- and coeval dip-slipping activity, this segment of PKB is extremely deformed and rigid blocks (klippen) are clockwise rotated (see below) and tilted. This central damage zone should be rimed by boundary dextral strike-slip faults. The Zázrivá fault damage zone gradually decreases to the both sides by decreasing number of N–S faults. These were interpreted in the klippe Kozinec as well in the flysch units of Outer Carpathians (Fig. 3.6).

3.2.2 Magnetotelluric model of crustal architecture in the Zázrivá sigmoid area

One of the ways to tackle the still enigmatic Zázrivá sigmoid phenomenon is the comparison of structures in the deeper parts of the crust on both sides of the sigmoid. This is possible thanks to magnetotelluric measurements realised for this very purpose in two parallel profiles Zaz-1 and Or-1 (Fig. 3.11).

The magnetotelluric (MT) method (Tikhonov, 1950; Cagniard, 1953) is one of the electromagnetic methods utilizing the diffusion of the source field over a wide range of periods to image the distribution of conductivity in the Earth from a depth of tens of meters down to the upper mantle. The measured time series of the magnetic and electric field components are transformed to the sounding

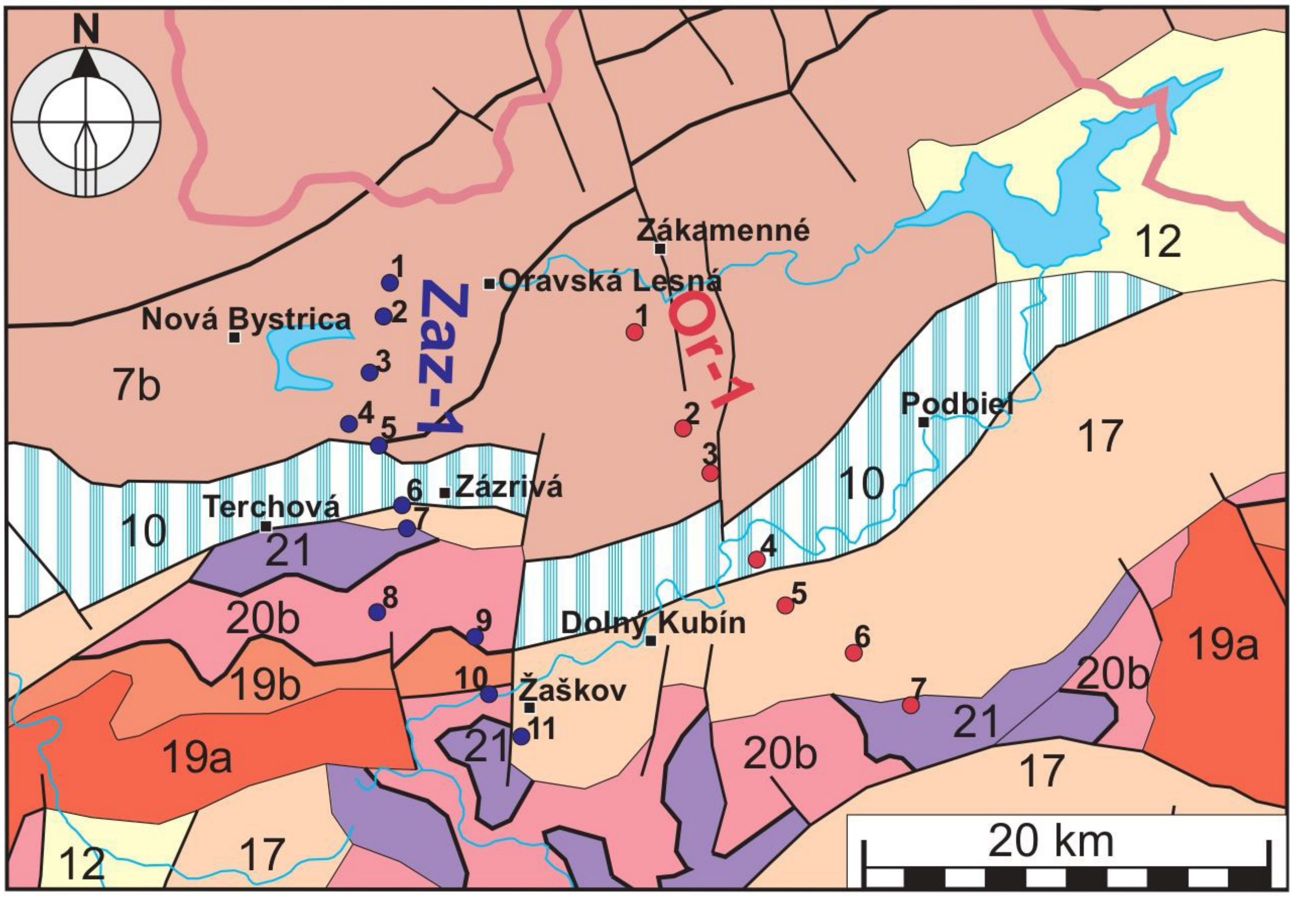


Figure 3.11 Position of measured MT sites on the profiles. Geological situation after Lexa et al., 2000): 7b – Flysch Belt (mostly Magura Unit); 10 – Klippen Belt; 12 – Neogene sediments; 17 – Central Western Carpathian Paleogene; 19 – Tatricum: a – crystalline units, b –mostly Mesozoic cover units; 20 b – Fatricum; 21 – Hronicum.

curves (Egbert, 1997) and then modelled by multidimensional inversion codes to create the geoelectrical models of subsurface structures (Rodi & Mackie, 2001). The method is used to detect the conductive contrasting structures for mineral, oil and gas exploration, geothermal surveys or tectonic studies. The information about electrical conductivity allows for a better understanding of the dynamic processes, as well as compositional and transport properties in the surveyed areas (Bedrosian, 2007).

The MT measurements in two profiles were conducted and both profiles run from the Flysch Belt, across the PKB, pass through Central Western Carpathian Paleogene formations and end in Mesozoic units (Fig. 3.11). The first north-south trending profile is located to the west of the Zázrivá fault and from the north it intersects the areas of villages Stará Bystrica, Terchová, Zázrivá, and Žaškov (section Zaz-1, Fig. 3.11). The second MT profile east of the sigmoid and with a north-northwest to south-southeast orientation starts south of the villages Zákamenné and Oravská Lesná, then runs east of Dolný Kubín and ends on the edge of the Chočské vrchy Hills (Or-1, Fig. 3.11).

The MT time series in the western profile Zaz-1 were measured by Institute of Geophysics of the Czech Academy of Sciences at 11 sites along the 26 km long profile in the years 2017 and 2018. The data for the eastern profile Or-1 were collected by the Koral company at 8 sites distributed on 28 km long profile in the year 2018. Two new broadband MT instruments (Metronix GmbH GMS-07) with induction coil magnetic sensors were used for shallow measurements at both profiles. The Metronix Mapros processing package (Friedrichs, 2004) with the implemented robust method was used to estimate the impedance transfer function in the 0.0001 to 100 seconds range. The data quality of the sounding curves decreased to the south due to the presence of DC traction railway approximately 5 km from the southernmost sites. The presence of high resistive geoelectrical structures caused unwanted noise from the railway and the nearby villages in our measurement points. For this reason, most of the periods above 1 second were distorted and not used in the final model. In the final modelling, one site in each profile had to be removed due to unreliable noise data within all periods. To allow and prepare the MT impedance transfer function for 2-D modelling, the dimensionality and strike analysis were performed and assumptions about the orientation of the geoelectrical 2-D strike were estimated. The final edited processing results were analysed using the McNeice and Jones (2001) multi-site and multi-frequency extension to the Groom-Bailey MT tensor decomposition technique (Groom & Bailey, 1989) with conversion to Niblett-Bosticks depths. The distortion decomposition of the impedance tensor to strike direction allowed us to eliminate some static shift distortion and provided the data suitable for 2-D modelling. The regional geoelectrical strike azimuth of N54°E for the Zaz-1 profile was determined for a depth range up to 10 km. Similar data noise assessments, strike analyses and decomposition to strike direction N72°E were performed for the eastern Or-1 profile.

A 2-D inversion code based on the nonlinear conjugate gradient algorithm of Rodi and Mackie (2001) was used to invert the decomposed MT impedance data for each profile. The default sets of regularization parameters for the model smoothness and the starting 100 Ωm half-space model were used. With error floors set to 20% for apparent resistivities and 5% to phases the final nRMS were 2.01 for Or-1 and 3.9 for Zaz-1 profile.

Zaz-1 profile cuts the western and Or-1 profile the eastern block of the Zázrivá sigmoid. The MT models and their tectonic interpretation are shown in Figure 3.12. Both profiles, as is the case with the 2T profile, which runs near Or-1, show an inclination of Flysch belt (FB) to the north (Bezák et al., 2020). This indicates south--vergent thrusting, that is in the opposite direction to the assumed Flysch Belt basin floor subduction followed by northvergent Inner Western Carpathians (IWC) collision with the European platform (EP) foreland. We prefer an explanation that the FB units were back-thrusted from the subduction zone situated further to the north of the Klippen Belt (KB). In the MT cross sections, the KB together with its original bedrock, i.e. Pieninic crust (PC) – the high-resistance bedrock in KB and FB shown in the cross-section, seems to be thrust back as well. This tectonic style is also indicated by preliminary, not yet published 3-D MT models of the given area.

There are differences in crustal architecture inferred from MT data in both cross-sections. North dipping tectonic contact of FB and KB is in Zaz-1 cross-section steeper than in Or-1 cross-section and KB in Zaz-1 is from the Tatricum unit separated by a subvertical dislocation, contrary to north dipping discontinuity in Or-1 cross-section. In MT models there is very well visible contrast between the Mesozoic units (M), FB and Inner Carpathian Paleogene units (ICP) low to middle resistant units with underlying high-resistant crystalline basement units (Tatricum crystalline basement, Pieninic crust). In the Zaz-1 cross-section, this middle-resistance/high-resistance boundary is much higher than in Or-1 cross-section. Zaz-1 cross-section shows that basement units in the

Peri-Klippen Zone are uplifted ca 4 km in comparison with Or-1 cross-section. There is a contrast between tectonic styles of both cross-sections as well. Or-1 displays a simple style of south-vergent, moderately inclined backthrusts. In Zaz-1 we see the same style, but affected by north-vergent forward thrusting resulting in steepening of FB and KB backthrusts and uplift of basement IWC units (Malá Fatra). The Zaz-1 cross-section shows the shortened and uplifted style of the Or-1 cross-section. This is why deeper structural levels are exhumed at the surface of the western block and only a remnant of Paleogene sediments (ICP) are preserved in a narrow belt. Unfortunately, the gained MT data do not always show a resistivity contrast between ICP and the Mesozoic units. Thus the ICP boundary can be in both cross-sections mostly roughly estimated.

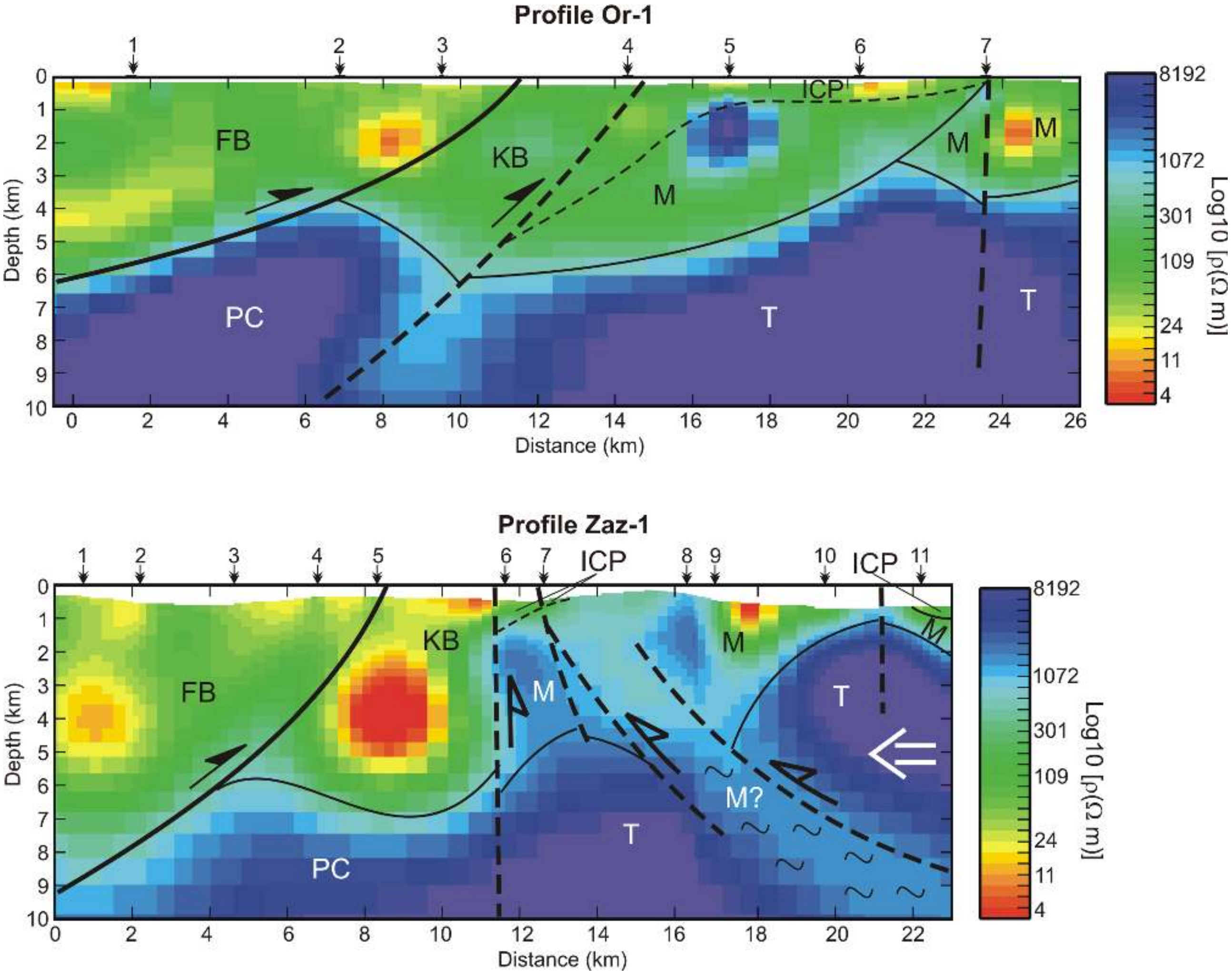


Figure 3.12 MT models of profiles Or-1 and Zaz-1 and their geological interpretation. FB – Flysch Belt; PC – Pienninic crust; KB – Klippen Belt; ICP – Inner Western Carpathian Paleogene sediments; M – Mesozoic units undivided (cover units and nappes); T – Tatricum crystalline basement. Filled arrowhead – back-thrusting, open arrowhead – younger shortening. Wave pattern – more conductive tectonic shear zone with presence of possible Mesozoic units. Arrow on the right side of Zaz-1 profile – direction of younger compression.

3.2.3 Discussion and conclusions

In the above discussed single models M1 – M4, which are not considering the role of deep crustal decollement of IWC in process of the Zázrivá sigmoid evolution, the continuation of the Zázrivá fault to the Outer Carpathians is expected and necessary. This fault continuation was also detected in OWC geophysically (Kadlečík et al., 1988) and structurally (Nemčok, 1993, 1994), and a suite of N–S faults was morphostructurally interpreted in geological maps as well. Nevertheless, the continuation of Zázrivá fault zone into Outer Carpathians is questionable. If the not uniform progress of the IWC rigid blocks in front of the orogen was the reason of the Zázrivá sigmoid origin, as already suggested by Andrusov (1926, 1938), the northward continuation of the Zázrivá fault is not necessary. In this case the fault does not affect the entire crust together with the EP section, and it follows the differences in morphology of the frontal IWC thrust in the upper crust. This problem can be a topic for further research, along with seeking for the geodymamic reasons for penetration of the Varín PKB segment to the north.

Finally, we present the reconstruction of the tectonic evolution of the Zázrivá sigmoid by Gaži (2006), which is based on field structural research and structural data analysis. Using a procedure of slickenside-related palaeostress analysis, he described succession of four palaeostress events with NW–SE, N–S and NE–SW oriented maximum principal stress axis (compression), the last event with the NW–SE oriented minimum principal stress axis (tension). Depending on the regional stress field changes reconstructed from the meso-scale brittle faults, he interpreted the origin, kinematics and geodynamic role of the Zázrivá fault zone (Fig. 3.13), which is consistent with the above discussed transtensional model M5 of the Zázrivá sigmoid evolution.

We can conclude that the Zázrivá sigmoid is a surface expression of a right-lateral ramp transform fault boundary of an independently northwardly propagated Inner Western Carpathian blocks. The southward shift of the Carpathian conductive zone (CCZ; Bezák et al., 2020) can be attributed to the activity of the Zázrivá tear fault, too. The different

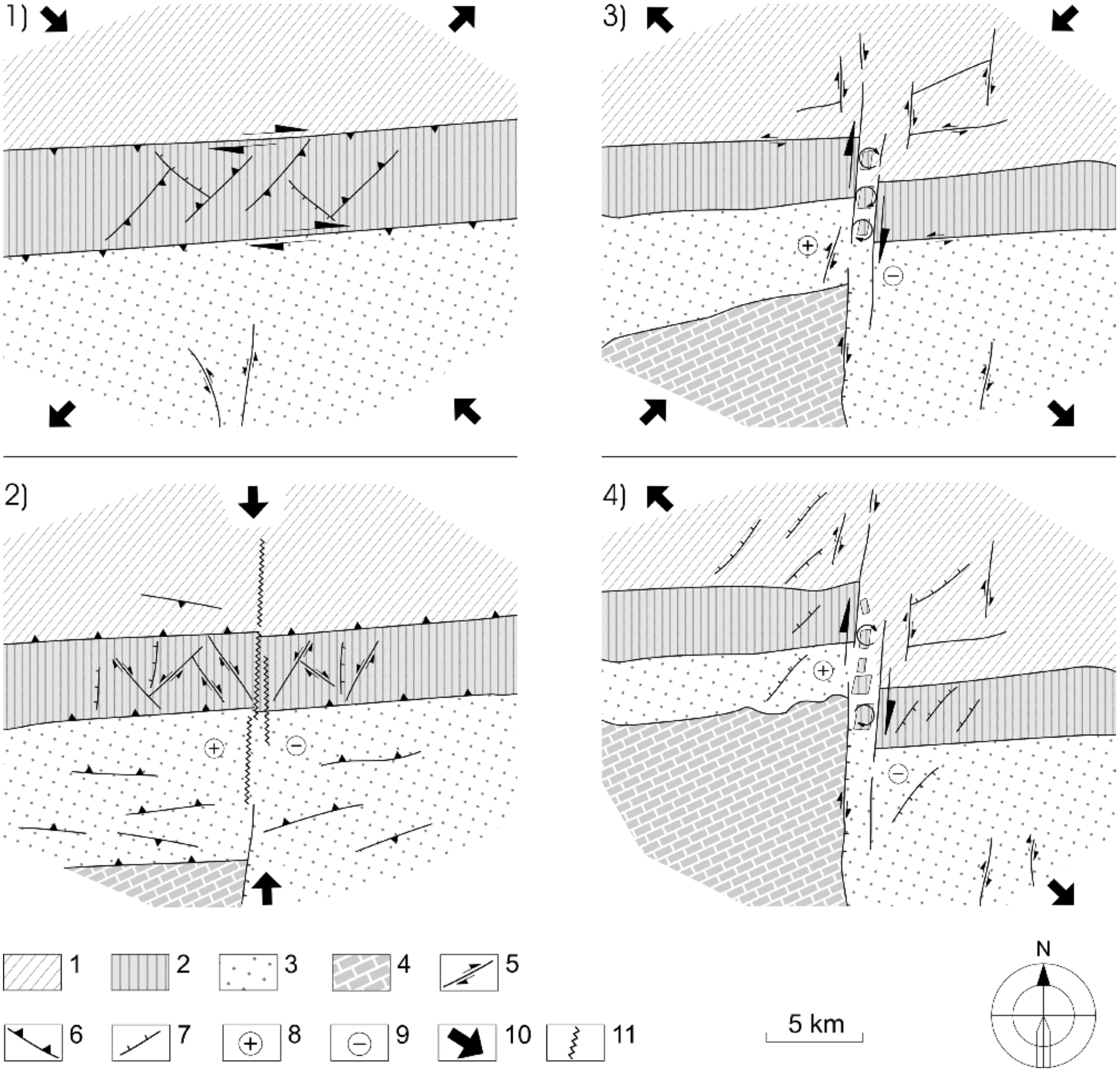


Figure 3.13 Reconstruction of the Zázrivá sigmoid evolution during the latest Oligocene (1), Early Miocene (2), Middle Miocene (3) and Late Miocene (4). Explanations: 1 – Magura unit, 2 – Pieniny Klippen Belt unit, 3 – Intra-Carpathian Paleogene unit, 4 – Undivided Inner Carpathians units, 5 – strike-slips, 6 – reverse faults and thrusts, 7 – normal faults, 8 – upthrown areas, 9 – downthrown areas, 10 – principal stress vectors, 11 – tension gashes.

slope and morphology of the foreland margin is responsible for the uplift of the western (Varín) block.

The activity of the subduction zone was probably increased eastwards. In the western part of the Carpathian arc transpression was dominated. In the region of the Zázrivá sigmoid, the IWC blocks during the subduction-transpressional movements probably collided with the southern bend of EP. This also caused flexure of the subduction zone and backward overthrust units. In same time the role of the CCZ was taken over by the southern transpressional shear zone within the IWC (roughly in area of Chočské vrchy Mts, see Fig. 3.5).

3.3 Geological structures across the contact between the External and Internal Western Carpathians based on 2D density modelling (northern Slovakia case study)

2D gravimetric modelling was performed and the results are presented here by L. Šamajová, J. Hók, K. Fekete, M. Bielik and F. Teťák. Modelling was carried out in order to clarify the geological structure in the deeper levels of contact between the External and Internal Western Carpathians in the north-western part of Slovakia (Fig. 3.14). The principal tectonic units – the Silesian-Krosno and

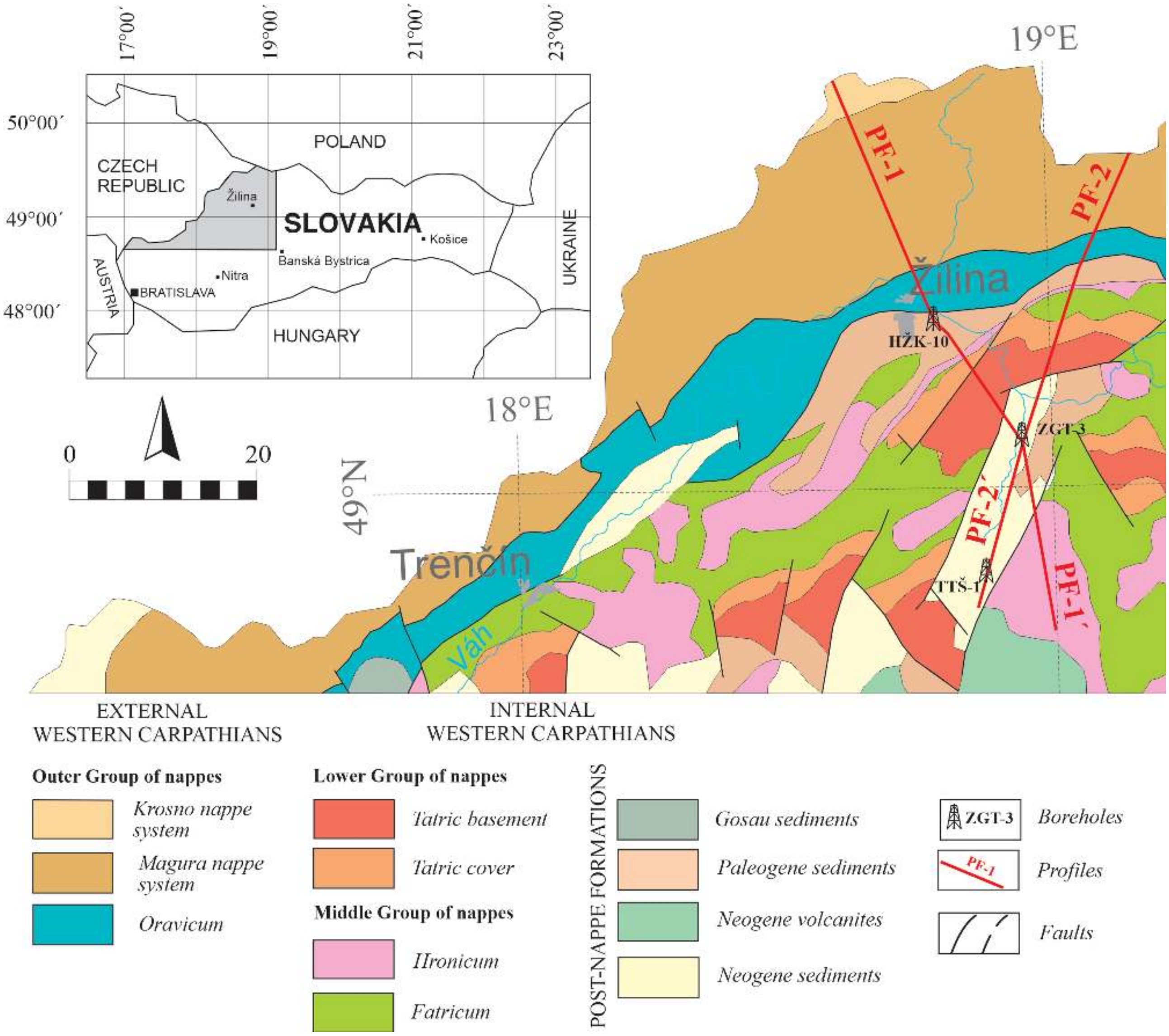


Figure 3.14 Simplified tectonic map of the northern part of Slovakia (modified after Hók et al., 2014) with position of gravimetric profiles and deep boreholes.

Magura nappe systems of the accretionary prism (Flysch Belt) and the Klippen Belt units (Oravicum) participate in the geological structure of the External Western Carpathians (EWECA). The Internal Western Carpathians (IWECA) are formed by the Tatric thick-skinned unit and the Fatric and Hronic cover nappes (Hók et al., 2019). In addition to the mentioned main tectonic units, Paleogene and Neogene overstepping cover sediments are present within the IWECA.

In the studied area, two gravimetric profiles PF-1 and PF-2 were constructed across significant structures and deep boreholes. Gravimetric models are composed of the closed polygons with representative density values derived from the lithological composition of the individual lithotectonic bodies (Šamajová & Hók, 2018). The geometry of the polygons representing individual tectonic units was constrained using the geological maps (Haško & Polák, 1978; Rakús et al., 1988; Gašparik & Halouzka, 1989; Polák et al., 1997; Potfaj et al., 2002; Sentpetery & Hók, 2012; Geologická mapa Slovenska 1: 50,000, 2013 [online]) and available seismic and magnetic profiles (Potfaj, 1988).

The profiles pass through deep boreholes which provided significant geological and tectonic data. Boreholes HŽK-10 and ŽK-3 are described in Šalagová et al. (1996a, b). Besides the 2,460 m well log, the borehole ZGT-3 (Fendek et al., 1990) yielded also the radiometric data from flat-lying mylonitic granite dated to 58–60 Ma (40K/40Ar; Kohút et al., 1998) and 60.2 ± 4.4 Ma ZFT data (Králiková et al., 2014). Borehole TTŠ-1 (1,458 m total depth) drilled the Hronic, Fatric and Tatric sediments (Géczy, 1990).

The gravity effects of the geological bodies have been calculated using the formula Talwani et al. (1959), with Won & Bevis's algorithm (GM-SYS User's Guide 4.9, 2004) in the GM-SYS software. All models extend to ± 30,000 km along the profiles to eliminate edge-effects. The input gravity data were obtained from the Bouguer anomaly map with the grid 200×200 m (Pašteka et al. 2014, 2017). The topography data were obtained from the Topographic Institute (2012). The Moho depth in the studied area was taken from papers Alasonati Tašárová et al. (2016) and Bielik et al. (2018). The lithosphere–asthenosphere boundary (LAB) was used from Dérerová et al. (2006) and Alasonati Tašárová et al. (2016). These depths are specific for individual profiles.

3.3.1 Geological overview

Tectonic units of the Oravicum, Magura and Krosno nappe systems belong to EWECA (Hók et al., 2019). The Krosno nappe system is represented by a Silesian unit (Late Cretaceous–Paleocene). The Magura nappe system includes the Siary, Rača, Bystrica, Krynica and Biele Karpaty units. These nappe systems are mainly formed by the deep water "flysch" sediments deposited by the gravity flows.

Oravicum (Pieniny Klippen Belt, PKB) represents the contact zone between the EWECA and IWECA. The studied Varín and partly Orava sections of the Klippen Belt are composed mostly of Jurassic–Lower Cretaceous sediments of the Kysuca Unit. Systematically overturned sequences of rocks are typical. Together with the Magura nappe system, the PKB

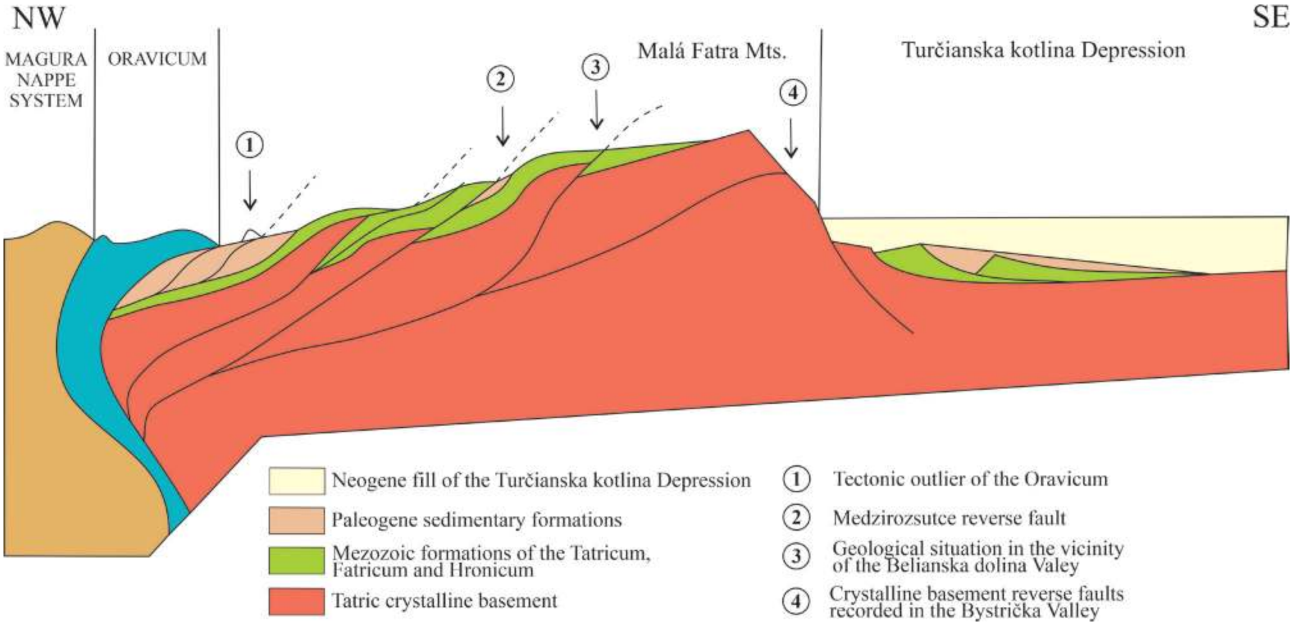


Figure 3.15 Tectonic model of the Krivánska Fatra Mts showing the major Cenozoic backthrust structures (Sentpetery, 2011).

participates at the bivergent structure (Fig. 3.15). The course of the structural fan axis is situated externally from the surface course of the PKB, which together with the northern IWECA margin forms its south-vergent branch. The development of the bivergent structure is the result of continuous deformation in the transpression regime during the ?Oligocene to the Early Miocene (Pešková et al., 2012).

IWECA are represented by the Tatricum, Fatricum and Hronicum tectonic units. Post-nappe formations are predominantly represented by Paleogene sediments of the Podtatra Group (Gross et al., 1984) and the Myjava-Hričov Group (Plašienka & Soták, 2015). Neogene sediments are concentrated in the Turčianska kotlina Depression (Kováč et al., 2011).

The Tatricum contains crystalline basement and Permian to Cretaceous sediments covering the crystalline basement. The basement is composed mainly of granitoids of the Upper Devonian to Carboniferous age (Shcherbak et al., 1990; Bagdasaryan et al., 1992; Petrík et al., 1994). Metamorphic rocks are less presented and occur on the eastern margin of the Lúčanská Fatra Mts (Janák & Lupták, 1997). Tatric cover sediments are present in the Lúčanská Fatra, Krivánska Fatra and Veľká Fatra Mts (Geologická mapa Slovenska 1: 50,000, 2013 [online]). The Tatric basement and cover sequence (Early Triassic – Early Cretaceous), together with the Fatricum and Hronicum is an integral part of the south-vergent structure in Krivánska Fatra Mts (Uhlig, 1902; Sentpetery, 2011; Pešková et al., 2012; Sentpetery & Hók, 2012).

The Fatric tectonic unit occurs predominantly on the northern slopes of the Krivánska Fatra Mts, where is deformed by post-nappe, south-vergent movements (Pešková et al., 2012; Sentpetery, 2011; Senpetery & Hók, 2012) including infolded Paleogene sediments. The Hronic tectonic unit is represented by Middle Triassic carbonates. Due to backthrusting, the Hronicum, Fatricum and Paleocene sediments of the Myjava-Hričov Group are situated in tectonic footwall of the Oravic units in the Krivánska Fatra Mts.

The Paleogene sediments of the Podtatra Group (Central Carpathian Paleogene Basin) transgressively overlie the Fatric and Hronic units. The substratum of the Paleogene sediments of the Myjava-Hričov Group is unknown. In most cases they occur below the backthrust Oravic units (Pešková et al., 2012). Neogene sediments are located in the Turčianska kotlina Depression, reaching a maximum thickness 1,027 metres in the area documented by the ZGT-3 borehole (Fendek et al., 1990). Several alluvial fans of Miocene to Pliocene sediments are present at the western margin of the Turčianska kotlina Depression (Hók et al., 1998; Kováč et al., 2011), containing mostly dolomite clasts derived from the Hronicum. Presence of the dolomites has a significant effect on the increasing density of modelled polygons.

3.3.2 Profile PF-1

The gravimetric profile PF-1 begins in the Turzovská vrchovina Mts including boreholes HŽK-1, ŽK-3 (Šalagová et al., 1996a, b) in the Žilinská kotlina Depression, ZGT-3 (Gašparik et al., 1995; Fendek et al., 1990) in the Turčianska kotlina Depression and is terminated in the Veľká Fatra Mts. The surface geometry of the modelled bodies was constrained by geological map (Geological map of Slovakia, 2013), borehole data and results of previous geophysical models (Panáček et al., 1991; Šalagová et al., 1996a, b). The density values were used according to the results of Panáček et al., (1991), Stránska et al., (1986a, b) and Šamajová and Hók (2018).

The course of the Moho discontinuity has a decreasing character from 35 km in EWC to 32 km in IWC (Alasonati Tašárová et al., 2016; Bielik et al., 2018). The LAB is constant in the depth of 110 km across the profile (Dérerová et al., 2006; Alasonati Tašárová et al., 2016). As indicated by the geological structure, the calculated curve includes several local anomalies (Fig. 3.16). The structural sedimentary wedge of the Magura and Krosno nappe systems is characterized by the gravity values that change in the interval of -20 to -59 mGal. The density value of the individual nappes differs depending on the predominant grain size. The Klippen Belt (Oravicum) consists of shallow structure with dim amplitude on the gravity. This structure is integral component of the bivergent wedge (Pešková et al., 2012). The interpretation of the Žilinská kotlina Depression was constructed according to results of the boreholes HŽK-10, ŽK-1, 2, 3 (Šalagová et al., 1996a, b) and gravimetric profile (Šalagová et al., 1996a, b). Below the Paleogene sediments, two tectonic slices of the Mesozoic sediments (Fatricum) were drilled in the borehole HŽK-10 (Šalagová et al., 1996a, b). In the borehole ŽK-3, Triassic carbonates of the Hronic Unit are present besides of the Paleogene and Mesozoic sediments of the Fatricum. The geological structure of the Žilinská kotlina Depression comprises the Paleogene sediments (Eocene), Triassic dolomites of the Hronicum and tectonic slices of the Fatricum overlying the Tatric cover unit. The relative gravity high of the Lúčanská Fatra Mts is the result of the gravity effects of the Mesozoic sediments, the Tatric crystalline basement and the elevation of the lower crust.

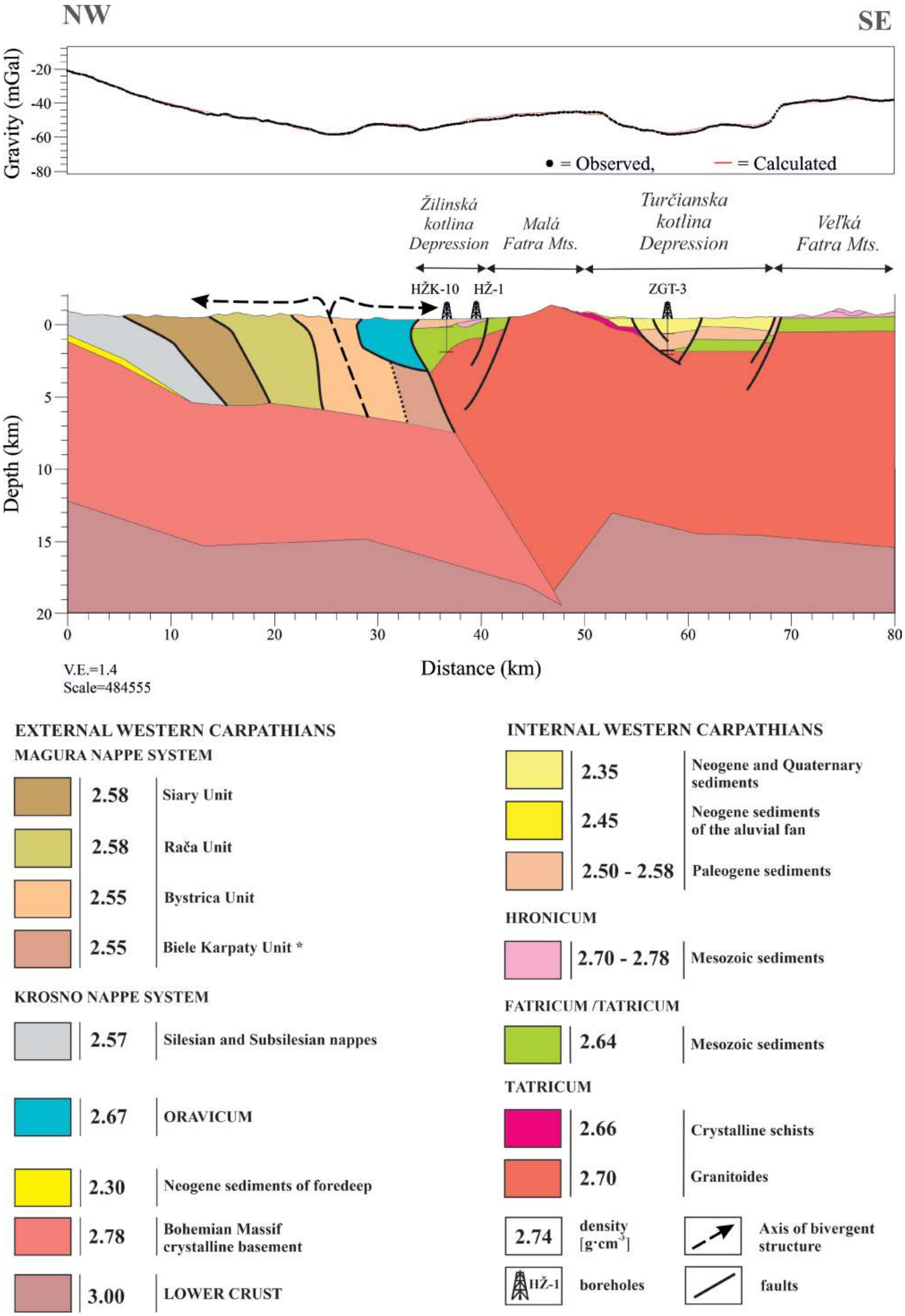


Figure 3.16 Gravimetric interpretation of the geological structures across the profile PF-1. * Expected occurrence of sediments of the Biele Karpaty Unit, not confirmed by boreholes data or outcrops.

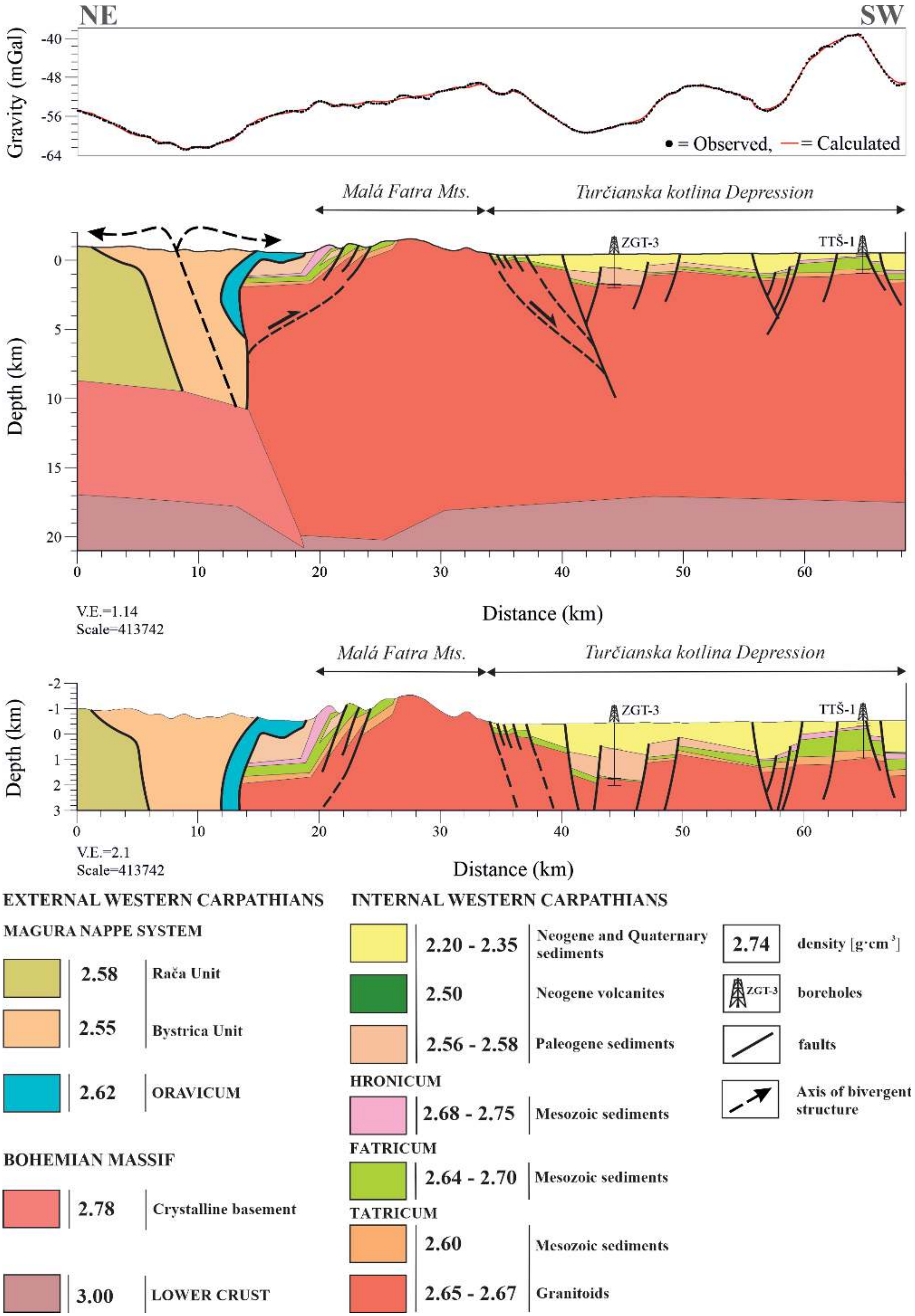


Figure 3.17 Gravimetric interpretation of the geological structures across the profile PF-2 with detail to 3 km.

The Turčianska kotlina Depression is characterized by significant gravity low with several local anomalies (Fig. 3.16). The interpretation of the pre-Neogene basement was constructed according to the data of deep borehole ZGT-3, seismic profiles K-III/75 (Leško et al., 1978; Hrdlička et al., 1983), 4AHR/68 and 519/87 (Tomek et al., 1990), regional magnetic profile TK-1 (Filo & Kubeš in Panáček, 1991) and gravimetric profile PF-VI, VII (Šefara in Panáček et al., 1991). The Neogene infill of the Turčianska kotlina Depression is significantly tilted to the west along the eastern margin. The contact of the Turčianska kotlina Depression and the Veľká Fatra Mts is represented by the significant horizontal gradient 1.5 mGal/km. The gravity high of the Veľká Fatra Mts is the result of the gravity effect linked with the presence of stacked slices of the Hronic dolomites and of the Tatric crystalline basement.

3.3.3 Profile PF-2

The gravimetric profile was constructed along a line from the Kysucké Beskydy Mts to the Turčianska kotlina Depression across the deep boreholes ZGT-3 (Gašparik et al., 1995; Fendek et al., 1990) and TTŠ-1 (Hradilová, 1988). Both profiles (PF-1 and PF-2) intersect at borehole ZGT-3 and PF-2 continues in NE–SW direction. The surface geological and structural data was taken from Geological map of Slovakia, 2013. Density values of the individual rock complexes were used according to Zbořil et al. (1979, 1985), Panáček et al. (1991), Stránska et al. (1986) and Šamajová & Hók (2018).

Moho depth ranges between 38 km in EWC and gradually decreases to 32 km in Turčianska kotlina Depression (Alasonati Tašárová et al., 2016; Bielik

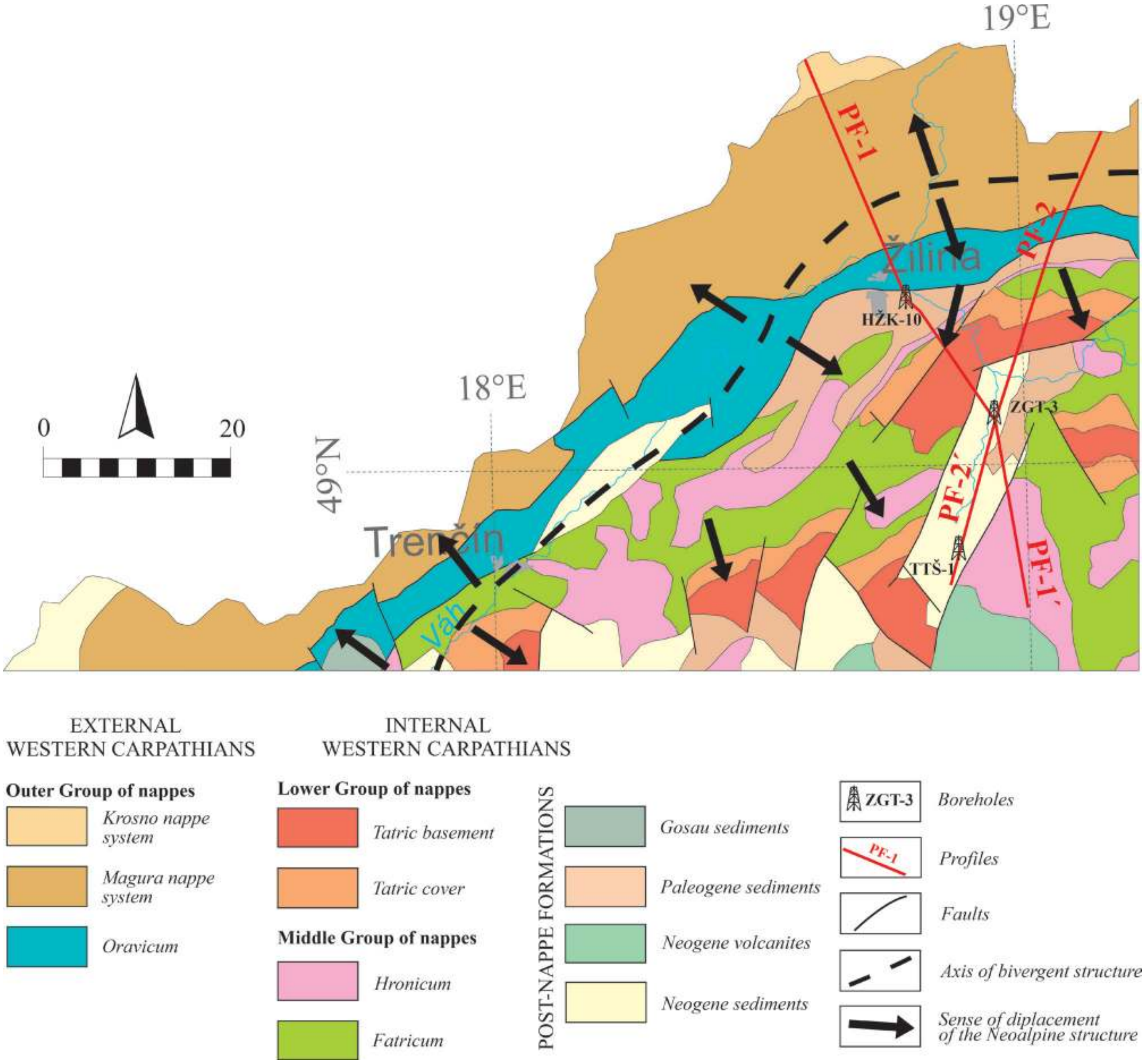


Fig. 3.18 Simplified geological map with the position of the bivergent structure (Sentpetery, 2011; Pešková et al., 2012; Pelech, 2015; Pelech et al., 2016, 2017b, 2018; Hók et al., 2016; Pelech & Olšavský, 2018; Pulišová et al., 2018).

et al., 2018). The LAB is constantly at 110 km along the profile (Dérerová et al., 2006; Alasonati Tašárová et al., 2016). The calculated gravity is composed of several local anomalies reflecting complicated geological structure of the studied area (Fig. 3.17).

The Flysch Belt sediments of the Magura nappe system belong to the Rača and Bystrica units. The PKB is represented by a shallow structure with insignificant gravity effect. The axis of the bivergent structural wedge observable in the north-eastern part of the profile is located in the Magura nappe system.

The notable gravity high of the Lúčanská Fatra Mts is the result of the joint gravity effects of the Mesozoic duplex structures and of the Tatric crystalline basement. The contact of the Lúčanská Fatra Mts and the Turčianska kotlina Depression sedimentary fill is characterized by considerable horizontal gradient of 1.25 mGal/km. Interpretation of the deeper structure of the Turčianska kotlina Depression was constructed according to the results of deep boreholes ZGT-3, TTŠ-1 and GHŠ-1, seismic profile 4HR/86 (Tomek et al., 1990) and gravimetric profile (Zbořil et al., 1985). The large gravity low with several local anomalies is caused by the block structure of the Turčianska kotlina Depression. Within the southern part of the PF-2 profile, significant, W–E oriented transversal faults can be observed (Fig. 3.17). The fault network creates the set of elevations and depressions. The interpretation of the pre-Neogene basement was controlled by the results of deep boreholes ZGT-3 and TTŠ-1.

3.3.4 Conclusions

2D gravity modelling was carried out along profiles PF-1 and PF-2 oriented across the significant geological structures, in order to clarify the character of oppositely vergent structures in the studied area. The results of the 2D modelling confirmed the presence of the bivergent structural wedge formed by tectonic units of the External and Internal Western Carpathians (Fig. 3.18). The course of its axis is variable depending on the position within the studied area. In the northern part of the studied area, the trace of the bivergent structure is verified by two gravity profiles. The wedge axis is located in the Magura nappe system. In the eastern part, the axis passes through the structure of the Klippen Belt. Below the sedimentary fill of the Ilavská kotlina Depression in SW, the trace of the wedge axis is located at the contact of the Klippen Belt with the Internal Western Carpathians. Subsequently the observed structure passes into the Internal Western Carpathians.

3.4 Tectonic evolution of the Klippen Belt

The tectonic edifice of the PKB exemplifies a combination of several structural styles which variously affected individual PKB sectors. In previous concepts of the tectonic development of the PKB part under question, these were defined as: (i) nappe thrusting of the principal PKB units like the Kysuca and Manín resp. Klape units (e.g.); (ii) south-vergent imbricated structure deforming the original nappe stack (e.g. Haško, 1978b; Haško & Polák, 1979; Potfaj, 1988, 1979, 1983); (iii) transpressional coulisse-like structure further complicating relationships of the PKB units (Maheľ, 1989). All these processes took part in the PKB structural evolution, but in the quoted papers they were based only on the large-scale tectonic considerations and not supported by a relevant structural documentation, except of frequently observed overturned bedding in flysch complexes.

Many of previous studies attributed the oldest principal deformation stages and palaeostress states to the Oligocene – Early Miocene times (Ratschbacher et al., 1993; Kováč & Hók, 1996; Pešková et al., 2009, 2012), consequently it means that the principal features of the PKB structure originated during the “Savian” tectogenesis (e.g. Sikora, 1974). However, these studies did not consider existence of various PKB units and their nappe positions. Origin of the nappe structures was also attributed to variously timing stages – pre-Albian “Pieniny (Austrian) phase” (later renamed as the “Manín phase” with generation of the Subpieniny, Pieniny and Manín nappes – Andrusov 1931b, 1938), pre-Gosauian “Mediterranean phase” (Andrusov et al., 1973; Salaj, 2006), various intra-Senonian “Subhercynian” phases (Andrusov & Scheibner 1960; Andrusov 1965, 1968; Scheibner, 1968b), and finally the end-Cretaceous “Laramian” tectogenesis (e.g. Andrusov 1972, 1974; Haško, 1978b; Gross et al., 1993). This view led Andrusov (1972, 1974) to affiliate the Manín Unit with the PKB Pienidic units, it means to the “Laramian” tectonic system of the PKB that is sharply separated from the “Subhercynian” tectonic system of the CWC. In the Polish Pieniny Mts, succession of several nappe-forming phases (Subhercynian, Laramian and Savian as the main events) was assumed by Birkenmajer (1960, 1970, 1986) and Jurewicz (1994). In the eastern Slovakian PKB branch, the main folding stage was attributed to the Late Eocene "Illyrian" or "Pyrenean" phases by some authors (e.g. Stráník, 1965; Leško & Samuel, 1968; Nemčok, 1971).

Based chiefly on the composition and age of pre- to syn-thrusting synorogenic flysch formations of the Oravic units and their structural position in the eastern PKB branch, Plašienka and co-authors (Plašienka & Mikuš, 2010; Plašienka, 2012a, b; Plašienka et al., 2012) deduced that the Pieniny Unit overrode the Maastrichtian Jarmuta Basin of the later Subpieniny Unit (Czorsztyn Ridge domain) during the earliest Paleocene and then the detached Subpieniny Unit was emplaced over the Proč Basin of the Šariš domain in the Middle Eocene times. With correlation of tectonic development between the eastern and western PKB branches, Plašienka et al. (2020) reconstructed eight principal evolutionary stages and postulated significant differences between the western vs. eastern branches from the Late Eocene onward. Hereafter, description of these tectonic stages recorded in the western branch is summarized and supplemented in Figure 3.19.

Stage S1. Based on the stratigraphic age of youngest Tatric cover sediments (Poruba Fm., middle Turonian – Boorová & Potfaj, 1997), the Fatric Krížna nappe was emplaced during the late Turonian. In the outer Tatric zones (Považský Inovec Mts. – cf. Pelech et al., 2017a), this event might have been younger – Coniacian to Santonian, i.e. some 90–85 Ma ago (Plašienka, 2018a, 2019 and references therein). In the CWC area, the top-to-NW thrusting direction of the Krížna nappe was documented by Plašienka (2003b) and Prokešová et al. (2012). The frontal Fatric nappe elements (Manín, Klape and Drietoma) glided beyond the outer Tatric edge, possibly as far as over the Vahic oceanic crust. This event was coeval with onset of subduction of the Vahic oceanic crust, as inferred from commencement of synorogenic flysch sedimentation in the Belice Unit (Plašienka et al., 1994).

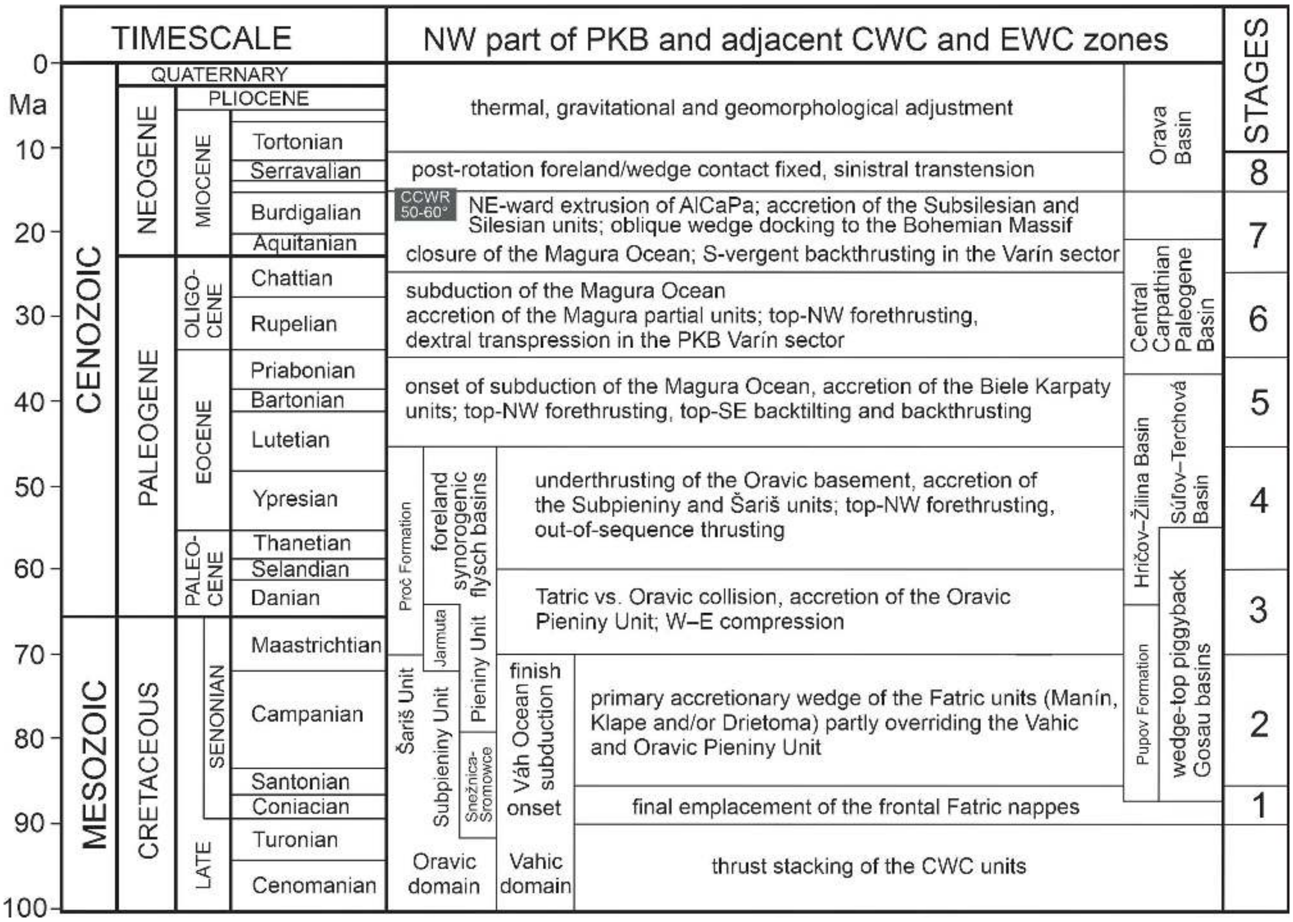


Figure 3.19 Summary of tectonic processes during evolutionary stages of the western PKB branch (modified after Plašienka et al., 2020).

Stage S2. In the course of subduction of the Piemont-Váh Ocean, the frontal Fatric units of the present-day Peri-Klippen zone became constituents of a nascent accretionary wedge. Folded and imbricated Manín and Klape units incorporated also shallow- to deep-marine synorogenic sediments deposited in the wedge-top, Gosau-type basins (Plašienka & Soták, 2015). During the closing stages of the Váh Ocean, the Fatric wedge toe overrode the southern foots of the Oravic continental fragment, which were the sedimentary area of the later Pieniny Unit. This phase covered a significant time span of 15 Myr from the Santonian to early Maastrichtian (85–70 Ma).

Stage S3. At the turn from Cretaceous to Paleogene, the Vahic subduction was terminated by the likely oblique collision of the outer (Tatric) CWC margin with the Oravic continental domain (Fig. 3.20). Shortening continued by detachment of the basinal Pieniny-type successions and their thrusting over the elevated part of the Oravic continental ribbon (Czorsztyn Ridge), along with the overlying frontal Fatric elements and piggyback Gosau basins. Sedimentary record includes the latest Cretaceous trench-type flysch deposits and olistostrome bodies in the Czorsztyn-type successions of the forthcoming, structurally lower Subpieniny Unit. Existing structural data document the W–E compression during the incipient collision ("cross folding", see above), followed by NW to NNW-ward overthrusting (Plašienka et al., 2018, 2020 and references therein). The S3 stage lasted probably until the Middle Paleocene (60 Ma).

Stage S4. During the Paleocene to Middle Eocene (60 to ca 45 Ma), convergence continued by sequential disconnection of the Oravic Subpieniny and Šariš units from their basement and their attachment to the tip of the advancing accretionary wedge, simultaneously with initial underthrusting of the Oravic crustal domain below the prograding CWC orogenic wedge (Fig. 3.20). The wedge propagated by repetition of several shortening and extensional events that were ruled by fluctuations of the wedge taper (Plašienka & Soták, 2015). Shortening phases are recorded by shallowing or non-deposition and erosion in the wedge-top basins, whereas the Oravic flysch trench basins were supplied by coarse-grained detritus produced by erosion of the wedge areas. The accretionary system attained a typical asymmetric wedge shape with frontal foreland-ward (NW- ward) thrusting, steepening of thrust imbricates and thickening of the central part, and back-tilting and backthrusting in the wedge rear (Plašienka et al., 2018b, 2020; Plašienka, 2019).

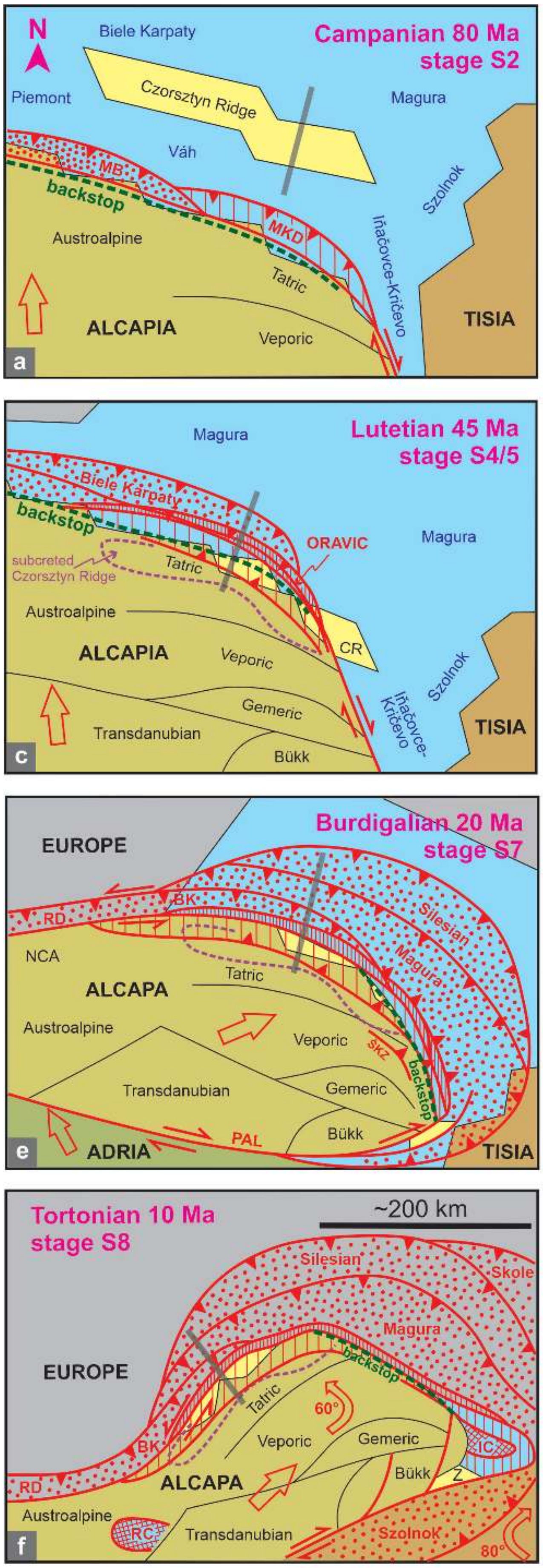
Stage S5. During the Middle–Late Eocene (45 to 35 Ma), the wedge grew by sequential frontal accretion of the Biele Karpaty and Magura units scraped off the subducting North Pennine (Rhenodanubian–Magura) at least partly oceanic lithosphere. Following the Lutetian collapse phase (Plašienka & Soták, 2015; Soták et al., 2017), the rear parts of the wedge thickened again by back-tilting and backthrusting. Foreland-directed forethrusts in the Magura units and hinterland-directed backthrusts in the PKB and CWC areas are arranged in a broad-scale fanwise structure centred in the OWC Bystrica Unit. By the S5 stage, the PKB Oravic units became to be completely uprooted and attached to the upper CWC plate within the convergence zone, i.e. they occupied a backstop position with respect to the forward expanding EWC accretionary wedge (Fig. 3.20; Plašienka et al., 2020).

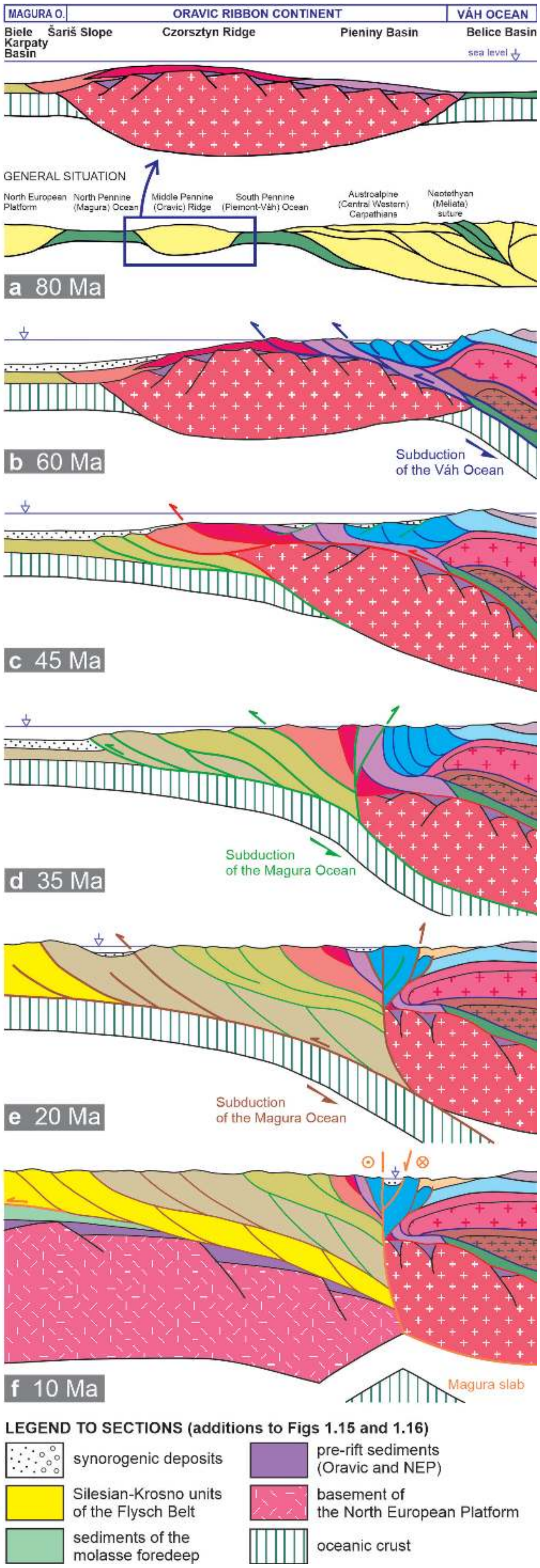
From the S5 stage onward, tectonic evolution of the western and the eastern PKB branches differed substantially (Plašienka et al., 2020). The NW–SE shortening and accretion of the Biele Karpaty units of the Flysch Belt continued in the western branch, whereas the eastern branch started to develop by translation of the Oravic and Peri-Klippen units along the right-lateral wrench corridor that followed the eastern transform boundary of the Western Carpathians.

Stage S6. The NW–SE oriented contraction continued also during the Late Eocene to Late Oligocene (35–25 Ma). Brittle deformational structures like joints, faults and slickensides affected already tilted, mostly steeply dipping strata. Due to thickening of the rear parts of the wedge, further NW–SE compression was accommodated by dextral transpression in the W–E trending Varín PKB sector and adjacent units (e.g. the Bytča-Žilina and Ráztoky fault zones). In the western part of the EWC Flysch Belt, the internal fold-thrust structure of the Magura units was nearly completed and then the EWC wedge propagated by accretion of the outer Flysch Belt units (e.g. Picha et al., 2006).

Stage S7. During the Late Oligocene to early Middle Miocene stage (25–15 Ma), the principal compression axis attained the NNW–SSE to N–S orientation. The leading large-scale deformation processes, i.e. the extensive backthrusting reaching at least 5 km (cf. Pešková et al., 2012) accompanied by strong internal imbrication and disintegration of of the original nappe structure, affected all PKB and adjacent units in the Varín sector. Southward oriented thrusting modified the bounding fault contacts of the PKB in particular, leading to conspicuous south-vergent fold and thrust deformation of the Paleogene CCPB flysch sediments just at the contact with the PKB (see stop B1). However, backthrusting affected also the adjoining zones of the Malá Fatra Mts by development of the prominent N-dipping reverse fault on the Mt. Rozsutec ridge (see chapter 1.1), as well as in several other areas (e.g. Sentpetery, 2011; Sentpetery & Hók, 2012).

During the Early Miocene, the EWC accretionary wedge propagated by accretion of the Fore-Magura, Silesian and Subsilesian units (cf. Picha et al., 2006). The S7 stage terminated by the large-scale counter-


N
Biele Karpaty
Campanian 80 Ma
stage S2
Czorsztyn Ridge
Piemont
Magura
Váh
MB
backstop
MKD
Szolnok
Iňačovce-Kričevo
Austroalpine
Tatric
ALCAPIA
Veporic
TISIA
a
Magura
Lutetian 45 Ma
stage S4/5
Biele Karpaty
backstop
ORAVIC
Magura
subcreted
Czorsztyn Ridge
Tatric
Austroalpine
CR
ALCAPIA
Veporic
Szolnok
Gemeric
Iňačovce-Kričevo
Transdanubian
TISIA
Bükk
c
EUROPE
Burdigalian 20 Ma
stage S7
BK
RD
Silesian
NCA
Magura
ALCAPA
Tatric
Austroalpine
Veporic
ŠKZ
Gemeric
Transdanubian
backstop
Bükk
PAL
ADRIA
TISIA
e
Tortonian 10 Ma
stage S8
~200 km
Silesian
Skole
Magura
EUROPE
backstop
Tatric
60°
Veporic
Gemeric
BK
IC
Bükk
Z
RD
ALCAPA
Austroalpine
RC
Transdanubian
Szolnok
80°
f


MAGURA O.
ORAVIC RIBBON CONTINENT
VÁH OCEAN
Biele Karpaty Basin
Šariš Slope
Czorsztyn Ridge
Pieniny Basin
Belice Basin
sea level
GENERAL SITUATION
North European Platform
North Pennine (Magura) Ocean
Middle Pennine (Oravic) Ridge
South Pennine (Piemont-Váh) Ocean
Austroalpine (Central Western) Carpathians
Neotethyan (Meliata) suture
a 80 Ma
Subduction of the Váh Ocean
b 60 Ma
c 45 Ma
Subduction of the Magura Ocean
d 35 Ma
Subduction of the Magura Ocean
e 20 Ma
f 10 Ma
Magura slab
LEGEND TO SECTIONS (additions to Figs 1.15 and 1.16)
synorogenic deposits
Silesian-Krosno units of the Flysch Belt
sediments of the molasse foredeep
pre-rift sediments (Oravic and NEP)
basement of the North European Platform
oceanic crust

clockwise block rotation of the entire Western Carpathian domain in the order of 50–60° (Márton et al., 2013, 2015). The Middle Miocene CCW rotation brought about termination of advancement and growth of the western part of the EWC accretionary wedge, which became to be fixed to the foreland plate (Bohemian Massif).

Stage S8. During the post-rotation of the WC block, in the Middle to early Late Miocene times (15–10 Ma; (Fig. 3.20), the ongoing NE-directed movement of the Carpathian part of the AlCaPa microplate resulted in the overall transtensional regime. Major sinistral strike-slip zones extending from the Eastern Alps affected the zones along the PKB by development of the extensive Vienna Basin at the Alpine–Carpathian junction area, but also with opening of several other small pull-aparts along the Váh River Valley (Trenčín and Ilava basins) up to the northernmost PKB bend from its WSW- to ESE trending sectors (Orava Basin; e.g. Ludwiniak et al., 2019 and references therein). The brittle structural record reveals shifting of the maximum horizontal stress axis from the N–S to the SW–NE orientation as documented at numerous places (e.g., Marko et al., 1995; Kováč & Hók, 1996; Šimonová & Plašienka, 2017). The SW–NE trending thrust faults separating nappes of the EWC Flysch Belt were also partly reactivated as left-lateral strike slips (Decker & Peresson, 1996; Beidinger & Decker, 2016). Simultaneously, the only important transversal zone with dextral offset that disturbs the nearly perfect, smoothly arching PKB curvature – the N–S trending Zázrivá–Párnica fault zone (or Zázrivá sigmoid) originated (see above).

Figure 3.20 Palaeotectonic interpretation of the main evolutionary stages of the western PKB branch (modified after Plašienka et al., 2020). MB – Matrei–Belice wedge; MKD – Manín–Klape–Drietoma belt; NCA – Northern Calcareous Alps; CR – Czorsztyn Ridge; RD – Rhenodanubian Flysch Belt; BK – Biele Karpaty Unit; ŠKZ – Šambron–Kamenica Zone; PAL – Peri-Adriatic Line; RC – Rechnitz core complex; IC – Iňačovce core complex.

Summary and conclusions

This monograph has aimed at summarizing the knowledge about the geology and tectonics of the Pieniny Klippen Belt (PKB) and adjacent frontal parts of the Central Western Carpathians (CWC) represented by the Malá Fatra core-mountains in north-western Slovakia, along with presentation of new data achieved during the last years by the authors. At the same time, it may serve as a guide-book for some key outcrops and sections in the area. The new results and interpretations can be briefly recapitulated as follows:

- Variscan granitoids of the Tatric crystalline basement show distributional zoning and evolution from arc-related magmatism at ca 353 Ma followed by collisional magmatism some 10 Myr later, exhumation by 330 Ma and Permian and Alpine thermal overprints. Details are provided by representative localities at the Dubná skala and Kraľovany-Bystrička quarries.
- The Cretaceous nappe structure of the CWC is presented along several sections in the Krivánska Malá Fatra Mts, e.g. around the eye-catching Mt. Rozsutec. The Fatric Krížna Nappe is characterized by duplex structures and diverticulation mode of final emplacement of the partial Fatric units. Structure of the Fatric and Hronic nappes in the north-western part of the Malá Fatra core-mountains, adjacent to the PKB, was affected by striking post-Paleogene backthrusts like the Medzirozsutce reverse fault.
- Structure of the eastern part of the Varín PKB sector is dominated by post-Paleogene backthrusting and transformation of the original nappe edifice of the Oravic units to the north-dipping, synclinorium-like arrangement. Oravic units form the imbricated limbs, while the Upper Cretaceous Pupov Formation of still problematic affiliation occurs in its centre. We recognized also the presence of the Šariš Unit in the area, which is characterized by some indicative formations like the Szlachtowa or Malinowa fms. The litho-biostratigraphy of several marly and flysch formations was demonstrated along sections exposed predominantly in temporary outcrops like road cuts and creek bedrocks.
- The origin of the Zázrivá-Párnica sigmoid and associated N–S trending faults that caused a distinctive transversal shift of the PKB was discussed. Based on the structural investigations and new data from magnetotelluric measurements it is inferred that this structure represented a lateral ramp with the sunken eastern Orava block during the backthrusting stage, which was modified by the Miocene dextral transtensional faulting.
- Due to the poor outcrop conditions and missing links between various units and formations, the western part of the Orava PKB sector is hitherto the least understood. Supposedly, it is composed only of the Oravic units – the Pieniny Unit in the centre and the Subpieniny and Šariš units along the imbricated limbs of a northward plunging synform.
- Finally, we presented a hypothetical model of the tectonic development of the PKB and contiguous zones in north-western Slovakia. The model assumes the long-term, latest Cretaceous to Lower Miocene NW–SE oriented forethrusting of units detached from the Oravic continental ribbon colliding with the backstop CWC block. The nappe structures of the PKB units in the backstop-edge position of the developing accretionary wedge of the Flysch Belt were then strongly modified by backthrusting-backtilting and transpressional movements.

We believe that every reader will find new and valuable information from his/her field of research in this book. Nevertheless, since the geological research is a never-ending process, no results can be final and many open problems still remain to be solved in the future. As usuall in science, we feel that during the field and laboratory works, and during compiling of this monograph, more questions arose than were answered. Hence we hope that the data presented, and particularly those which are problematic or still missing, will inspire our followers to continue investigations of this fascinating piece of the Western Carpathian geology. If this happens, the purpose of the presented monograph will be met.

References

Alasonati Tašárová Z., Fullea J., Bielik M. & Środa P., 2016: Lithospheric structure of Central Europe: Puzzle pieces from Pannonian Basin to Trans-European Suture Zone resolved by geophysical-petrological modelling. Tectonics, 35, 1–32.

Aleksandrowski P., 1989: Geologia strukturalna płaszczowiny magurskiej w rejonie Babiej Góry [English summary: Structural geology of the Magura nappe in the Mt. Babia Góra region, Western Outer Carpathians]. Studia Geologica Polonica, 46, 3–140.

Ando A., Huber B.T. & Premoli Silva I., 2013: Paraticinella rohri (Bolli, 1959) as the valid name for the latest Aptian zonal marker species of planktonic foraminifera traditionally called bejaouaensis or eubejaouaensis. Cretaceous Research, 45, 275–287.

Andrusov D., 1926: O sigmoidálních ohybech pásma bradlového mezi Oravou a Kysucou [About sigmoidal bends of the Klippen Belt between the Orava and Kysuca regions]. Věstník Státního geologického ústavu ČSR, 2, 4-6.

Andrusov D., 1929: Příspěvek ku geologii severozápadních Karpat. IV. Útesové pásmo v Pěninách [Notes sur la géologie des Carpathes du Nord-Ouest, IV. Les Klippes piénines]. Věstník Státního geologického ústavu ČSR, 5, 6, 327–342.

Andrusov D., 1931a: Geologický výzkum vnitřního bradlového pásma v Západních Karpatech. Část I.: Úvod, Část II.: Stratigrafie (trias a lias) [Étude géologique de la zone des Klippes internes des Carpathes Occidentales. I-iére partie: Introduction, II-iéme partie: Stratigraphie (Trias et Lias)]. Rozpravy Státního geologického ústavu ČSR, 6, 167 p.

Andrusov D., 1931b: La „Zone des Klippes internes“ dans le bassin de l´Orava. In Matějka A. & Andrusov D. (eds): Guide des excursions dans les Carpathes Occidentales. Troisième réunion de l´Association pour l´Advancement de la Géologie des Carpathes. Knihovna Státního geologického ústavu ČSR, 13.A, 317–351.

Andrusov D., 1936: Subtatranské příkrovy Západních Karpat [Subtatra nappes of the Western Carpathians]. Carpatica, 1B, 3–50.

Andrusov D., 1938: Geologický výzkum vnitřního bradlového pásma v Západních Karpatech. Část III.: Tektonika [Étude géologique de la zone des Klippes internes des Carpathes Occidentales, IIIe partie: Tectonique]. Rozpravy Státního geologického ústavu ČSR, 9, 135 p.

Andrusov D., 1945: Geologický výskum vnútorného bradlového pásma v Západných Karpatoch. Časť IV. Stratigrafia doggeru a malmu, Časť V. Stratigrafia kriedy. Práce Štátneho geologického ústavu, 13, 176 p.

Andrusov D., 1953: Étude géologique de la zone des Klippes internes des Carpathes Occidentales. Partie IV. Stratigraphie du Dogger et du Malm. Partie V. Stratigraphie du Crétacé. Geologické práce, Sošit, 34, 148 p.

Andrusov D., 1965: Geologie der tschechoslowakischen Karpaten II. Akademie Verl., Berlin, Verlag Slov. Akad. Wissensch., Bratislava, 443 p.

Andrusov D., 1968: Grundriss der Tektonik der nördlichen Karpaten. Verlag Slov. Akad. Wissensch., Bratislava, 188 p.

Andrusov D., 1972: Sur l’ampleur de la nappe du Manín (Zone des Klippes Piénines, Carpathes Occidentales, Slovaquie). Geologický zborník – Geologica Carpathica, 23, 2, 227–234.

Andrusov D., 1974: The Pieniny Klippen Belt. In M. Maheľ (ed.): Tectonics of the Carpathian-Balkan regions. Geol. Inst. D. Štúr, Bratislava, 145–158.

Andrusov D. & Samuel O., 1973: Cretaceous–Paleogene of the West Carpathians Mts. X Congress Carpath.-Balkan Geol. Assoc., Guide to excursion E. Geol. Inst. D. Štúr, Bratislava, 78 p.

Andrusov D. & Scheibner E., 1960: Prehľad súčasného stavu poznatkov o geológii bradlového pásma medzi Vlárou a Tvrdošínom [English summary: An outline of the present state of knowledge about the geology of the Klippen Belt between R. Vlára and T. Tvrdošín]. Geologický sborník, 11, 2, 239–279.

Andrusov D. & Scheibner E., 1968: Classification of “Klippes” or “Klippen”. Proc. XXIII Internat. Geol. Congr., Prague, vol. 3, 93–102.

Andrusov D., Bystrický J. & Fusán O., 1973: Outline of the structure of the West Carpathians. X Congress of Carpathian-Balkan Geological Association, Guide-book for geological excursion, Geol. Inst. D. Štúr, Bratislava, 44 p.

Aubrecht R., 1997a: Indications of the Middle Jurassic emergence in the Czorsztyn Unit (Pieniny Klippen Belt, Western Carpathians). Geologica Carpathica, 48, 2, 71–84.

Aubrecht R., 1997b: Signs of Laramian resedimentation and submarine volcanic activity near Zázrivá – Grúne (Orava part of the Pieniny Klippen belt). Mineralia Slovaca, 29, 39–49.

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

Aubrecht R., 2001b: Jurassic heavy mineral distribution provinces in the Western Carpathians. Mineralia Slovaca, 33, 473–486.

Aubrecht R. & Ožvoldová L., 1994: Middle Jurassic – Lower Cretaceous development of the Pruské Unit in the western part of the Pieniny Klippen Belt. Geologica Carpathica, 45, 4, 211–223.

Aubrecht R. & Szulc J., 2006: Deciphering of the complex depositional and diagenetic history of a scarp limestone breccia (Middle Jurassic Krasin Breccia, Pieniny Klippen Belt, Western Carpathians). Sedimentary Geology, 186, 265–281.

Aubrecht R. & Túnyi I., 2001: Original orientation of neptunian dykes in the Pieniny Klippen Belt (Western Carpahtians): the first results. Contributions to Geophysics and Geodesy, 31, 3, 557–578.

Aubrecht R., Mišík M. & Sýkora M., 1997: Jurassic synrift sedimentation on the Czorsztyn Swell of the Pieniny Klippen Belt in Western Slovakia. In Plašienka D., Hók J., Vozár J. & Elečko M. (eds.): Alpine evolution of the Western Carpathians and related areas. Internat. conf., Sept. 1997, Introduct. articles to the excursion, Geol. Survey Slov. Rep., D. Štúr Publ., Bratislava, 53–64.

Aubrecht R., Szulc J., Michalík J., Schlögl J. & Wagreich M., 2002: Middle Jurassic stromatactis mud-mound in the Pieniny Klippen Belt (Western Carpahtians). Facies, 47, 113–126.

Aubrecht R., Gaži P., Bučová J., Hlavatá J., Sestrienka J., Schlögl J. & Vlačiky M., 2004: On the age and nature of the so called Zázrivá Beds (Pieniny Klippen Belt, Western Carpathians). Mineralia Slovaca, 36, 1, 1–6.

Aubrecht R., Krobicki M., Sýkora M., Mišík M., Boorová D., Schlögl J., Šamajová E. & Golonka J., 2006: Early Cretaceous hiatus in the Czorsztyn Succession (Pieniny Klippen Belt, Western Carpathians): submarine erosion or emersion? Annales Societatis Geologorum Poloniae, 76, 161–196.

Aubrecht R., Schlögl J., Krobicki M., Wierzbowski H., Matyja B.A. & Wierzbowski A., 2009: Middle Jurassic stromatactis mud-mounds in the Pieniny Klippen Belt (Carpathians) – A possible clue to the origin of stromatactis. Sedimentary Geology, 213, 3-4, 97–112

Aubrecht R., Sýkora M., Uher P., Li X.-H., Yang Y.-H., Putiš M. & Plašienka D., 2017a: Provenance of the Lunz Formation (Carnian) in the Western Carpathians, Slovakia: Heavy mineral study and in situ LA-ICP-MS U-Pb detrital zircon dating. Palaeogeography, Palaeoclimatology, Palaeoecology, 171, 233–253.

Aubrecht R., Schlögl J., Krobicki M. & Wierzbowski A., 2017b: Czorsztyn Ridge was not uniform: new data from the Ukrainian part of the Pieniny Klippen Belt (Eastern Carpathians). Acta Geologica Slovaca, 9, 2, 115–137.

Aubrecht R., Bellová S. & Mikuš T., 2020: Provenance of Albian to Cenomanian exotics-bearing turbidites in the Western Carpathians: a heavy mineral analysis. Geological Quarterly, 64, 3, 658–680.

Bagdasaryan G.P., Gukasyan R. Ch., Cambel B., Kamenický L. & Macek J., 1992: Granitoids of the Malá Fatra and Velká Fatra Mts.: Rb/Sr isochron geochronology (Western Carpathians). Geologica Carpathica, 43, 1, 21–25.

Bąk K. 2000: Biostratigraphy of deep-water agglutinated Foraminifera in Scaglia Rossa-type deposits of the Pieniny Klippen Belt, Carpathians, Poland. In Hart M.B., Kaminski M.A. & Smart C.W. (eds): Proceedings of the Fifth International Workshop on Agglutinated Foraminifera. Grzybowski Foundation Special Publication, 7, 15–41.

Barski M., Matyja B.A., Segit T. & Wierzbowski A., 2012: Early to late Bajocian age of the “black flysch” (Szlachtowa Fm.) deposits: implications for the history and geological structure of the Pieniny Klippen Belt, Carpathians. Geological Quarterly, 56, 391–410.

Batchelor R.A & Bowden P., 1985: Petrogenetic interpretation of granitoid rock series using multi-cationic parameters. Chemical Geology, 29, 183–210.

Bedrosian P., 2007: MT+, integrating magnetotellurics to determine earth structure, physical state, and processes. Surveys in Geophysics, 28, 121–167.

Began A. 1969: Geologické pomery bradlového pásma na strednom Považí [German summary: Geologische Verhältnisse des mittleren Waagtales]. Zborník geologických vied, rad ZK 11, 55–103.

Began A. & Samuel O., 1975: K interpretácii strednej a vrchnej kriedy bradlového pásma Oravy [English summary: Interpretation of Upper and Middle Cretaceous of Klippen Belt in Orava]. Geologické práce, Správy, 63, 215–219.

Beidinger A. & Decker K., 2016: Paleogene and Neogene kinematics of the Alpine-Carpathian fold-thrust belt at the Alpine-Carpathian transition. Tectonophysics, 690, 263–287.

Beidinger A., Decker K., Zamolyi A. & Lee E.Y., 2011: Deciphering polyphase deformation in the Žilina segment of the Pieniny Klippen Belt (Steny ridge, NW Slovakia). Abstracts of the 9th Central European Tectonic Groups meeting, Hotel Skalský Dvůr, Czech Republic, 13.-17. April 2011. Travaux Géophysiques, 40, p. 5.

Bezák V. (ed.), Broska I., Ivanička J., Reichwalder P., Vozár J., Polák M., Havrila M., Mello J., Biely A., Plašienka D., Potfaj M., Žec B., Vass D., Elečko M., Janočko J., Pereszlényi M., Marko F., Maglay J. & Pristaš J., 2004: Tectonic map of Slovak Republic 1: 500,000 with explanations. State Geol. Inst. D. Štúr, Bratislava.

Bezák V. (ed.), Broska I., Biely A., Bóna J., Buček S., Elečko M., Filo I., Fordinál K., Gazdačko Ľ., Grecula P., Hraško Ľ., Ivanička J., Jacko S. st., Jacko S. ml., Janočko J., Kaličiak M., Kobulský J., Kohút M., Konečný V., Kováčik M., Kováčik M., Lexa J., Madarás J., Maglay J., Mello J., Nagy A., Németh Z., Olšavský M., Plašienka D., Polák M., Potfaj M., Pristaš J., Siman P., Šimon L., Teťák F., Vozárová A., Vozár J. & Žec B., 2009: Vysvetlivky k Prehľadnej geologickej mape Slovenskej republiky 1:200 000 [English summary: Explanations to the General geological map of Slovak Republic 1:200,000]. State Geol. Inst. D. Štúr, Bratislava, 534 p.

Bezák V., Pek J., Vozár J., Majcin D., Bielik M., & Tomek Č., 2020: Geoelectrically distinct zones in the crust of the Western Carpathians : A consequence of Neogene strike-slip tectonics. Geologica Carpathica, 71, 1, 14–23.

Bielik M., Makarenko I., Csicsay K., Legostaeva O., Starostenko V., Savchenko A., Šimonová B., Dérerová J., Fojtíková L., Pašteka R. & Vozár, J. 2018: The refined Moho depth map in the Carpathian-Pannonian region. Contributions to Geophysics and Geodesy, 48, 2, 179–190.

Birkenmajer K., 1957: Sedimentary characteristics of the Flysch-Aalenian in the Pieniny Klippen Belt (Central Carpathians). Bulletin de l´Académie Polonaise des Sciences Cl. III, 5, 4, 451–456.

Birkenmajer K., 1959: Seria czertezicka – nowa seria skałkowa Pienin [English summary: A new klippen series in the Pieniny Mts., Carpathians – the Czertezik series]. Acta Geologica Polonica, 9, 499–517.

Birkenmajer K., 1960: Geology of the Pieniny Klippen Belt of Poland. Jahrbuch der Geologischen Bundesanstalt, 103, 1–36.

Birkenmajer K., 1970: Przedeoceńskie struktury fałdowe w pienińskim pasie skałkowym Polski. [English summary: Pre-Eocene fold structures in the Pieniny Klippen Belt (Carpathians) of Poland]. Studia Geologica Polonica, 31, 81 p.

Birkenmajer K., 1977: Jurassic and Cretaceous lithostratigraphic units of the Pieniny Klippen Belt, Carpathians, Poland. Studia Geologica Polonica, 45, 1–158.

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

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

Birkenmajer K. & Gedl P., 2004: Dinocyst ages of some Jurassic strata, Grajcarek Unit at Sztolnia Creek, Pieniny Klippen Belt (Poland). Studia Geologica Polonica, 123, 245–277.

Birkenmajer K. & Gedl P., 2017: The Grajcarek succession (Lower Jurassic–Mid Paleocene) in the Pieniny Klippen Belt, West Carpathians, Poland: a stratigraphic synthesis. Annales Societatis Geologorun Poloniae, 87, 55–88.

Birkenmajer K., Gedl P., Myczyński R. & Tyszka J., 2008: "Cretaceous black flysch" in the Pieniny Klippen Belt, West Carpathians: a case of geological misinterpretation. Cretaceous Research, 29, 535–549.

Boorová D. & Potfaj M., 1997: Biostratigraphical and lithological evaluation of the profile "BALCOVÁ", Šiprúň sequence, Veľká Fatra Mts. Slovak Geological Magazine, 3, 4, 315–329.

Borza K., Michalík J. & Vašíček Z. 1987: Lithological, biofacial and geochemical characterization of the Lower Cretaceous pelagic carbonate sequence of Mt. Butkov (Manín Unit, Western Carpathians). Geologický zborník – Geologica Carpathica 38: 323–348.

Broska I. & Svojka M. 2020: Lower Carboniferous successive I/S-type granite magmatism recorded in the Malá Fatra Mountains by LA-ICP-MS zircon dating (Western Carpathians). Geologica Carpathica, 71, 5, 391–401.

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

Broska I., Petrík I. & Benko P., 1997: Petrology of the Malá Fatra granitoid rocks (Western Carpathians, Slovakia). Geologica Carpathica, 48, 27–37.

Broska I., Petrík I., Be´eri-Shlevin Y., Majka J. & Bezák V., 2013: Devonian/Mississippian I-type granitoids in the Western Carpathians: A subduction-related hybrid magmatism. Lithos, 162-163, 27–36.

Bown P.R. & Cooper M.K.E., 1998: Jurassic. In Bown P.R. (ed.): Calcareous Nannofossil Biostratigraphy. British Micropalaeontological Society Series. Chapman and Hall/Kluwer Academic Publishers, London, 86–131.

Bubík M., 1995: Cretaceous to Paleogene agglutinated foraminifera of the Bílé Karpaty unit (West Carpathians, Czech Republic). In Kaminsk, M.A., Geroch S. & Gasiński M.A. (eds): Proceedings of the Fourth International Workshop on Agglutinated Foraminifera. Grzybowski Foundation, Spec. Publ. No 3, 71–116.

Buček S. & Köhler E., 2017: Palaeocene reef complex of the Western Carpathians. Slovak Geological Magazine, 17, 1, 3–163.

Bučová J., 2013: Geologická stavba a štruktúrny vývoj západnej časti pieninského bradlového pásma [English abstract: Geological structure and structural evolution of the western part of the Pieniny Klippen Belt]. Unpublished PhD. Thesis, Dept. Geol. Palaeontol., Comenius University in Bratislava, 147 p.

Bučová J., Plašienka D. & Mikuš V., 2010: Geology and tectonics of the Vršatec Klippen area (Pieniny Klippen Belt, Western Slovakia). In Christofides G., Kantiranis N., Kostopoulos D.S. & Chatzipetros A.A. (eds): Proceedings 19th Congress of the Carpathian-Balkan Geological Association. Scientific Annals of the School of Geology, Aristotle University, Thessaloniki, Spec. Vol. 100, 197–207.

Cagniard L. 1953: Basic theory of the magneto-telluric method of geophysical prospecting. Geophysics, 18, 605–635.

Caron M., 1985: Cretaceous planktic foraminifera. In Bolli H.M., Saunders J.B. & Perch Nielsen K. (Eds): Plankton stratigraphy. Cambridge University Press, Cambridge, 17–86.

Castro A., 2013: Tonalite-granodiorite suites as a cotectic systems: A review of experimental studies with applications to granitoid petrogeneisi. Earth Science Reviews, 124, 68–95.

Castro A., Moreno-Ventas I. & de la Rosa J.D. 1991: H-type (hybrid) granitoids: a proposed revision of the granite type classification and nomenclature. Earth Science Reviews, 31, 237–253.

Danišík M., Kohút M., Broska I. & Frisch W., 2010: Thermal evolution of the Malá Fatra Mountains (Central Western Carpathians): insights from zircon and apatite fission track thermochronology. Geologica Carpathica, 61, 1, 19–27.

Decker K. & Peresson H., 1996: Tertiary kinematics in the Alpine–Carpathian–Pannonian system: links between thrusting, transform faulting and crustal extension. In Wessely G. & Liebl W. (eds): Oil and gas in Alpidic thrustbelts and basins of Central and Eastern Europe. EAGE Spec. Publ., 5, 69–77.

Dérerová J., Zeyen H., Bielik M. & Salman K., 2006: Application of integrated geophysical modelling for determination of the continental lithospheric thermal structure in the eastern Carpathians. Tectonics, 25, 3, 1–12. TC3009

Egbert G.D., 1997: Robust multiple-station magnetotelluric data processing. Geophysical Journal International, 130, 2, 475–496.

Faryad S.W. & Dianiška I., 2002: Ti-bearing andradite-prehnite-epidote assemblage from the Malá Fatra granodiorite and tonalite (Western Carpathians). Schweizerische Mineralogische und Petrographische Mitteilungen, 83, 47–56.

Fejdiová O., 1977: Development of the Lower Triassic clastics in the Central Western Carpathians. Geologický Zborník – Geologica Carpathica, 28, 167–176.

Fejdiová O., 1980: Lúžňanské súvrstvie – formálna spodnotriasová litostratigrafická jednotka [Liptovská Lúžna Sequence – formal Lower Triassic lithostratigraphic unit]. Geologické práce, Správy, 74, 95–101.

Fekete K., Soták J., Boorová D., Lintnerová O., Michalík J. & Grabowski J. 2017: An Albian demise of the carbonate platform in the Manín Unit (Western Carpathians, Slovakia). Geologica Carpathica, 68, 385–402.

Fendek M., Gašparik J., Gross P., Jančí J., Kohút M., Kráľ J., Kullmanová A., Planderová E., Raková J., Rakús M., Snopková P., Tuba Ľ., Vass D. & Vozárová A., 1990: Správa o výskumnom geotermálnom vrte ZGT-3 Turiec v Martine a prognózne zdroje GE v oblasti Martina [Report about the geothermal prospecting drilling ZGT-3 Turiec in town Martin and prognostic sources in the Martin area]. Manuscript, Archives Geol. Inst. D. Štúr, Bratislava, 1–86.

Friedrichs B., 2004: Mapros, (Ver. 0.87b freeware), Metronix Measurement Instruments and Electronics Ltd., https://www.metronix.de/metronixweb/en/geophysik/documents/

Froitzheim N., Plašienka D. & Schuster R., 2008: Alpine tectonics of the Alps and Western Carpathians. In McCann T. (ed.): The Geology of Central Europe. Volume 2: Mesozoic and Cenozoic. Geological Society Publishing House, London, 1141–1232.

Frost C.D., Barnes C.G., Collins W.J., Arculus R.J., Ellis D.J. & Frost C.D., 2001: A geochemical classification for granitic rocks. Journal of Petrology, 42, 2033–2048.

Gašparik J. & Halouzka R. (eds.), 1989: Geologická mapa Turčianskej kotliny 1: 50 000 [Geological map of the Turčianska kotlina Depression]. Geol. Inst. D. Štúr, Bratislava.

Gašparik J., Halouzka R., Miko O., Rakús M., Bujnovský A., Lexa J., Panáček A., Samuel O., Gašpariková A., Planderová E., Snopková P., Fendek M., Hanáček J., Motlidba I., Klukanová A., Žáková E., Horniš J. & Ondrejičková A., 1995: Vysvetlivky ku geologickej mape Turčianskej kotliny 1: 50 000 [Explanations to the Geological map of the Turčianska kotlina Depression]. Geol. Inst. D. Štúr, Bratislava, 196 p.

Gawlick H.J., Havrila M., Krystyn L., Lein R. & Mello J., 2002: Conodont colour alteration indices (CAI) in the Central Western Carpathians and the Northern Calcareous Alps – a comparison. Geologica Carpathica, 53, spec. issue, 15–17.

Gaži P., 2006: Štruktúrny výskum bradlového pásma v oblasti Zázrivskej sigmoidy [Structural investigation of the Klippen Belt in the Zázrivá sigmoid area]. Unpublished MSc. Thesis, Dept. Geol. Paleont., Comenius University, Bratislava, 70 p.

Gaži P. & Marko F., 2006: The Zázrivá fault – paleostress history and kinematics (Pieniny Klippen Belt, North Slovakia). Geolines, 20, 37–38.

Géczy J., 1990: Turčianske Teplice – ochranné pásmo, reinterpretácia geofyzikálnych prác. Manuscript report, Geofond archives, State Geol. Inst. D. Štúr, Bratislava.

Gedl P., 2008: Organic-walled dinoflagellate cyst stratigraphy of dark Middle Jurassic marine deposits of the Pieniny Klippen Belt, West Carpathians. Studia Geologica Polonica, 131, 7–227.

Gedl P., 2013: Dinoflagellate cysts from the Szlachtowa Formation (Jurassic) and adjacent deposits (Jurassic–Cretaceous) of the Grajcarek Unit at Sczawnica-Zabaniszcze (Pieniny Klippen Belt, Carpathians, Poland). Geological Quarterly, 57, 3, 485–502.

Gedl P. & Józsa Š, 2015: Early?–Middle Jurassic dinoflagellate cysts and foraminifera from the dark shale of the Pieniny Klippen Belt between Jarabina and Litmanová (Slovakia): age and palaeoenvironment. Annales Societatis Geologorum Poloniae, 85, 1, 91–122.

Geologická mapa Slovenska M 1: 50 000, 2013: Bratislava, Štátny Geologický Ústav Dionýza Štúra. Available on web: http://apl.geology.sk/gm50js

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.J. (ed.): BENTHOS '83: 2nd International Symposium on Benthic Foraminifera (Pau, April 11-15, 1983), Elf-Aquitane, ESO REP and TOTAL CFP, Pau & Bordeaux, 225–239.

GM-SYS® User`s Guide for version 4.9. 2004: Northwest Geophysical Associates Inc. Corvallis.

Golonka J., Krobicki M., Waśkowska A., Cieszkowski M. & Ślączka A., 2015: Olistostromes of the Pieniny Klippen Belt, Northern Carpathians. Geological Magazine, 152, 2, 269–286.

Golonka J., Pietch K., Marzec P., Kasperska M., Dec J., Cichostępski K. & Lasocki S., 2019: Deep structure of the Pieniny Klippen Belt in Poland. Swiss Journal of Geosciences, 112, 475–506.

Groom R.W. & Bailey R.C., 1989: Decomposition of magnetotelluric impedance tensors in the presence of local three-dimensional galvanic distortion. Journal of Geophysical Research, 94, B2, 1913–1925.

Gross P., 2008: Litostratigrafia Západných Karpát: Paleogén – podtatranská skupina [English summary: Lithostratigraphy of Western Carpathians: Paleogene – Podtatranská Group]. ŠGÚDŠ, Bratislava, 78 p.

Gross P., Köhler E. & Samuel O., 1984: Nové litostratigrafické členenie vnútrokarpatského paleogénu [English summary: A new lithostratigraphical division of the Inner-Carpathian Paleogene]. Geologické práce, Správy, 81, 103–117.

Gross P., Köhler E., Mello J., Haško J., Halouzka R. & Nagy A., 1993: Geológia južnej a východnej Oravy [English summary: Geology of southern and eastern Orava]. Geol. Inst. D. Štúr, Bratislava, 320 p.

Haas J., Mioč P., Pamić J., Tomljenović B., Árkai P., Bérczi-Mak A., Koroknai B., Kovács S. & Felgenhauer E.R., 2000: Complex structural pattern of the Alpine–Dinaridic–Pannonian triple junction. International Journal of Earth Sciences, 89, 377–389.

Handy M.R., Schmid S.M., Bousquet R., Kissling E. & Bernoulli D., 2010: Reconciling plate-tectonic reconstructions of Alpine Tethys with the geological–geophysical record of spreading and subduction in the Alps. Earth-Science Reviews, 102, 121–158.

Hansen H.J., Rasmussen K.L. & Gwozdz R., 1990: Paleomagnetic stratigraphy and iridium abundance of the Cretaceous–Tertiary boundary at Žilina, Slovakia. Geologický zborník – Geologica Carpathica, 41, 1, 23–28.

Haško J., 1975: Le membre de Kozinec – nouvelle unité stratigraphique de la succession piénine de passage de la zone des klippes (Carpathes de la Slovaquie). Geologický zborník – Geologica Carpathica, 26, 83–84.

Haško J., 1976: Czertezický vývin bradlového pásma v Zázrivej-Plešivej [English abstract: Czertezik development of the Pieniny Klippen Belt in Zázrivá-Plešivá]. Geologické práce, Správy, 65, 91–95.

Haško J., 1977: Nová geologická interpretácia poznatkov o bradle Havranský vrch a Kozinec pri Zázrivej [English abstract: New geological interpretation of data about the Havranský vrch klippe and Kozinec near Zázrivá].

Geologické práce, Správy, 68, 39–47.

Haško J., 1978a: Oravská séria – nová séria bradlového pásma Západných Karpát [English abstract: Orava series – a new series of the Pieniny Klippen Belt, Western Carpathians]. Geologické práce, Správy, 70, 115–121.

Haško J., 1978b: Tektonické pomery bradlového pásma Kysuckej vrchoviny [English abstract: Tectonics of the Klippen Belt in the Kysucká vrchovina Mountains]. Geologické práce, Správy, 70, 123–128.

Haško J. & Planderová E., 1977: Zázrivské vrstvy – nová litostratigrafická jednotka kysuckej série bradlového pásma [German summary: Die Zázrivá-Schichten – eine neue lithostratigraphische Einheit der Kysuca-Serie der Klippenzone]. Mineralia Slovaca, 9, 3, 207–212.

Haško J. & Polák M., 1978: Geologická mapa Kysuckých vrchov a Krivánskej Malej Fatry 1:50 000 [Geological map of the Kysucké vrchy and Krivánska Malá Fatra Mts]. State Geol. Inst. D. Štúr, Bratislava.

Haško J. & Polák M., 1979: Vysvetlivky ku geologickej mape Kysuckých vrchov a Krivánskej Malej Fatry 1:50 000 [English summary: Explanations to the geological map of the Kysucké vrchy Hills and Kriváň part of the Malá Fatra Mts.]. Geol. Inst. D. Štúr, Bratislava, 145 p.

Haško J. & Samuel O., 1977: Stratigrafia kriedy varínskeho úseku bradlového pásma [English summary: Stratigraphy of the Cretaceous in the Varín part of the Klippen Belt]. Geologické práce, Správy, 68, 49–67.

Havrila M., 2011: Hronikum: paleogeografia a stratigrafia (vrchný pelsón – tuval), štrukturalizácia a stavba [English summary: Hronicum: palaeogeography and stratigraphy (late Pelsonian–Tuvalian), deformation and structure]. Geologické práce, Správy, 117, 7–103.

Havrila M., Boorová D. & Havrila J., 2019: Paleogeografická schéma depozičného priestoru sedimentov reingrabenského a lunzského eventu (centrálne Západné Karpaty): rešerš, poznámky, dierkavce [English summary: Paleogeographic scheme of the Reingraben and Lunz event sediments depositional area (Central Western Carpathians): research, notes, foraminifers]. Geologické práce, Správy, 134, 3–32.

Havrila M. & Olšavský M., 2015: Správa o geologickom mapovaní vrstvového sledu Kozla medzi Turskou dolinou a údolím Porubského potoka [English abstract: Report about geological mapping of the Kozol succession between the Turská dolina and Porubský potok valleys]. Geologické práce, Správy, 127, 7–79.

Hart M.B., Hudson W., Smart C.W. & Tyszka J., 2012: A reassessment of "Globigerina bathoniana" Pazdrowa, 1969 and the palaeoceanographic significance of Jurassic planktic foraminifera from southern Poland. Journal of Micropaleontology, 31, 97–109.

Henriques M.H.P. & Canales M.L., 2013: Ammonite-benthic foraminifera turnovers across the Lower-Middle Jurassic transition in the Lusitanian Basin (Portugal). Geobios, 46, 395–408.

Hók J. & Littva J., 2018: Chtelnické súvrstvie – nová litostratigrafická jednotka sladkovodných vápencov vrchnej kriedy v Brezovských Karpatoch a Čachtických Karpatoch (západné Slovensko) [The Chtelnica Formation – a new lithostratigraphic unit of the Upper Cretaceous freshwater limestones in the Brezovské Karpaty Mts. and Čachtické Karpaty Mts. (Western Slovakia)]. Geologické práce, Správy, 132, 53–58.

Hók J., Kováč M., Rakús M., Kováč P., Nagy A., Kováčová-Slamková M., Sitár V. & Šujan M., 1998: Geologic and tectonic evolution of the Turiec depression in the Neogene. Slovak Geological Magazine, 4, 3, 165–176.

Hók J., Siman P., Frank W., Kráľ J., Kotulová J. & Rakús M., 2000: Origin and exhumation of mylonites in the Lúčanská Malá Fatra Mts., (the Western Carpathians). Slovak Geological Magazine, 6, 4, 325–334.

Hók J., Matejček A., Sýkora M., Dianiška I., Rakús M., Kráľ J., Kotulová J., Broska I., Hrdlička M., Kubiš M. & Uher P., 2002: Tektonické a regionálne geologické zhodnotenie výsledkov prieskumných prác zo štôlne Višňové – Dubná Skala [Tectonic and regional geological evaluation of results of survey in the Višňové – Dubná Skala adit]. Manuscript report, Geol. Survey Slovak Rep., Bratislava, 190 p.

Hók J., Pešková I. & Potfaj M., 2009: Litostratigrafická náplň a tektonická pozícia drietomskej jednotky (západný úsek bradlového pásma) [English summary: Lithostratigraphy and tectonic position of the Drietoma Unit (western part of the Pieniny Klippen Belt, Western Carpathians)]. Mineralia Slovaca, 41, 313–320.

Hók J., Šujan M. & Šipka F., 2014: Tectonic division of the Western Carpathians: an overview and a new approach. Acta Geologica Slovaca, 6, 2, 135–143.

Hók J., Pelech O., Teťák F., Németh Z. & Nagy A., 2019: Outline of the geology of Slovakia (W. Carpathians). Mineralia Slovaca, 51, 31–60.

Hók J., Sýkora M., Matejček A., Kotulová J. & Rakús M., 2020: Geologická stavba severozápadného okraja Lúčanskej Fatry v prieskumnej štôlni Višňové – Dubná Skala [English summary: Geological structure of the NW part of the Lúčanská Fatra Mts. in the reconnaissance gallery Višňové – Dubná Skala (Western Carpathians)]. Geologické práce, Správy, 135, 41–46.

Horwitz L., 1963: Budowa geologiczna Pienin [English summary: Geology of the Pieniny Mts. – posthumous paper. Comments by K. Birkenmajer]. Prace Institutu geologicznego, Warszawa, 38, 152 p.

Hovorka D., Ivan P., Kratochvíl M., Reichwalder P., Rojkovič I., Spišiak J. & Turanová L., 1985: Ultramafic rocks of the Western Carpathians. Geol. Inst. D. Štúr, Bratislava, 258 p.

Hradilová M., 1988: Karotážní zpráva vrtu TTŠ-1, Turčianske Teplice. Manuscript, UNIGE0, Ostrava.

Hrdlička M., 2006: Granite petrology of the Malá Fatra Mts.: Implication to the tectogenesis of collisional West-Carpathians I-type granitic suite. PhD thesis, 147 p.

Hrdlička M., Mayerová M., Nehybka J., Novotný M., Sedlák J., Huňáček F. & Viščor J., 1983: Reinterpretace profilu K-III. Manuscript report, Geofond archives, Bratislava.

Hrdlička M., Broska I., Siman P. & Košler J. 2005: Nové geochronologické údaje kryštalinika Malej Fatry [English summary: New geochronological data from granitoids of Malá Fatra crystalline basement]. Mineralia Slovaca, 37, 3, 243–245.

Hrouda F. & Chadima M., 2020: Examples of tectonic overprints of magnetic fabrics in rocks of the Bohemian Massif and Western Carpathians. International Journal of Earth Sciences, 109, 4, 1321–1336.

Hrouda F. & Potfaj M., 1993a: Magnetická anizotropie jako indikátor slabé duktilní deformace vnitrokarpatského paleogénu a magurského flyše [English summary: Magnetic anisotropy as an indicator of weak ductile deformation of the Inner Carpathian Paleogene and Magura Flysch]. Západné Karpaty, sér. Geológia, 17, 121–134.

Hrouda F. & Potfaj M., 1993b: Deformation of sediments in the post-orogenic Intra-Carpathian Paleogene Basin as indicated by magnetic anisotropy. Tectonophysics, 224, 4, 425–434.

Hrouda F., Krejčí O., Potfaj M. & Stráník Z., 2009: Magnetic fabric and weak deformation in sandstones of accretionary prisms of the Flysch and Klippen Belts of the Western Carpathians: Mostly offscraping indicated. Tectonophysics, 479, 254–270.

Ivanov M. & Kamenický L., 1957: Poznámky ku geológii a petrografii kryštalinika Malej Fatry [German summary: Bemerkungen zur Geologie und Petrographie des Kristallinikums des Gebirges Malá Fatra]. Geologické Práce, Zošit, 45, 187–212.

Ivanova D.K., Schlögl J., Tomašových A., Lathuilière B. & Golej, M. 2019: Revisiting the age of Jurassic coral bioherms in the Pieniny Klippen Belt (Western Carpathians) on the basis of benthic foraminifers. Geologica Carpathica, 70, 2, 113–134.

Jablonský J., 1978: Príspevok k poznaniu albu zliechovskej série Strážovských vrchov [English summary: Contribution to knowledge of the Albian of the Zliechov Group in the Strážovské vrchy Mts.]. In J. Vozár (ed.): Paleogeografický vývoj Západných Karpát [Paleogeographic evolution of the Western Carpathians]. Konf. Symp. Sem., GÚDŠ Bratislava, 175–187.

Jablonský J. & Marschalko R., 1992: Pre-flysch olistostromes in Central Western Carpathians, Barremian – Aptian of Krížna Nappe, Slovakia. Geologica Carpathica, 43, 15–20.

Jablonský J., Sýkora M. & Aubrecht R, 2001: Detritické Cr spinely v sedimentárnych horninách mezozoika Západných Karpát (prehľad nových poznatkov) [English summary: Detritic Cr-spinels in Mesozoic sedimentary rocks of the Western Carpathians (overview of the latest knowledge)]. Mineralia Slovaca, 33, 487–498.

Jacko S. & Janočko J., 2000: Kinematic evolution of the Central-Carpathian Paleogene Basin in the Spišská Magura region (Slovakia). Slovak Geological Magazine, 6, 4, 409–418.

Jamrichová M., Józsa Š., Aubrecht R. & Schlögl J., 2012: Lower Cretaceous palaeokarst in a klippe of the Czorsztyn Succession north of Zázrivá (Pieniny Klippen Belt, Orava sector, northern Slovakia). Acta Geologica Slovaca, 4, 75–90.

Janák M., 1994: Variscan uplift of the crystalline basement Tatra Mts., Central Western Carpathians: Evidence from ^{39}Ar /^{40}Ar laser probe dating of biotite and P-T-t paths. Geologica Carpathica, 45, 293–300.

Janák M. & Lupták B., 1997: Pressure-temperature conditions of high-grade metamorphism and migmation in the Malá Fatra crystalline complex, the Western Carpathians. Geologica Carpathica, 48, 5, 287–302.

Janák M., Plašienka D., Frey M., Cosca M., Schmidt S.Th., Lupták B. & Méres Š., 2001a: 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. Journal of Metamorphic Geology, 19, 197–216.

Janák M., Plašienka D. & Petrík I., 2001b: Excursion to the Tatra Mountains, Central Western Carpathians: Tectonometamorphic records of Variscan and Alpine orogeny. 6th meeting Czech Tectonic Studies Group “Donovaly 2001”. Geolines, 13, 141–148.

Janák M., Mikuš T., Pitoňák P. & Spišiak J., 2009: Eclogites overprinted in the granulite facies from the Ďumbier crystalline complex (Low Tatra Mountains, Western Carpathians). Geologica Carpathica, 60, 3, 193–204.

Janák M., Méres Š. & Medaris L.G. Jr., 2020: Eclogite facies metaultramafite from the Veporic Unit (Western Carpathians, Slovakia). Geologica Carpathica, 71, 3, 209–220.

Jendrejáková O., 1968: Bentonische foraminiferen des Albs der Westkarpaten. Geologický Sborník – Geologica Carpathica, 19, 2, 311–329.

Jeřábek P., Lexa O., Schulmann K. & Plašienka D., 2012: Inverse ductile thinning via lower crustal flow and fold-induced doming in the West Carpathian Eo-Alpine collisional wedge. Tectonics, 31, TC5002, doi:10.1029/2012TC003097

Józsa Š., 2019: Early Tithonian deep-water colonization by benthic foraminifera in the Magura Basin (Pieniny Klippen Belt, Western Carpathians): a clue to the origins of deep-water foraminifera. Rivista Italiana di Paleontologia e Stratigrafia, 125, 2, 401–419.

Józsa Š. & Aubrecht R., 2008: Barremian-Aptian erosion of the Kysuca-Pieniny trough margin (Pieniny Klippen Belt, Western Carpathians). Geologica Carpathica, 59, 2, 103–116.

Jurewicz E., 1994: Analiza strukturalna pienińskiego pasa skałkowego okolic Jaworek [English summary: Structural analysis of the Pieniny Klippen Belt at Jaworki, Carpathians, Poland]. Studia Geologica Polonica, 106, 7–87.

Jurewicz E., 1997: The contact between the Pieniny Klippen Belt and Magura Unit (the Małe Pieniny Mts.). Geological Quarterly, 41, 3, 315–326.

Jurewicz E., 2005: Geodynamic evolution of the Tatra Mts. and the Pieniny Klippen Belt (Western Carpathians): problems and comments. Acta Geologica Polonica, 55, 295–338.

Jurewicz E., 2018: The Šariš Transitional Zone, revealing interactions between Pieniny Klippen Belt, Outer Carpathians and European platform. Swiss Journal of Geosciences, 111, 1-2, 245–267.

Kadlečík J., Daněček O., Chudomil J., Kaňová M., Klíč M., Kolman L., Kouřil M., Malý J., Novák J., Ondrák J., Schwarz J., Viewegh J. & Zbořil A., 1988: Reflexne seizmický prieskum flyšového pásma a vnútrokarpatských jednotiek [Reflection-seismic investigation of the Flysch Belt and Inner-Carpathian units]. Manuscript report, Geofyzika Brno, arch. No 72198, Archives ŠGÚDŠ, Bratislava, 59 p.

Kamenický L., Macek J. & Krištín J., 1987: Príspevok ku petrografii a geochémii granitoidov Malej Fatry [English summary: Contribution to the petrography and geochemistry of the Malá Fatra granitoid rocks]. Mineralia Slovaca, 19, 311–324.

Kissová D., Dunkl I., Plašienka D., Frisch W. & Marschalko R., 2005: The Pieninic exotic cordillera (Andrusov Ridge) revisited: new zircon FT ages of granite pebbles from Cretaceous conglomerates of the Pieniny Klippen Belt (Western Carpathians, Slovakia). Slovak Geological Magazine, 11, 17–28.

Kočický D. & Ivanič B., 2011: Geomorfologické členenie Slovenska [Geomorphological division of Slovakia]. https://apl.geology.sk/mapportal/img/pdf/tm19a.pdf

Köhler E. & Gross P., 1994: Rekonštrukcia vrstevného sledu v pribradlovom pásme na Orave [English abstract: Reconstruction of sedimentary succession of the Periklippen belt in the Orava region]. Geologické práce, Správy, 99, 47–57.

Kohút M. & Larionov A.N., 2021: From subduction to collision: Genesis of the Variscan granitic rocks from the Tatric Superunit (Western Carpathians, Slovakia). Geologica Carpathica, 72, 96–113.

Kohút M., Kráľ J., Michalko J. & Wiegerová V., 1998: Hercýnske vychladnutie masívu Veľkej Fatry – evidencie z ^{40}K/^{40}Ar a ^{40}Ar/^{39}Ar termochronometrických minerálnych údajov a súčasný stav termochronometrie [English summary: The Hercynian cooling of the Veľká Fatra Mts. Massif – evidences from ^{40}K/^{40}Ar and ^{40}Ar/^{39}Ar thermochronometry and the current status of thermochronometry]. Mineralia Slovaca, 30, 4, 253–264.

Kohút M., Kotov A.B., Salnikova E.B. & Kovach V.P., 1999: Sr and Nd isotope geochemistry of Hercynian granitic rocks from the Western Carpathians – implication for granite genesis and crustal evolution. Geologica Carpathica, 50, 477–487.

Kohút M., Uher P., Putiš M., Ondrejka M., Sergeev S., Larionov A. & Paderin I., 2009: SHRIMP U-Th-Pb zircon dating of the granitoid massifs in the Malé Karpaty Mountains (Western Carpathians): evidence of Meso-Hercynian successive S- to I-type granitic magmatism. Geologica Carpathica, 60, 345–350.

Korikovsky S.P., Janák M. & Lupták B., 1998: Phase relations in olivine-orthopyroxene-chlorite-spinel-hornblende metaultramafics from the Malá Fatra Mts., Western Carpathians. Geologica Carpathica, 49, 369–376.

Kováč M., Hók J., Minár J., Vojtko R., Bielik M., Pipík R., Rakús M., Kráľ J., Šujan M. & Králiková S., 2011: Neogene and Quaternary development of the Turiec Basin and landscape in its catchment: a tentative mass balance model. Geologica Carpathica, 62, 4, 361–379.

Kováč M., Plašienka D., Soták J., Vojtko R., Oszczypko N., Less Gy., Ćosović V., Fügenschuh B. & Králiková S. 2016: Paleogene palaeogeography and basin evolution of the Western Carpathians, Northern Pannonian domain and adjoining areas. Global and Planetary Change, 140, 9–27.

Kováč M., Márton E., Oszczypko N., Vojtko R., Hók J., Králiková S., Plašienka D., Klučiar T., Hudáčková N. & Oszczypko-Clowes M., 2017: Neogene palaeogeography and basin evolution of the Western Carpathians, Northern Pannonian domain and adjoining areas. Global and Planetary Change, 155, 133–154.

Kováč, P. 1995: Stredoslovenské zlomové pámo a jeho postavenie počas terciéneho vývoja Západných Karpát [Central Slovakian fault zone and its role during the Tertiary evolution of the Western Carpathians]. Unpublished PhD Thesis, Dept. Geol. Palaeontol., Comenius University in Bratislava.

Kováč P. & Havrila M., 1998: Inner structure of Hronicum. Slovak Geological Magazine, 4, 275–280.

Kováč P. & Hók J., 1993: The Central Slovak Fault System – the field evidence of a strike slip. Geologica Carpathica, 44, 3, 155–159.

Kováč P. & Hók J., 1996: Tertiary development of the western part of Klippen Belt. Slovak Geological Magazine, 2/96, 137–149.

Kozur H., 1991: The evolution of the Meliata-Hallstatt ocean and its significance for the early evolution of the Eastern Alps and Western Carpathians. Palaeogeography, Palaeoclimatology, Palaeocology, 87, 109–135.

Kráľ J., 1992: The sketch of the isotope evolution of Sr in the Tatric and Veporic crystalline complexes, Mineralia Slovaca, 24, 197–208.

Kráľ J., 1994: Strontium isotopes in granitic rocks of the Western Carpathians. Mitteilungen der Österreichischen Geologischen Gesellschaft, 86, 75–81.

Králiková S., Vojtko R., Andriessen P., Kováč M., Fügenschuh B., Hók J. & Minár J., 2014: Late Cretaceous–Cenozoic thermal evolution of the northern part of the Central Western Carpathians (Slovakia): revealed by zircon and apatite fission track thermochronology. Tectonophysics, 615-616, 142–153.

Králiková S., Vojtko R., Hók J., Fügenschuh B. & Kováč M., 2016: Low-temperature constraints on the Alpine thermal evolution of the Western Carpathian basement rock complexes. Journal of Structural Geology, 91, 144–160.

Krawczyk A.J., Muszyński M. & Słomka T., 1987: Okruchy skal w psamitach formacji szlachtowskiej pienińskiego pasa skałkowego [English summary: Exotic rock fragments from psammitic roks of the Szlachtowa Formation (Jurassic flysch) of the Pieniny Klippen Belt, Carpathians]. Studia Geologica Polonica, 92, 75–86.

Krobicki M., 1996: Valanginian (Early Cretaceous) brachiopods of the Spisz Limestone Formation, Pieniny Klippen Belt, Polish Carpathians: their stratigraphic ranges and palaeoenvironment. Studia Geologica Polonica, 109, 87–102.

Krobicki M., 2009: Bajoska tektonika synsedymentacyjna i jej znaczenie w jurajskiej ewolucji pienińskiego basenu skałkowego [English abstract: Bajocian synsedimentary tectonics and its significance in Jurassic evolution of the Pieniny Klippen Basin]. Geologia, 35, 3/1, 65–78.

Krobicki M., 2018: Berriasian peperites in the Ukrainian Carpathians – their biostratigraphical control and sedimentological significance. JK2018 – December 5-7, 2018, Muséum d'Histoire naturelle de Genève, 31–36.

Krobicki M. & Wierzbowski A., 1996: New data on stratigraphy of the Spisz Limestone Formation (Valanginian) and the brachiopod succession in the lowermost Cretaceous of the Pieniny Klippen Belt, Carpathians, Poland. Studia Geologica Polonica, 109, 53–67.

Krobicki M. & Wierzbowski A. 2004: Pozycja stratygraficzna i paleogeograficzne znaczenie bajoskich wapieni krynoidowych w ewolucji pienińskiego basenu skałkowego [English abstract: Stratigraphic position of the Bajocian crinoidal limestones and their palaeogeographic significance in evolution of the Pieniny Klippen Basin]. Tomy Jurajskie, 2, 69–82.

Krobicki M., Kruglov S.S., Matyja B.A., Wierzbowski A., Aubrecht R., Bubniak A. & Bubniak I. 2003: Relation between Jurassic klippen successions in the Polish and Ukrainian parts of the Pieniny Klippen Belt. Mineralia Slovaca, 35, 1, 56–58.

Krobicki M., Poprawa P., Nejbert K., Armstrong R. & Pécskay Z., 2018: New geochemical and geochronological data of magmatic and sub-volcanic exotic rocks from the Late Cretaceous and Paleogene gravelstones (Pieniny Klippen Belt, Carpathians, Poland). In Šujan M., Csibri T., Kiss P. & Rybár S. (eds): Environmental, Structural and Stratigraphical Evolution of the Western Carpathians. 11th ESSEWECA Conference, Abstract Book, November 29– 30, 2018, Bratislava, Slovakia, 54–55.

Krobicki M., Feldman-Olszewska A., Hnylko O. & Iwańczuk J., 2019: Peperites and other volcano-sedimentary deposits (lowermost Cretaceous, Berriasian) of the Ukrainian Carpathians. In Broska I., Kohút M. &

Tomašových A. (eds): Proceedings of the Geologica Carpathica 70 Conference, Smolenice Castle, Slovakia, October 9–11, 2019, 146–150.

Kullmanová A. & Gašpariková V., 1982: Vrchnokriedové sedimenty v severnej časti pohoria Považský Inovec [German summary: Oberkretazische Sedimente im nördlichen Teil des Považský Inovec – Gebirges]. Geologické práce, Správy, 78, 85–95.

Leško B. & Samuel O., 1968: Geológia východoslovenského flyšu [English summary: The geology of the East Slovakian Flysch]. Vyd. Slov. akad. vied, 280 s.

Leško B., Ďurkovič T., Gašpariková V., Kullmanová A. & Samuel O., 1978: Nové poznatky o geológii Myjavskej pahorkatiny na základe vrtu Lubina-1 [English summary: New data on geology of the Myjavská pahorkatina upland based on the results of the drill hole Lubina-1]. Geologické Práce, Správy, 70, 35–56.

Lexa J., Bezák V., Elečko M., Mello J., Polák M., Potfaj M. & Vozár J. (eds), 2000: Geological map of the Western Carpathians and adjacent areas, scale 1: 500,000. State Geol. Inst. D. Štúr, Bratislava.

Łoziński J., 1956: Minerały ciężkie piaskowców aalenu fliszowego w pienińskim pasie skałkowym [English summary: Heavy minerals in Flysch Aalenian sandstones from the Pieniny Klippen-Belt. Conspectus, 10–13]. Acta Geologica Polonica, 6, 1, 15–23.

Ludwiniak M., 2018: Miocene transpression effects at the boundary of Central Carpathian Paleogene Basin and Pieniny Klippen Belt: examples from Polish-Slovakian borderland. Geology, Geophysics & Environment, 44, 1, 91–110.

Ludwiniak M., Śmigielski M., Kowalczyk S., Łoziński M., Czarniecka U. & Lewińska L., 2019: The intramontane Orava Basin – evidence of large-scale Miocene to Quaternary sinistral wrenching in the Alpine-Carpathian-Pannonian area. Acta Geologica Polonica, 69, 339–386.

Macek J., Cambel B., Kamenický L. & Petrík I. 1982: Documentation and basic characteristic of granitoid rock samples of the West Carpathians. Geologický zborník – Geologica Carpathica, 33, 5, 601–621.

Madzin J., Sýkora M. & Soták J., 2014: Stratigraphic position of alkaline volcanic rocks in the autochthonous cover of the High-Tatric Unit (Western Tatra Mts., Central Western Carpathians, Slovakia). Geological Quarterly, 58, 1, 163–180.

Madzin J., Márton E., Starek D. & Mikuš T., 2021: Magnetic fabrics in the turbidite deposits of the Central Carpathian Paleogene Basin in relation to sedimentary and tectonic fabric elements. Geologica Carpathica, 72, 2, 134–154.

Maheľ M., 1980: Pribradlová zóna: charakteristika a význam [English summary: The Peri-klippen zone: nearer characterization and significance]. Mineralia Slovaca, 12, 3, 193–207.

Maheľ M., 1981: Island character of the Klippen Belt; Vahicum – continuation of Southern Penninicum in West Carpathians. Geologický zborník – Geologica Carpathica, 32, 3, 293–305.

Maheľ M., 1983: Návrh na novú tektonickú nomenklatúru základných tektonických elementov Západných Karpát [English summary: Proposal of the new tectonic nomenclature of basic tectonic elements in the West Carpathians]. Mineralia Slovaca, 15, 6, 559–565.

Maheľ M., 1985: Neskoroalpínska tektonika Strážovských vrchov a jej širší význam [English summary: Late Alpine tectonics of the Strážovské vrchy Mts. and its wider significance]. Západné Karpaty, sér. geológia, 10, 7–37.

Maheľ M., 1989: Bradlové pásmo z aspektu geodynamického modelu [English summary: The Klippen Belt from the aspect of the geodynamic model]. Mineralia Slovaca, 21, 99–108.

Maheľ M., Kamenický J., Fusán O. & Matějka A., 1967: Regionální geologie ČSSR, díl II - Západní Karpaty, svazek 2 [Regional geology of Czechoslovakia]. Academia, Praha, 486 s.

Majdán M., Putiš M. & Ondrejka M., 2004: Orthogneisses of the Veľká Lúčanská Massif in the Malá Fatra Mts. Mineralia Slovaca, 36, 157–168.

Marko F., 2003: Slickensides and related paleostress field in the western part of the Pieniny Klippen Belt. In Golonka J. & Lewandowski M. (eds): Geology, Geophysics, Geothermis and deep structure of the Western Carpathians and their basement. Publications of the Institute of Geophysics, Polish Academy of Sciences. Monographic volume 28 (363), Warszawa, Poland, 145–146.

Marko F., Plašienka D. & Fodor L., 1995: Meso-Cenozoic tectonic stress fields within the Alpine-Carpathian transition zone: a review. Geologica Carpathica, 46, 19–27.

Marko F., Vojtko R., Plašienka D., Sliva Ľ., Jablonský J., Reichwalder P. & Starek D., 2005: A contribution to the tectonics of the Periklippen zone near Zázrivá (Western Carpathians). Slovak Geological Magazine, 11, 37–43.

Marko F., Andriessen P.A.M., Tomek Č., Bezák V., Fojtíková L., Bošanský M., Piovarči M. & Reichwalder P., 2017: Carpathian shear corridor – A strike-slip boundary of an extruded crustal segment. Tectonophysics, 703-704, 119–134.

Marschalko R., 1986: Vývoj a geotektonický význam kriedového flyšu bradlového pásma [English summary: Evolution and geotectonic significance of the Klippen Belt Cretaceous flysch in the Carpathian megastructure]. Veda Publ., 140 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. Conference, Introductory articles to the excursion. Geol. Survey Slovak Rep., Bratislava, 71–78.

Marschalko R., Haško J. & Samuel O., 1979: Záskalské brekcie a proces vzniku olistostómov [English summary: Záskalie breccias and genesis of olistostromes]. Geologické práce, Správy 73, 75–88.

Márton E., Jeleńska M., Tokarski K.A., Soták J., Kováč M. & Spišiak J., 2009: Current independent paleomagnetic declinations in flysch basins: a case study from the Inner Carpathians. Geodinamica Acta, 22, 73–82.

Márton E., Grabowski J., Plašienka D., Túnyi I., Krobicki M., Haas J. & Pethe M., 2013: New paleomagnetic results from the Upper Cretaceous red marls of the Pieniny Klippen Belt, Western Carpathians: Evidence for general CCW rotation and implications for the origin of the structural arc formation. Tectonophysics, 592, 1–13.

Márton E., Grabowski J., Tokarski A. & Túnyi I., 2015: Palaeomagnetic results from the fold and thrust belt of the Western Carpathians: an overview. In Pueyo E.L., Cifelli F., Sussman A.J. & Oliva-Urcia B. (eds): Palaeomagnetism in fold and thrust belts: new perspectives. Geological Society, London, Spec. Publ., 425, 7–36.

Marzec P., Golonka J., Pietch K., Kasperska M., Dec J., Cichostępski K. & Lasocki S., 2019: Seismic imaging of mélanges; Pieniny Klippen Belt case study. Journal of the Geological Society, London, 176, 629–646.

Matějka A., 1931: La partie orientale de la Malá Fatra. In Matějka A. & Andrusov D. (eds): Guide des excursions dans les Carpathes occidentales. Knihovna Státního geologického ústavu ČSR, 13A, 303–316.

Mattioli E. & Erba E., 1999: Synthesis of calcareous nannofossil events in tethyan Lower and Middle Jurassic successions. Rivista Italiana di Paleontologia e Stratigrafia 105, 3, 343–376.

McNeice G.W. & Jones A.G., 2001: Multisite, multifrequency tensor decomposition of magnetotelluric data. Geophysics, 66, 1, 158–173.

Menhert K.R., 1968: Migmatites and the origin of granitic rocks. Elsevier Publ. Comp., 388 p.

Méres Š., Sýkora M., Plašienka D. & Aubrecht R., 2012: Pôvod granátov zo siliciklastických sedimentov szlachtowského súvrstvia (stredná jura, bradlové pásmo, Zázriva, laz Sihla) [Origin of garnets from siliciclastic sediments of the Szlachtowa Formation (Middle Jurassic, Klippen Blet, Zázrivá, settlement Sihla)]. In Jurkovič Ľ., Slaninka I. & Ďurža O. (eds): Geochémia 2012. Konf. Symp. Sem., Geol. Ústav D. Štúra, Bratislava, 120–123.

Michalík J., 2007: Sedimentary rock record and microfacies indicators of the latest Triassic to mid-Cretaceous tensional development of the Zliechov Basin (Central Western Carpathians). Geologica Carpathica, 58, 443–453.

Michalík J. & Soták J. 1990: Lower Cretaceous shallow marine buildups in the Western Carpathians and their relationship to pelagic facies. Cretaceous Research, 11, 211–227.

Michalík J. & Vašíček Z. 1987: Geológia a stratigrafia ložiska spodnokriedových vápencov Butkov (manínska jednotka, stredné Považie) [English summary: Geology and stratigraphy of the Butkov Lower Cretaceous limestone deposits, Manín Unit, Middle Váh Valley (Western Slovakia)]. Mineralia Slovaca, 19, 115–134.

Michalík J., Vašíček Z., Peterčáková M. & Soták J., 1990: Ku spodnokriedovej bio- a litostratigrafii tatrickej spodnokriedovej sekvencie v Zázrivskej doline (Bralo pri Párnici, Malá Fatra) [English summary: To the Lower Cretaceous bio- and lithostratigraphy of the Tatric Lower Cretaceous sequence in Zázrivá Valley, Malá Fatra Mts. (Central West Carpathians)]. Knihovnička Zemního plynu a nafty, 9b, 7–22.

Michalík J., Reháková D., Halásová E. & Lintnerová O., 2009: The Brodno section – a potential stratotype of the Jurassic/Cretaceous boundary (Western Carpathians). Geologica Carpathica, 60, 3, 213–232.

Michalík J., Lintnerová O., Reháková D., Boorová D. & Šimo V. 2012: Early Cretaceous sedimentary evolution of a pelagic basin margin (the Manín Unit, central Western Carpathians, Slovakia). Cretaceous Research, 38, 68–79.

Mišík M., 1968: Traces of submarine slumping and evidences of hypersaline environment in the Middle Triassic of the West Carpathian core mountains. Geologický zborník – Geologica Carpathica, 19, 205–224.

Mišík M., 1979: Sedimentologické a mikrofaciálne štúdium jury bradla vršateckého hradu (neptunické dajky, biohermný vývoj oxfordu) [English summary: Sedimentological and microfacial study in the Jurassic of the Vršatec (castle) klippe (neptunic dykes, Oxfordian bioherm facies)]. Západné Karpaty, sér. Geológia, 5, 7–56.

Mišík M., 1994: The Czorsztyn submarine ridge (Jurassic – Lower Cretaceous, Pieniny Klippen Belt): An example of a pelagic swell. Mitteilungen der Österreichischen Geologischen Gesellschaft, 86 (1993), 133–140.

Mišík M. & Jablonský J., 2000: Lower Triassic quartzites of the Western Carpathians: transport directions, source of clastics. Geologica Carpathica, 51, 251–264.

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: Pieninský exotický chrbát rekonštruovaný z valúnov karbonátových hornín kriedových zlepencov bradlového pásma a manínskej jednotky [German summary: Der pieninische exotische Rücken, rekonstruiert aus Geröllen karbonatischer Gesteine kretazischer Konglomerate der Klippenzone und der Manín-Einheit]. Západné Karpaty, sér. Geológia, 7, 7–111.

Mišík M., Mock R. & Sýkora M., 1977: Die Trias der Klippen-Zone der Karpaten. Geologický zborník – Geologica Carpathica, 28, 27–69.

Mišík M., Jablonský J., Mock R. & Sýkora M., 1981: Konglomerate mit exotischen Material in dem Alb der Zentralen Westkarpaten – paläogeographische und tektonische Interpretation. Acta Geologica et Geographica Universitatis Comenianae, Geologica, 37, 5–55.

Mišík M., Sýkora M. & Aubrecht R., 1994a: Middle Jurassic scarp breccias with clefts filled by Oxfordian and Valanginian-Hauterivian sediments, Krasín near Dolná Súča (Pieniny Klippen Belt). Geologica Carpathica, 45, 6, 343–356.

Mišík M., Siblík M., Sýkora M. & Aubrecht R., 1994b: Jurassic brachiopods and sedimentological study of the Babiná klippe near Bohunice (Czorsztyn Unit, Pieniny Klippen Belt). Mineralia Slovaca, 26, 4, 255–266.

Mišík M., Aubrecht R., Sýkora M. & Ožvoldová L., 1996: New lithostratigraphic units in the Klippen Belt. Slovak Geological Magazine, 1/1996, 17–19.

Molčan Matejová M., 2019: Geologická stavba oravského úseku pieninského bradlového pásma [English abstract: Geology of the Orava part of the Pieniny Klippen Belt]. Unpublished PhD. Thesis, Dept. Geol. Paleont., Comenius University, Bratislava, 114 p.

Molčan Matejová M., Józsa Š., Halásová E. & Aubrecht R., 2019: Interpretation of the geological structure of an atypical klippe in the Orava sector of the Pieniny Klippen Belt near Revišné. Acta Geologica Slovaca, 11, 2, 75–89.

Morgiel J. & Olszewska B., 1981: Biostratigraphy of the Polish External Carpathians based on agglutinated foraminifera. Micropaleontology, 27, 1, 1–30.

Narr W. & Suppe J., 1994: Kinematics of basement-involved compressive structures. American Journal of Science, 294, 802–860.

Neagu T., 2011: Uvigerammina MAJZON, 1943 (agglutinated foraminifera, morpho-systematic considerations). Rev. Roum. Géologie, 55, 31–39.

Nemčok J., 1971: Prejavy ilýrskej fázy vrásnenia vo flyši východného Slovenska [English summary: Results of Illyrian folding phase in East-Slovakian Flysch]. Geologické práce, Správy, 57, 369–378.

Nemčok J., 1980: Non-traditional view of East-Slovakian Klippen Belt. Geologický zborník – Geologica Carpathica, 31, 563–568.

Nemčok M., 1993: Transition from convergence to escape: field evidence from the West Carpathians. Tectonophysics, 217, 117–142.

Nemčok M., 1994: Deformation sequence in the Oravská Lesná area, Flysch Belt of the Western Carpathians. Geologica Carpathica, 45, 3, 185–191.

Nemčok M. & Nemčok J., 1994: Late Cretaceous deformation of the Pieniny Klippen Belt, West Carpathians. Tectonophysics, 239, 81–109.

Nemčok M. & Nemčok J., 1998: Dynamics and kinematics of the Cirocha, Trangoška and Zázrivá strike-slip faults, Western Carpathians. Geologica Carpathica, 49, 2, 85–98.

Nemčok J., Kullmanová A. & Ďurkovič T., 1989: Vývoj a stratigrafické postavenie gregorianskych brekcií bradlového pásma na východnom Slovensku [English summary: Facies and stratigraphical analyses of Gregorianka breccias in Klippen Belt of East Slovakia]. Geologické práce, Správy, 89, 11–37.

Nemčok M., Houghton J.J. & Coward M.P., 1998: Strain partitioning along the western margin of the Carpathians. Tectonophysics, 292, 119–143.

Neumayr M., 1871: Jurastudien. 5. Das Pieninische Klippenzug. Jahrbuch der kaiserlich-königlichen geologischen Reichsanstalt, 21, 4, 451–536.

O'Dogherty L., Goričan Š. & Gawlick H-J., 2017: Middle and Late Jurassic radiolarians from the Neotethys suture in the Eastern Alps. Journal of Paleontology, 91, 1, 25–72.

Olšavský M., 2008: Litostratigrafia a sedimentogenéza vrchnopaleozoických súvrství v severnej časti Považského Inovca [English summary: Lithostratigraphy and sedimentogenesis of the Upper Paleozoic Formations in the northern part of the Považský Inovec Mts. (Western Carpathians, Slovakia)]. Mineralia Slovaca, 40, 1, 1–16.

Olszewska B., 1997: Foraminiferal biostratigraphy of the Polish Outer Carpathians: a record of basin geohistory. Annales Societatis Geologorum Poloniae, 67, 325–337.

Ondrášik R., Putiš M., Gajdoš V., Sulák M. & Durmeková T., 2009: Blastomylonitovo-kataklazitové zóny a ich vplyv na svahové deformácie v Lúčanskej Fatre [English summary: Blastomylonitic-cataclastic zones and their influence on slope deformations in the Lúčanská Fatra Mts.]. Mineralia Slovaca, 41, 395–406.

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, 25, 89–113.

Oszczypko N., Salata D. & Krobicki M., 2012a: Early Cretaceous intra-plate volcanism in the Pieniny Klippen Belt – a case study of the Velykyi Kamenets'/Vilkhivchyk (Ukraine) and the Biała Woda (Poland) sections. Geological Quarterly, 56, 4, 629–648.

Oszczypko N., Olszewska B. & Malata E., 2012b: Cretaceous (Aptian/Albian – ?Cenomanian) age of "black flysch" and adjacent deposits of the Grajcarek thrust-sheets in the Małe Pieniny Mts. (Pieniny Klippen Belt, Polish Outer Carpathians). Geological Quarterly, 56, 411–440.

Ožvoldová L., 1988: Radiolarian associations from radiolarites of the Kysuca Succession of the Klippen Belt in the vicinity of Myjava-Turá Lúka (West Carpathians). Geologický zborník – Geologica Carpathica, 39, 3, 369–392.

Ožvoldová L., 1998: Middle Jurassic radiolarian assemblages from radiolarites of the Silica Nappe (Slovak Karst, Western Carpathians). Geologica Carpathica, 49, 4, 289–296.

Ožvoldová L. & Frantová L., 1997: Jurassic radiolarians from the eastern part of the Pieniny Klippen Belt (Western Carpathians). Geologica Carpathica, 48, 1, 49–61.

Panáček A., Šefara J., Filo M., Stránska M., Filo M., Kubeš P., Halmešová S., Novák J., Muška P., Steiner A., Gašparík J., Gorek J., Miko O., Rakús M., Havrila M., Polák M., Bujnovský A., Halouzka R., Pivko D., Medo S., Vrábľová D., Rosová M. & Kandrík M., 1991: Mapa geofyzikálnych indícií a interpretácií [Map of geophysical indications and interpretations]. Manuscript, Geofond archives, Bratislava.

Pašteka R., Zahorec P., Mikuška J., Szalaiová V., Papčo J., Krajňák M., Kušnirák D., Pánisová J., Vajda P. & Bielik M., 2014: Recalculation of regional and detailed gravity database from Slovak Republic and qualitative interpretation of new generation Bouguer anomaly map. Geophysical Research Abstracts, 16, EGU2014-9439.

Pašteka R., Záhorec P., Kušnirák D., Bošanský M., Papčo J., Marušiak I., Mikuška J. & Bielik M., 2017: High resolution Slovak Bouguer gravity anomaly map and its enhanced derivative transformations: new possibilities for interpretation of anomalous gravity fields. Contributions to Geophysics and Geodesy, 47/2, 81–94.

Pečeňa Ľ. & Vojtko R., 2011: Nové poznatky o geologickej stavbe fatrickej jednotky v okolí Valaskej Belej (Strážovské vrchy, Západné Karpaty) [New knowledge about the geological setting of the Fatric Unit near Valaská Belá village (English summary: Strážovské vrchy Mts., Western Carpathians)]. Mineralia Slovaca, 43, 19–30.

Pelech O. 2015: Kinematická analýza tektonických jednotiek Považského Inovca [Kinematic analysis of tectonic units in the Považský Inovec Mts]. Unpublished PhD thesis, Dept. Geol. Palaeontol., Comenius Univ. Bratislava.

Pelech O. & Olšavský M., 2018: Post-early Eocene backthrusting in the northeastern Strážovské vrchy Mts. (Western Carpathians). Mineralia Slovaca, 50, 149–158.

Pelech O., Hók J., Havrila M. & Pešková I., 2016: Structural position of the Upper Cretaceous sediments in the Považský Inovec Mts. (Western Carpathians). Acta Geologica Slovaca, 8, 1, 43–58.

Pelech O., Vozárová A., Uher P., Petrík I., Plašienka D. & Rodionov N., 2017a: Late Permian age of volcanic dykes in the crystalline basement of the Považský Inovec Mts. (Western Carpathians): U–Th–Pb zircon SHRIMP and monazite chemical dating. Geologica Carpathica, 68, 6, 530–542.

Pelech O., Hók J. & Józsa Š., 2017b: Turonian–Santonian sediments in the Tatricum of the Považský Inovec Mts. (Internal Western Carpathians, Slovakia). Austrian Journal of Earth Sciences, 110, 1, 21–35.

Pelech O., Józsa Š. & Fajdek P., 2018: Fold deformation of the Fatricum – a case study from the Banka section (Považský Inovec Mts., Slovakia). Mineralia Slovaca, 50, 25–36.

Pešková I., Vojtko R., Starek D. & Sliva Ľ., 2009: Late Eocene to Quaternary deformation and stress field evolution of the Orava region (Western Carpathians). Acta Geologica Polonica, 59, 1, 73–91.

Pešková I., Hók J., Potfaj M. & Vojtko R., 2012: Štruktúrna interpretácia varínskeho a oravského úseku bradlového pásma [English abstract: Structural interpretation of the Varín and Orava segment of the Klippen Belt]. Geologické práce, Správy, 120, 51–64.

Petrík I. & Kohút M., 1997: The evolution of granitoid magmatism during the Hercynian orogen in the Western Carpathians. In Grecula P., Hovorka D. & Putiš M. (eds): Geological Evolution of the Western Carpathians. Mineralia Slovaca, Monography, 235–252.

Petrík I., Broska I. & Uher P., 1994: Evolution of the Western Carpathian granite magmatism: age, source rock, geotectonic setting and relation to the variscan structure. Geologica Carpathica, 45, 5, 283–291.

Picha F.J., Stráník Z. & Krejčí O., 2006: Geology and hydrocarbon resources of the Outer Western Carpathians and their foreland, Czech Republic. In Golonka J. & Picha F.J. (eds): The Carpathians and their foreland: Geology and hydrocarbon resources. AAPG Memoir, 84, 49–175.

Pivko D., 1990: Geologická stavba juhovýchodného úpätia Malej Fatry [English summery: Geological structure of the south-eastern foothills of the Malá Fatra Mts.]. Geologické práce, Správy, 91, 33–39.

Plašienka D., 1990: Regionálne strižné a transpresné zóny v tatriku Malých Karpát [English summary: Regional shear and transpression zones in the Tatric unit of the Little Carpathians]. Mineralia Slovaca, 22, 55–62.

Plašienka D., 1991: Mesozoic tectonic evolution of the epi-Variscan continental crust of the Western Carpathians – a tentative model. Mineralia Slovaca, 23, 447–457.

Plašienka, D., 1995a: 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. Geologica Carpathica, 46, 101–112.

Plašienka D., 1995b: Passive and active margin history of the northern Tatricum (Western Carpathians, Slovakia). Geologische Rundschau, 84, 748–760.

Plašienka D., 1995c: Pôvod a štruktúrna pozícia vrchnokriedových sedimentov v severnej časti Považského Inovca. Druhá časť: Štruktúrna geológia a paleotektonická rekonštrukcia [English summary: Origin and structural position of the Upper Cretaceous sediments in the northern part of the Považský Inovec Mts. Part 2: Structural geology and paleotectonic reconstruction]. Mineralia Slovaca, 27, 179–192.

Plašienka D., 1995d: Cleavages and folds in changing tectonic regimes: The Veľký Bok Mesozoic cover unit of the Veporicum (Nízke Tatry Mts., Central Western Carpathians). Slovak Geological Magazine, 2/95, 97–113.

Plašienka D., 2003a: Dynamics of Mesozoic pre-orogenic rifting in the Western Carpathians. Mitteilungen der Österreichischen Geologischen Gesellschaft, 94 (2001), 79–98.

Plašienka D., 2003b: Development of basement-involved fold and thrust structures exemplified by the Tatric-Fatric-Veporic nappe system of the Western Carpathians. Geodinamica Acta, 16, 21–38.

Plašienka D., 2012a: Jurassic syn-rift and Cretaceous syn-orogenic, coarse-grained deposits related to opening and closure of the Vahic (South Penninic) Ocean in the Western Carpathians – an overview. Geological Quarterly, 56, 601–628.

Plašienka D., 2012b: Early stages of structural evolution of the Carpathian Klippen Belt (Slovakian Pieniny sector). Mineralia Slovaca, 44, 1–16.

Plašienka D., 2018a: Continuity and episodicity in the early Alpine tectonic evolution of the Western Carpathians: How large-scale processes are expressed by the orogenic architecture and rock record data. Tectonics, 37, 7, 2029–2079.

Plašienka D., 2018b: The Carpathian Klippen Belt and types of its klippen – an attempt at a genetic classification. Mineralia Slovaca, 49, 1, 1–24.

Plašienka D., 2019: Linkage of the Manín and Klape units with the Pieniny Klippen Belt and Central Western Carpathians: balancing the ambiguity. Geologica Carpathica, 70, 1, 35–61.

Plašienka D. & Marko F., 1993: Geologická stavba strednej časti Považského Inovca [English summary: Geological structure of the middle part of the Považský Inovec Mts. (Western Carpathians)]. Mineralia Slovaca, 25, 11–22.

Plašienka D. & Mikuš M., 2010: Geologická stavba pieninského a šarišského úseku bradlového pásma medzi Litmanovou a Drienicou na východnom Slovensku [English summary: Geological structure of the Pieniny and Šariš sectors of the Klippen Belt between the Litmanová and Drienica villages in eastern Slovakia]. Mineralia Slovaca, 42, 155–178.

Plašienka D. & Soták J., 2015: Evolution of Late Cretaceous–Palaeogene synorogenic basins in the Pieniny Klippen Belt and adjacent zones (Western Carpathians, Slovakia): tectonic controls over a growing orogenic wedge. Annales Societatis Geologorum Poloniae, 85, 1, 43–76.

Plašienka D., Michalík J., Gross P. & Putiš M., 1991: Paleotectonic evolution of the Malé Karpaty Mts. – an overview. Geologica Carpathica, 42, 195–208.

Plašienka D., Korikovsky S.P. & Hacura A., 1993: Anchizonal Alpine metamorphism of Tatric cover sediments in the Malé Karpaty Mts. (Western Carpathians). Geologica Carpathica, 44, 365–371.

Plašienka D., Marschalko R., Soták J., Uher P. & Peterčáková M., 1994: Pôvod a štruktúrne postavenie vrchnokriedových sedimentov v severnej časti Považského Inovca. Prvá časť: Litostratigrafia a sedimentológia [English summary: Origin and structural position of Upper Cretaceous sediments in the northern part of the Považský Inovec Mts. Part 1: Lithostratigraphy and sedimentology]. Mineralia Slovaca, 26, 311–334.

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 Slovaca, 29, 173–184.

Plašienka D., Soták J., Jamrichová M., Halásová E., Pivko D., Józsa Š., Madzin J. & Mikuš V., 2012: Structure and evolution of the Pieniny Klippen Belt demonstrated along a section between Jarabina and Litmanová villages in Eastern Slovakia. Mineralia Slovaca, 44, 17–38.

Plašienka D., Józsa Š., Gedl P. & Madzin J., 2013: Fault contact of the Pieniny Klippen Belt with the Central Carpathian Paleogene Basin (Western Carpathians): new data from a unique temporary exposure in Ľutina village (Eastern Slovakia). Geologica Carpathica, 64, 2, 165–168.

Plašienka D., Michalík J., Soták J. & Aubrecht R., 2017: Discussion of "Olistostromes of the Pieniny Klippen Belt, Northern Carpathians". Geological Magazine, 154, 1, 187–192.

Plašienka D., Šimonová V. & Bučová J., 2018: Nucleation and amplification of doubly-plunging anticlines – the Butkov pericline case study (Manín Unit, Western Carpathians). Geologica Carpathica, 69, 4, 165–181.

Plašienka D., Méres Š., Ivan P., Sýkora M., Soták J., Lačný A., Aubrecht R., Bellová S. & Potočný T., 2019: Meliatic blueschists and their detritus in Cretaceous sediments: New data constraining tectonic evolution of the West Carpathians. Swiss Journal of Geosciences, 112, 1, 55–81.

Plašienka D., Bučová J. & Šimonová V., 2020: Variable structural styles and tectonic evolution of an ancient backstop boundary – the Pieniny Klippen Belt of the Western Carpathians. International Journal of Earth Sciences, 109, 4, 1355–1376.

Polák M., 1975: Poznámky k tektonickej stavbe horskej skupiny Veľkého Rozsutca Malej Fatry [English abstract: Notes to the tectonic structure of the Veľký Rozsutec mountain group in the Malá Fatra Mts.]. Geologické práce, Správy, 63, 85–90.

Polák M., 1976: Litológia, mikrofácie a dolomitizácia stredného triasu obalovej série Malej Fatry [English abstract: Lithology, microfacies and dolomitization of the Middle Triassic of the Tatrides in the Malá Fatra Mts.]. Geologické práce, Správy, 65, 163–169.

Polák M., 1978: Jura tatríd Malej Magury, Malej a Veľkej Fatry (litológia a paleogeografia) [English abstract: Jurassic of Tatrides of the Malá Magura, Malá and Veľká Fatra Mts. (lithology and paleogeography)]. Geologické práce, Správy, 70, 91–114.

Polák M., 1979: Geologické profily Krivánskou Malou Fatrou [English summary: Geological profiles through the Malá Fatra Mts.]. In Maheľ M. (ed.): Tektonické profily Západných Karpát [Tectonic profiles through the Qwest Carpathians]. Konf., Symp., Sem., GÚDŠ, Bratislava, 77–84.

Polák M. & Bujnovský A., 1979: The Lučivná formation (New designation of a formal lithostratigraphic unit of the Lower Cretaceous of envelope groups in the West Carpathians). Geologické práce, Správy, 73, 61–70.

Polák M. & Ondrejičková A., 1993: Lithology, microfacies and biostratigraphy of radiolarian limestones, radiolarites in the Krížna nappe of the Western Carpathians. Mineralia Slovaca, 25, 391–410.

Polák M. & Ondrejičková A., 1995: Lithostratigraphy of radiolarian limestones and radiolarites of the envelope sequence in the Veľká Fatra Mts. Slovak Geological Magazine, 2/95, 153–158.

Polák M. & Rakús M., 1973: Le Lias de la nappe de la Krížna dans la Malá Fatra (Karpates Occidentales). Geologický zborník – Geologica Carpathica, 24, 2, 449–452.

Polák M., Bujnovský A., Kohút M., Filo I., Pristaš J., Havrila M., Vozár J., Mello J., Buček S. & Lexa J., 1997: Geologická mapa Veľkej Fatry 1: 50 000 [Geolgical map of the Veľká fatra Mts]. Geol. Survey Slovak Rep., Bratislava.

Polák M., Ondrejičková A. & Wieczorek J., 1998: Lithobiostratigraphy of the Ždiar Formation of the Krížna nappe (Tatry Mts.). Slovak Geological Magazine, 4, 35–52.

Polák M. (ed.), Potfaj M., Filo I., Broska I., Kohút M., Mello J., Bezák V., Teťák F., Gross P., Biely A., Rakús M., Hók J., Vozár J., Nagy A. & Maglay J., 2008: Prehľadná geologická mapa Slovenskej republiky 1: 200 000, mapový list 26 – Žilina [General geological map of Slovak Republic, map sheet 26 – Žilina]. MŽP SR, ŠGÚDŠ, Bratislava.

Potfaj M. 1988: Štruktúrny výskum flyšového pásma západného Slovenska s využitím interpretácie geofyzikálnych prác (Orava) [Structural investigations of Flysch belt in western Slovakia using interpretations of geophysical measurements (Orava region)]. Unpublished CSc. thesis, Geofond archives, Bratislava.

Potfaj M., 1979: Tektonický profil styku bradlového pásma a magurskej jednotky v oblasti Oravskej Magury [English summary: Tectonic profile of the contact between the Klippen Belt and Oravská Magura in the Oravská Magura region]. In Maheľ M. (ed.): Tektonické profily Západných Karpát [Tectonic profiles through the West Carpathians]. Konf., Symp., Sem., Geol. Inst. D. Štúr, Bratislava, 37–40.

Potfaj M., 1983: Postavenie magurských pieskovcov a malcovské vrstvy na Orave [English summary: Magura Sandstones and Malcov Beds in Orava region, West Carpathians]. Geologické práce, Správy, 79, 117–140.

Potfaj M., 1993: Postavenie bielokarpatskej jednotky v rámci flyšového pásma Západných Karpát [English summary: Position and role of the Biele Karpaty Unit in the Flysch zone of the West Carpathians]. Geologické práce, Správy, 98, 55–78.

Potfaj M., Samuel M., Raková J. & Samuel O., 1991: Geologická stavba Kubínskej hole (Orava) [English summary: Geologic structure of Kubínska hoľa Range (Orava)]. Západné Karpaty, sér. Geológia, 15, 25–66.

Potfaj M. (ed.), Maglay J., Šlepecký T. & Teťák F., 2002: Geologická mapa regiónu Kysúc 1: 50 000 [Geological map of the Kysuce region]. State Geol. Inst. D. Štúr, Bratislava.

Potfaj M. (ed.), Šlepecký T., Maglay J., Hanzel V., Boorová D., Žecová K., Kohút M., Nagy A., Teťák F., Vass B., Sandanus M., Buček S., Sýkora M., Köhler E., Fejdiová O., Kandera K., Samuel O., Bubík M. & Beleš F., 2003: Vysvetlivky ku geologickej mape regiónu Kysuce 1:50 000 [English summary: Geology of the Kysuce region]. State Geol. Inst. D. Štúr, Bratislava, 193 p.

Prokešová R., Plašienka D. & Milovský R. 2012: Structural pattern and emplacement mechanisms of the Krížna cover nappe (Western Carpathians, Slovakia). Geologica Carpathica, 63, 13–32.

Pulišová Z., Soták J. & Šimonová V., 2018: Multi-phase development of the faults and joints in the Súľov Conglomerates (Súľovské vrchy Mts., Slovakia): Implications for palaeostress history. Mineralia Slovaca, 50, 137–148.

Putiš M., 1991: Geology and petrotectonics of some shear zones in the West Carpathian crystalline complexes. Mineralia Slovaca, 23, 459–473.

Putiš M., 1992: Variscan and Alpidic nappe structures of the Western Carpathian crystalline basement. Geologica Carpathica, 43, 369–380.

Putiš M., Kotov A.B., Petrík I., Korikovsky S.P., Madarás J., Salnikova E.B., Yakovleva S.Z., Berezhnaya N.G., Plotkina Y.V., Kovach V.P., Lupták B. & Majdán M., 2003: Early- vs. late orogenic granitoids relationships in the Variscan basement of the Western Carpathians. Geologica Carpathica, 54, 163–174.

Putiš M., Gawlick H.-J., Frisch W. & Sulák M., 2008: Cretaceous transformation from passive to active continental margin in the Western Carpathians as indicated by the sedimentary record in the Infratatric unit. International Journal of Earth Sciences, 97, 799–819.

Putiš M., Frank W., Plašienka D., Siman P., Sulák M. & Biroň A., 2009: Progradation of the Alpidic Central Western Carpathians orogenic wedge related to two subductions: constrained by ^{40}Ar/^{39}Ar ages of white micas. Geodinamica Acta, 22, 1–3, 31–56.

Putiš M., Danišík M., Siman P., Nemec O., Tomek Č. & Ružička P., 2019: Cretaceous and Eocene tectonothermal events determined in the Inner Western Carpathians orogenic front Infratatricum. Geological Quarterly, 63, 2, 248–274.

Rakús M. 1995: Liassic ammonites of the Western Carpathians – 2nd part; Sinemurian. Partial final report of the project 17-517-02, Regional geological research of Slovakia. 5th stage, 172/10 Phanerozoic biostratigraphy of the Western Carpathians. Archives of the Geological Survey of Slovak Republic, Bratislava, 48 p. (in Slovak)

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. Introduct. Art., Geol. Surv. Slov. Rep., Bratislava, 79–97.

Rakús M. & Hók J. 2005: Manínska a klapská jednotka – litostratigrafická náplň, tektonické zaradenie, paleogeografická pozícia a vzťah k váhiku [English summary: The Manín and Klape units: Lithostratigraphy, tectonic classification, paleogeographic position and relationship to Váhicum]. Mineralia Slovaca, 37, 9–26.

Rakús M. & Ožvoldová L., 1999: On the age of radiolarites from the Manín Unit (Butkov Klippe, Middle Váh valley, Western Carpathians). Mineralia Slovaca, 31, 79–86.

Rakús M., Elečko M., Gašparik J., Gorek J., Halouzka R., Havrila M., Horniš J., Kohút M., Kysela J., Miko O., Pristaš J., Pulec M., Vozár J., Vozárová A. & Wunder D., 1988: Geologická mapa Lúčanskej Malej Fatry, 1: 50 000 [Geological map of the Lúčanská Malá fatra Mts.]. Slovenský geologický úrad, Geologický ústav Dionýza Štúra, Bratislava.

Rapánová S., 2006: Stratigrafické postavenie flyšových súborov v okolí Zázrivej na Orave a ich vekové rozčlenenie na základe mikrofauny [Stratigraphy of flysch complexes in surroundings of Zázrivá in the Orava region and their age determination based on microfauna]. Unpublished diploma thesis, Dept. Geol. Paleont., Comenius University, Bratislava, 76 p.

Ratschbacher L., Frisch W., Linzer H.-G., Sperner B., Meschede M., Decker K., Nemčok M., Nemčok J. & Grygar R., 1993: The Pieniny Klippen Belt in the Western Carpathians of northeastern Slovakia: structural evidence for transpression. Tectonophysics, 226, 471–483.

Roberts M.P. & Clemens J.D., 1993: Origin of high-potassium, calc-alcaline, I-type granitoids. Geology, 21, 825–828.

Rodi W. & Mackie R.L., 2001: Nonlinear conjugate gradients algorithm for 2-D magnetotelluric inversion. Geophysics, 66, 1, 174–187.

Salaj J., 1994a: Geológia stredného Považia. Bradlové a pribradlové pásmo so súľovským paleogénom a mezozoikom severnej časti Strážovských vrchov – 1. časť [English summary: Geology of Middle Váh valley, Klippen and Periklippen belt, Súľov Paleogene and Mesozoic of northern part of Strážovské vrchy hills – part 1]. Zemní plyn a nafta, 39, 3, 195–291.

Salaj J., 1994b: Geológia stredného Považia. Bradlové a pribradlové pásmo so súľovským paleogénom a mezozoikom severnej časti Strážovských vrchov – 2. časť [English summary: Geology of Middle Váh valley, Klippen and Periklippen belt, Súľov Paleogene and Mesozoic of northern part of Strážovské vrchy hills – part 2]. Zemní plyn a nafta, 39, 4, 197–395.

Salaj J., 1995: Geológia stredného Považia. Bradlové a pribradlové pásmo so súľovským paleogénom a mezozoikom severnej časti Strážovských vrchov – 3. časť [English summary: Geology of Middle Váh valley, Klippen and Periklippen belt, Súľov Paleogene and Mesozoic of northern part of Strážovské vrchy hills – part 3]. Zemní plyn a nafta, 40, 1, 3–51.

Salaj J., 2006: Microbiostratigraphy of the Gosau development in the Klape Unit, Western Carpathian Paleoalpine accretionary belt. Mineralia Slovaca, 38, 1–6.

Salaj J. & Samuel O., 1966: Foraminifera der Westkarpaten-Kreide. GÚDŠ, 291p.

Samuel O., 1972: Niekoľko poznámok k litologicko-faciálnemu a stratigrafickému členeniu paleogénu bradlového pásma [English summary: Remarks on the lithological-facial and stratigraphical division of the Paleogene of the Klippen Belt]. Geologické práce, Správy, 59, 285–299.

Samuel O. & Haško J., 1978: Nové poznatky o paleogéne sv. časti Žilinskej kotliny [English summary: New data on the Paleogene of the northeastern part of the Žilinská kotlina depression]. Geologické práce, Správy, 70, 83–90.

Scheibner E., 1967: Nižná Subunit – new stratigraphical sequence of the Klippen Belt (West Carpathians). Geologický zborník – Geologica Carpathica, 18, 1, 133–140.

Scheibner E., 1968a: Contribution to the knowledge of the Palaeogene reef-complexes of the Myjava–Hričov–Haligovka zone (West Carpathians). Mitt. Bayer. Staatssamml. Paläont. Hist. Geol., 8, 67–97.

Scheibner E., 1968b: Carpathian Klippen Belt. In Maheľ M. & Buday T. (eds): Regional geology of Czechoslovakia. Volume 2, Western Carpathians. Akademie, Praha, 304–371.

Scheibner E. & Scheibnerová V., 1961: O výskyte danu v bradlovom pásme na Slovensku [English summary: On the occurrence of Danian in the Klippen Belt of West Carpathians at Slovakia]. Geologický sborník, 5, 193–199.

Schlögl J., Aubrecht R. & Tomašových A., 2000: The first find of the Orava Unit in the Púchov section of the Pieniny Klippen Belt (Western Slovakia). Mineralia Slovaca, 32, 1, 45–54.

Schlögl J., Rakús M., Krobicki M., Matyja B.A., Wierzbowski A., Aubrecht R., Sitár V. & Józsa Š., 2004: Beňatina Klippe – lithostratigraphy, biostratigraphy, palaeontology of the Jurassic and Lower Cretaceous deposits (Pieniny Klippen Belt, Western Carpathians, Slovakia). Slovak Geological Magazine, 10, 4, 241–262.

Schlögl J., Košťák M. & Hyžný M., 2012: First record of a gladius-bearing coeloid *Teudopsis bollensis* Voltz (Cephalopoda, Coeloidea) in the Toarcian of the Western Carpathians (Slovakia). Paläontologisches

Zeitschrift, 86, 367–375.

Schmid S.M., Bernoulli D., Fügenschuh B., Matenco L., Schefer S., Schuster R., Tischler M. & Ustaszewski K., 2008: The Alpine-Carpathian-Dinaridic orogenic system: correlation and evolution of tectonic units. Swiss Journal of Geosciences, 101, 1, 139–183.

Segit T., 2010: Stratygrafia, zróżnicowanie facjalne i środowisko sedymentacji aalenu i niższego bajosu pienińskiego basenu skałkowego w wybranych profilach Polski i Słowacji. PhD Thesis, Uniwersytet Warszawski, Wydział Geologii, Instytut Geologii Podstawowej, Warszawa, 152 p. (in Polish)

Segit T., Matyja B.A. & Wierzbowski A., 2015: The Middle Jurassic succession in the central sector of the Pieniny Klippen Belt (Sprzycne Creek): implications for the timing of the Czorsztyn Ridge development. Geologica Carpathica, 66, 4, 285–302.

Sentpetery M., 2011: South-vergent structures observed in the western part of the Krivánska Fatra Mts. (Central Western Carpathians). Acta Geologica Slovaca, 3, 2, 123–129.

Sentpetery M. & Hók J., 2012: Geologická stavba tatrika a fatrika v oblasti medzi Belianskou a Vrátnou dolinou (Krivánska Fatra) [English summary: Geological structure of the Tatric and Fatric units among the Belianska and Vrátna dolina valleys (the Krivánska Fatra Mts.)]. Acta Geologica Slovaca, 4, 1, 65–74.

Sentpetery M., Olšavský M., Kohút M. & Pešková I., 2020: Geologická stavba záveru Vrátnej doliny (Krivánska Fatra) [English summary: Geological structure of the Vrátna dolina Valley headslopes (Krivánska Fatra Mts.)]. Geologické práce, Správy, 135, 17–40.

Shand S.J., 1943: Eruptive Rocks. Their genesis, composition, classification and their relation to ore-deposits with a Chapter on meteorite. John Wiley & Sons, New York.

Shcherbak N.P., Cambel B., Bartnitsky E.N. & Stepanyuk L.M., 1990: U-Pb age of granitoid rock from the quarry Dubná Skala – Malá Fatra Mts. Geologický zborník – Geologica Carpathica, 41, 4, 407–414.

Sikora W., 1974: The Pieniny Klippen Belt (Polish Carpathians). In M. Maheľ (ed.): Tectonics of the Carpathian-Balkan regions. Geol. Inst. D. Štúr, Bratislava, 177–180.

Soták J., Pereszlényi M., Marschalko R., Milička J. & Starek D., 2001: Sedimentology and hydrocarbon habitat of the submarine-fan deposits of the central Carpathian Paleogene Basin (NE Slovakia). Marine and Petroleum Geology, 18, 87–114.

Soták J., Pulišová Z., Plašienka D. & Šimonová V., 2017: Stratigraphic and tectonic control of deep-water scarp accumulation in Paleogene synorogenic basins: a case study of the Súľov Conglomerates. Geologica Carpathica, 68, 5, 403–418.

Soták J., Kováč M., Plašienka D. & Vojtko R., 2019: Orogenic wedging and basin formation in the Central Western Carpathians: New insights from Súľov–Domaniža and Žilina–Rajec basins. In Broska I., Kohút M. & Tomašových A. (eds): Proceedings of the “Geologica Carpathica 70 Conference”, 9–11 October, 2019, Smolenice, Slovakia; Earth Science Institute of the Slovak Academy of Sciences, p. 43–44.

Spišiak J. & Hovorka D., 1997: Petrology of the Western Carpathians Cretaceous primitive alkaline volcanics. Geologica Carpathica, 48, 113–121.

Spišiak J. & Hovorka D., 1998: Mafic dykes in Variscan tonalities of the Malá Fatra Mts. (Western Carpathians). Slovak Geological Magazine, 4, 3, 157–164.

Spišiak J., Plašienka D., Bučová J., Mikuš T. & Uher P., 2011: Petrology and palaeotectonic setting of Cretaceous alkaline basaltic volcanism in the Pieniny Klippen Belt (Western Carpathians, Slovakia). Geological Quarterly, 55, 27–48.

Spišiak J., Vetráková L., Chew D., Ferenc Š., Mikuš T., Šimonová V. & Bačík P., 2018: Petrology and dating of the Permian lamprophyres from the Malá Fatra Mts. (Western Carpathians, Slovakia). Geologica Carpathica, 69, 5, 453–466.

Spišiak J., Vetráková L., Mikuš T., Chew D., Ferenc Š., Šimonová V. & Siman P., 2019: Mineralogy and geochronology of calc-alkaline lamprophyres from the Nízke Tatry Mts. crystalline complex (Western Carpathians). Mineralia Slovaca, 51, 61–78.

Starek D., Aubrecht R., Sliva Ľ. & Józsa Š., 2010: Sedimentary analysis of the Cretaceous flysch sequences at the Zemianska Dedina locality (Nižná Unit, Pieniny Klippen Belt, northern Slovakia). Mineralia Slovaca, 42, 2, 179–188.

Stráník Z., 1965: Geologie magurského flyše Čerchovského pohoří a západní části Ondavské vrchoviny [German summary: Zur Geologie des Magura-Flysches im Gebirge Čerchovské pohoří und Ondavská vrchovina]. Sborník geologických vied, rad ZK, 3, 125–178.

Stránska M., Ondra P., Husák Ľ. & Hanák J. 1986: Hustotná mapa hornín Západných Karpát na území ČSSR [Density map of the Western Carpathian rocks on the territory of ČSSR]. Manuscript report, Bratislava, Brno, 261 p.

Streckeisen A. & Le Maitre R.W., 1979: A chemical approximation to the modal QAPF of the igneous rocks. Neues Jahrbuch für Mineralogie, Abhandlungen, 136, 169–206.

Suan G., Schöllhorn I., Schlögl J., Segit T., Mattioli E., Lécuyer Ch. & Fourel F., 2018: Euxinic conditions and high sulfur burial near the European shelf margin (Pieniny Klippen Belt, Slovakia) during the Toarcian oceanic anoxic event. Global and Planetary Change, 170, 246–259.

Sýkora M., Siblík M. & Soták J., 2011: Siliciclastics in the Upper Triassic dolomite formations of the Krížna Unit (Malá Fatra Mountains, Western Carpathians): constraints for the Carnian Pluvial Event in the Fatric Basin. Geologica Carpathica, 62, 2, 121–138.

Šalagová V., Frličková M., Šalaga I. & Urbaník J., 1996a: Paleogén Žilinskej kotliny – vyhľadávací hydrogeologický prieskum [Paleogene of the Žilina Depression – hydrogeological prospecting]. Manuscript, IGHP, Žilina.

Šalagová V., Frličková M., Šalaga I. & Urbaník J., 1996b: Hydrogeologické pomery paleogénu žilinskej kotliny [Hydrogeology of Paleogene of the Žilinská kotlina Depression]. Podzemná voda, 2, 1, 5–22.

Šamajová L. & Hók J., 2018: Hustota horninových komplexov Západných Karpát na území Slovenska [English summary: Densities of rock formations of the Western Carpathians on the territory of Slovakia]. Geologické práce, Správy, 132, 31–52.

Šimonová V. & Plašienka D., 2017: Stepwise clockwise rotation of the Cenozoic stress field in the Western Carpathians as revealed by kinematic analysis of minor faults in the Manín Unit (western Slovakia). Geological Quarterly, 61, 1, 252–265.

Talwani M., Worzel J.L. & Landisman M., 1959: Rapid gravity computations for two dimensional bodies with application to the Mendocino submarine fracture zone. Journal of Geophysical Research, 64, 49–59.

Tari G., Báldi T. & Báldi-Beke M., 1993: Paleogene retroarc flexural basin beneath the Neogene Pannonian Basin: a geodynamic model. Tectonophysics, 226, 433–455.

Teťák F., Pivko D. & Kováčik M., 2019: Depositional systems and paleogeography of Upper Cretaceous–Paleogene deep-sea flysch deposits of the Magura Basin (Western Carpathians). Palaeogeography, Palaeoclimatology, Palaeoecology, 533, 109250, 21 p.

Tikhonov A., 1950: On determining electrical characteristics of the deep layers of the earth's crust. Sov. Math. Dokl., 73, 2, 295–297.

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

Tomek Č., Ibrmajer I., Koráb T., Biely A., Dvořáková L., Lexa J. & Zbořil A. 1989: Korové struktury Západních Karpat na hlubinném reflexním seizmickém profilu 2T [English summary: Crustal structures of the West Carpathians on deep reflection seismic line 2T]. Mineralia Slovaca, 21, 1, 3–26.

Tomek Č. et al., 1990: Výsledky na hlubinných reflexné seismických profilech [Results on deep reflection seismic lines]. In: Bližkovský et al.: Geofyzikálni výzkum zemské kúry pro potreby ložiskového výzkumu v ČSSR. Manuscript report, Geofyzika, Brno.

Topographic Institute 2012: Digital terrain model version 3 (online). http://www.topu.mil.sk/14971/digitalny-model-reliefu-urovne-3-%28dmr-3%29.php.

Twiss R.J. & Moores E.M., 1992: Structural geology. W.H. Freeman and Company, New York, 532 p.

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.

Tyszka J., 1999: Foraminiferal biozonation of the Early and Middle Jurassic in the Pieniny Klippen Belt (Carpathians). Bulletin of the Polish Academy of Sciences, 47, 1, 27–46.

Uher P., Broska I., Krzeminska E., Ondrejka M., Mikuš T. & Vaculovič T., 2019: Titanite composition and SHRIMP U-Pb dating as indicator of postmagmatic tectono-thermal activity: Variscan I-type tonalites to granodiorites, the Western Carpathians. Geologica Carpathica, 70, 6, 449–470.

Uhlig V., 1890: Ergebnisse geologischer Aufnahmen in den westgalizischen Karpathen. II. Der pieninische Klippenzug. Jahrbuch der k.k. geologischen Reichsanstalt, 40, 3-4, 559–824.

Uhlig V., 1902: Beiträge zur Geologie des Fatrakriván-Gebirges. Denkschriften der Keiserlichen Akademie der Wissenschaften in Wien, 72, 519–561.

Uhlig V., 1904: Über die Klippen der Karpathen. Congrès Géologique International Compte Rendu de la IX. Session, Vienne 1903, Premier Fascicule, Imprimerie Hollinek Fréres, Vienne, 427–453.

Uhlig V., 1907: Über die Tektonik der Karpathen. Sitzungsberichte der Kaiserischen Akademie der Wissenschaften, matematisch-naturwissenschaftliche Klasse, 116, part I, 871–982.

Vojtko R., Hók J., Kováč M., Sliva Ľ., Joniak P. & Šujan M., 2008: Pliocene to Quaternary stress field changes in the Western Carpathians (Slovakia). Geological Quarterly, 52, 1, 19–30.

Vojtko R., Tokárová E., Sliva Ľ. & Pešková I., 2010: Cenozoic palaeostress field reconstruction and revised tectonic history in the northern part of the Central Western Carpathians (the Spišská Magura and Tatra Mountains). Geologica Carpathica, 61, 3, 211–225.

Vozárová A. & Vozár J., 1988: Late Paleozoic in West Carpathians. Geol. Inst. D. Štúr, Bratislava, 314 p.

Vrána S. & Vozár J., 1969: Minerálna asociácia pumpelyit/prehnit/kremennej fácie z Nízkych Tatier [German summary: Über die Mineralgemeinschaft der Pumpellyit-Prehnit-Quartzfazies in der Niederen Tatra]. Geologické práce, Správy, 49, 91–99.

Wagreich M. & Marschalko R., 1995: Late Cretaceous to Early Tertiary palaeogeography of the Western Carpathians (Slovakia) and the Eastern Alps (Austria): implications from heavy mineral data. Geologische Rundschau, 84, 187–199.

Whalen J.B., Currie L.C., & Chappell B.W., 1987: A-type granites: geochemical characteristics, discrimination and petrogenesis. Contributions to Mineralogy and Petrology, 95, 407–419.

Wierzbowski A., Aubrecht R., Krobicki M., Matyja B.A. & Schlögl J., 2004: Stratigraphy and palaeogeographic position of the Jurassic Czertezik Succession, Pieniny Klippen Belt (Western Carpathians) of Poland and Eastern Slovakia. Annales Societatis Geologorum Poloniae, 74, 3, 237–256.

Wierzbowski A., Krobicki M. & Matyja B.A., 2012: The stratigraphy and palaeogeographic position of the Jurassic successions of the Priborzhavske-Perechin Zone in the Pieniny Klippen Belt of the Transcarpathian Ukraine. Volumina Jurassica, 10, 25–60.

Zbořil L., Szalaiová V. & Stránska M., 1979: Geofyzikálny výskum hlbokých hydrogeologických štruktúr Turčianska kotlina – Gravimetrické mapovanie [Geophysical investigation of deep hydrogeological structures of the Turčianska kotlina Depression – Gravimetric mapping]. Manuscript, Geofond archives, Bratislava.

Zbořil L., Šefara J., Halmešová S., Král M., Puchnerová M., Stránska M. & Szalaiová V., 1985: Geofyzikálny výskum Turčianskej kotliny [Geophysical investigations in the Turčianska kotlina Depression]. Manuscript, Geofond archives, Bratislava.

Structure, composition and tectonic evolution of the Pieniny Klippen Belt – Central Western Carpathian contiguous zone (Kysuce and Orava regions, NW Slovakia)

Authors: Plašienka D., Aubrecht R., Bezák V., Bielik M., Broska I., Bučová J., Fekete K., Gaži P., Gedl P., Golej M., Halásová E., Hók J., Hrdlička M., Jamrich M., Józsa Š., Klanica R., Konečný P., Kubiš M., Madarás J., Majcin D., Marko F., Molčan Matejová M., Potočný T., Schlögl J., Soták J., Suan G., Šamajová L., Šimonová V., Teťák F., Vozár J.

Graphic design and make-up: Andrej Ruman and Tomáš Potočný
Cover figure: The digital relief model of the Kriváň part of Malá Fatra Mts; designed by Tomáš Potočný
First edition: 148 pages, 81 figures, 14.52 AH
Year of the publication: 2021

Published by: Comenius University Bratislava, Slovakia
ISBN: 978-80-223-5237-6 (online PDF version)
978-80-223-5236-9 (printed version)

COMENIUS UNIVERSITY
BRATISLAVA

FACULTY OF
NATURAL SCIENCES

MINISTRY
OF EDUCATION, SCIENCE,
RESEARCH AND SPORT
OF THE SLOVAK REPUBLIC

SLOVAK RESEARCH
AND DEVELOPMENT AGENCY

INTERNATIONAL GEOSCIENCE
PROGRAMME UNESCO

ISBN: 978-80-223-5237-6