World Geomorphological Landscapes

Tomáš Pánek
Jan Hradecký *Editors*

Landscapes and Landforms of the Czech Republic

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Series Editor Preface

Landforms and landscapes vary enormously across the Earth, from high mountains to endless plains. At a smaller scale, nature often surprises us creating shapes which look improbable. Many physical landscapes are so immensely beautiful that they receive the highest possible recognition—they hold the status of World Heritage Sites. Apart from often being immensely scenic, landscapes tell stories which not uncommonly can be traced back in time for tens of million years and include unique geological events such as meteorite impacts. In addition, many landscapes owe their appearance and harmony not solely to the natural forces. For centuries, and even millennia, they have been shaped by humans, who have modified hill slopes, river courses and coastlines, and erected structures which often blend with the natural landforms to form inseparable entities.

These landscapes are studied by geomorphology—'the science of scenery'—a part of earth sciences that focuses on landforms, their assemblages, surface and subsurface processes that moulded them in the past and that change them today. To show the importance of geomorphology in understanding the landscape, and to present the beauty and diversity of the geomorphological sceneries across the world, we have launched a book series called *World Geomorphological Landscapes*. It aims to be a scientific library of monographs that present and explain physical landscapes, focusing on both representative and uniquely spectacular examples. Each book will contain details on geomorphology of a particular country or a geographically coherent region. This volume presents the impressive geodiversity of the Czech Republic. This Central European country may seem small but it hosts a very wide range of landscapes and landforms, the origin of which can be traced back to the Mesozoic. Among geomorphic highlights of the Czech Republic are block-faulted mountains with elevated planation surfaces and the evidence of past mountain glaciation, karst plateaus, deep fluvial canyons, astounding 'rock cities' in sandstone, flysch mountain ranges affected by huge landslides, and many others. They are presented and illustrated through carefully selected 25 examples from the entire country.

The World Geomorphological Landscapes series is produced under the scientific patronage of the International Association of Geomorphologists (IAG)—a society that brings together geomorphologists from all around the world. The IAG was established in 1989 and is an independent scientific association affiliated with the International Geographical Union (IGU) and the International Union of Geological Sciences (IUGS). Among its main aims are to promote geomorphology and to foster dissemination of geomorphological knowledge. I believe that this lavishly illustrated series, which keeps to the scientific rigour, is the most appropriate means to fulfil these aims and to serve the geoscientific community. To this end, my great thanks go to Tomáš Pánek and Jan Hradecký for agreeing to coordinate this volume. I am also very grateful to all individual authors who accepted invitations to contribute and delivered fine contributions which collectively show how varied and geomorphologically rich even a relatively small country can be.

For me, to write the preface to the Czech Republic volume is of particular pleasure. Living just across the border, I consider this country—within an easy reach of a day trip—as part of my homeland. I was fortunate to be able to see many geomorphological landscapes of this country myself and even to carry out some research. A little evidence of this involvement is my own modest contribution to this volume, regarding the granite landscape of Jizerské hory, in the northern part of the country.

I hope that the book will convince the readers that a little geomorphological paradise is located right in the heart of Europe.

Piotr Migoń

Contents

Short Biodata of Authors

Jiří Adamovič is a researcher at the Institute of Geology of the CAS, v.v.i. in Prague, Czech Republic. His subjects of study include sedimentology, stratigraphy and petrology of detrital sedimentary rocks. He has been involved in projects dealing with sandstone tectonics, lithological controls on the origin of sandstone relief, and hydrothermal alteration of sandstone upon its interaction with magma. He is the prime author of the recently published Atlas of sandstone rock cities of the Czech Republic and Slovakia.

Břetislav Balatka is a senior research member of the Department of Physical Geography and Geoecology at Faculty of Science, Charles University in Prague. He is known as an excellent teacher and tutor in the field of geography. His research interests are focused on physical geography and regional geomorphology of Central Europe, including the origin and morphostratigraphy of fluvial accumulation terraces, landform evolution during the Quaternary, recent and present-day geomorphologic processes and their impacts on the environment.

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Jan Mertlík is a geomorphologist and conservationist who worked for the Nature Conservation Agency of the Czech Republic for many years. He also promotes the area of the Bohemian Paradise in a local development agency based at Turnov. He regularly organizes field seminars called "Klokočky" focused on the spread of geological and geomorphological knowledge of this area.

Piotr Migoń is Professor of Geography at the University of Wrocław, Poland, and Director of Institute of Geography and Regional Development. His main subjects of research are rock control in geomorphology, especially in granite and sandstone areas, weathering, mass movement in mountain terrains and long-term landform evolution. The Sudetes Mountains in Central Europe is his main research area, but he was also involved in projects in other European countries (Czech Republic, Sweden, Great Britain, Portugal), in the United States, Mexico, China, Jordan and Namibia. During 1997–2001 he was the Secretary of the International Association of Geomorphologists, and its Vice-President in 2009–2013.

Jan Miklín is Assistant Professor at the Department of Physical Geography and Geoecology of University of Ostrava, with specialization on cartography, geoinformatics, landscape ecology and nature conservation.

Jan Mrlina is a geophysicist in the Department of Tectonics and Geodynamics of the Institute of Geophysics at the Academy of Sciences in Prague, Czech Republic. His research is focused on various applications of gravity surveying in geodynamics, mineral resources exploration, archaeology, geoengineering, etc. His special interest is related to volcanic structures in the Czech Republic and Greece, with constraining geophysical and geomorphological data. Besides discovering the only Quaternary maar in the Bohemian Massif, and studying the internal structure of volcanoes, he also performs gravity monitoring with the aim of detecting subsurface mass movements under the volcanic landforms.

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Tomáš Pánek is Associate Professor in Physical Geography and Geoecology at the Faculty of Science, University of Ostrava. His research interests involve geomorphology and Quaternary geology with a special focus on mass movements, neotectonics and palaeoenvironmental reconstructions in the Western Carpathians, Bohemian Massif, Crimean peninsula, Taurus Mountains in Turkey, Caucasus, Caspian Sea region of Kazakhstan, etc. He has published more than 40 peer-reviewed papers and acts as a reviewer in leading journals in the field of earth sciences.

Vlastimil Pilous studied Geography at the Charles University in Prague and worked in the Krkonoše National Park Management Headquarters. In his studies he deals with mesoforms and microforms (e.g. evorsion potholes) concentrating on the Krkonoše-Jizera Pluton and Crystalline as well as mid-mountain landforms affected by geomorphological processes (especially water and glacial erosion and waterfalls) and slope movements (debris flows). Having created a typology of travertine and tufa landforms, he also continuously studies historical anthropogenous (particularly mining-related) landforms in the Krkonoše Mountains and their role in mountain landscape evolution.

Petr Popelka is Associate Professor of Czech and Czechoslovak History in the Department of History, Faculty of Arts, University of Ostrava (since 2013 the head of this department) and research fellow at the Centre for Economic and Social History University of Ostrava. In his research work, he focuses mainly on the history of entrepreneurs and enterprise in the era of industrialisation, on the genesis of modern transport infrastructure in Central Europe in the eighteenth and nineteenth centuries and on landscape changes in the nineteenth and twentieth centuries.

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Jakub Stemberk is currently a Ph.D. student in the Department of Physical Geography and Geoecology, Faculty of Sciences, Charles University in Prague. His research topics are tectonic geomorphology, long-term morphotectonic relief evolution, especially evolution of river basins and valley forms in the Sudetes Mountains.

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Zuzana Vařilová is a geologist with focus on regional geology—especially Cretaceous sandstones and sandstone landscapes, weathering processes, rock-slope instability and landslides. She has worked more than 10 years in the Bohemian Switzerland NP Administration, where an integrated rock-fall risk management has been developed (including risk mapping and evaluation, monitoring system and remedial works). Now she works as a Curator of Geological Collections and Scientific Secretary at the Museum of the city of Ústí nad Labem. She has studied at the Faculty of Science, Charles University in Prague. A comprehensive research of sandstone rock form deterioration—case study Pravčická brána Arch was carried out within her Ph.D. study. She has participated in research projects in the Czech Republic and abroad (e.g. Ethiopian Highlands).

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Jan Vítek is Associate Professor of Physical Geography at the Faculty of Science, University of Hradec Králové, Czech Republic. His research focuses on mesoforms and microforms on the rock surface, incurred by weathering of sandstones, marlites, granitoids, metamorphic rocks and others. He designed typology of pseudokarst forms in the Czech republic.

Karel Žák is a geologist and geochemist at the Institute of Geology of the Czech Academy of Sciences. His main scientific interests are in the application of isotope geochemistry in environmental studies, including study of karst processes. During the last several years, his studies focused on processes occurring in caves during glacials. He is also interested in hydrothermal processes and ore deposit formation.

1 Introduction

Tomáš Pánek and Jan Hradecký

Although the territory of the Czech Republic lacks numerous attractive types of landscapes which are common in the neighbouring European countries (e.g. rugged alpine mountains, floodplains of large rivers or scenic coastlines), it is a country of exceptionally diverse landforms. Owing to its position in Central Europe, landscapes and landforms of the Czech Republic bear imprints of the intersection of major Eurasian geotectonic and bioclimatic domains. Strongly denuded Proterozoic and Paleozoic basement of the Variscan Bohemian Massif meets here with the young Cenozoic fold-and-thrust belt of the Western Carpathians. Sudetic Mountains with tundra-like landscapes and periglacial phenomena on watersheds are in contrast to vineyard-covered limestone hills in Southern Moravia resembling the Mediterranean realm. Due to complex geotectonic and geomorphological evolution, many landscapes in the Czech Republic can be classified as geo-regions of first-order importance. The area of Late Cretaceous transgression in the Central and Eastern Bohemia includes spectacular "rock cities" which are without any doubt most impressive in Europe and some of the largest on the world-wide scale. Some of the regions in the Czech Republic obtained their credit due to the traditional history of scientific research. It pays e.g. for loess sections in Southern Moravia, which are among the most investigated and important natural archives of Late Quaternary climate changes in Eurasia. Other examples are small young volcanoes in Western Bohemia (especially Komorní hůrka/Kammerberg volcano) which were fascinating for J.W. Goethe at the beginning of the nineteenth century and inspired him to contribute to the theories of neptunism and plutonism, i.e. great geological paradigms of that time. A possibility to expand long-term research in a geologically and geomorphologically rich country is still highly attractive for geoscientists from all around the world.

The Czech Republic is located in the contact zone of four important European geomorphological provinces—Bohemian Highlands, Central Polish Lowland, Western Carpathians and West-Pannonian Basin (Czudek 2005). The Bohemian Highlands occupy 84 % of the total area of the Czech Republic and their origin is related to the Variscan orogeny at the end of the Paleozoic era. Thereby, they represent the largest and at the same time the oldest geomorphological province of the Czech Republic containing the highest peak of the CR—Sněžka Mt (1603 m) as well as other high mountain ranges of the CR—Hrubý Jeseník Mts (Praděd Mt 1491 m), Králický Sněžník Mts (Králický Sněžník 1423 m) and Šumava Mts (Plechý Mt 1378 m). The altitude of the CR territory ranges from 115 m (Labe/Elbe River valley near Hřensko) up to 1602 m (Sněžka Mt in the Krkonoše Mts). Western Carpathians (c. 9 % of the CR total area) are built partly by a system of hilly lands, highlands and uplands in the easternmost part of the republic and partly by a system of lowlands (the so-called Carpathian Foredeep) in the mountain range foreground. West-Pannonian Basin occupies 6.5 % of the total CR area. It represents lowland (exceptionally hilly) relief overreaching into the Czech territory from the territory of Austria and Slovakia in a form of Dolnomoravský úval and Dyjskosvratecký úval basins. Central Polish Lowland occupies as little as about 0.5 % of the total state territory.

Czech geomorphologists (Demek et al. 2006) proposed a very detailed geomorphological division of the country. This approach is based on the delineation of morphostructures, morphography and general morphometric properties. The scheme of the geomorphological division is presented in Fig. 1.1 where localisation of geomorphological provinces and geomorphological units is shown.

This book is not intended to act as a textbook whose aim is to systematically describe all regions in the Czech Republic. A lot of basic regional-geomorphological units displayed in Fig. 1.1 are not included in the text. Rather,

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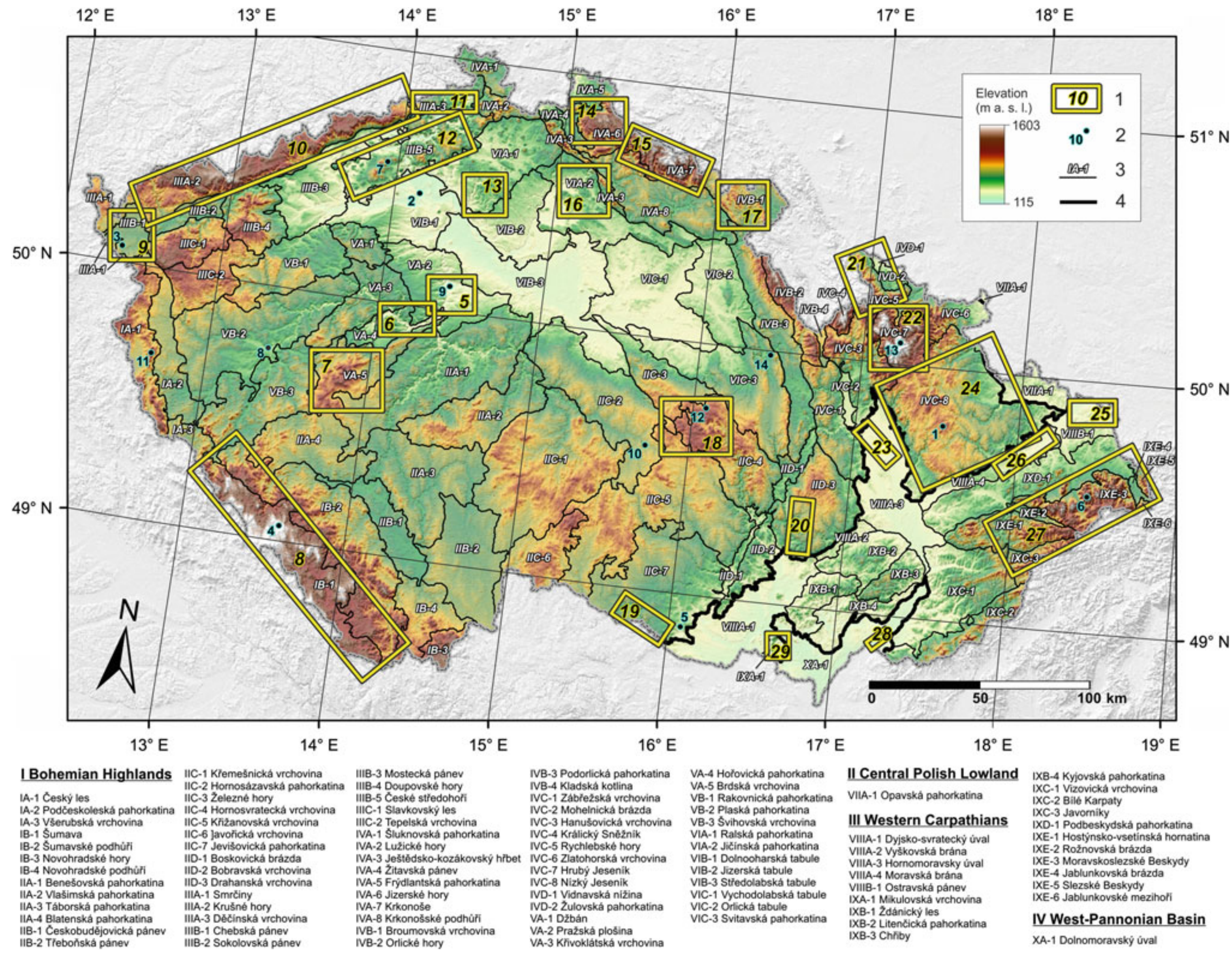

Fig. 1.1 Geomorphological division of the Czech Republic based on Demek et al. (2006): *1* localisation of the studied geomorphological landscapes in this book—numbers represent the number of a given chapter; *2* climatological stations—for details see Chap. 3 and Table 3.1; *3* borders of geomorphological units; *4* border of European geomorphological provinces within the Czech Republic)

the book covers those landscapes which best represent both geomorphological particularities and diversity of the country. It involves areas with magnificent landscapes forming natural background, famous historical sites and scientifically valuable regions representing geosites that are of crucial importance for the understanding of geomorphological evolution of Central Europe. A special intention was to include geomorphological regions from where recent intensive investigations have brought a new insight into the geodynamics of the region. In such a way, the book emphasizes internationally well-known geomorphological highlights of the country (e.g. sandstone "rock cities"; Chaps. 11, 13, 16 and 17), but it also tends to describe so far less popular landform assemblages (e.g. abundant cryogenic landforms in the Brdy area which have been hidden to the public for decades due to the presence of the army; Chap. 7).

The book is divided into three sections. In the first section, it introduces the main aspects of geology and tectonic development (Chap. 2). Then, it deals with the past and recent climatic pattern of the country (Chap. 3) and finally, it summarizes long-term geomorphological history of the Czech Republic as an interplay of complex morphotectonic evolution, rock control and Cenozoic climatic oscillations (Chap. 4).

The core of the book is the second section, which represents 25 geomorphologically most spectacular regions of the Czech Republic. Starting in the historical heart of the Czech Republic and one of the most impressive towns in Europe, Prague (Chap. 5), it describes the most interesting geomorphological landscapes of the Central Bohemia such as Bohemian Karst (Chap. 6) and Brdy Highland (Chap. 7). From the point of view of tectonics, these regions belong to the most stable regions in Central Europe. Thanks to the presence of planation surfaces, unique karst landforms and complete assemblage of Quaternary river terraces, they host some of the most valuable imprints of the long-term landscape evolution in the Czech Republic. Long-term landscape evolution is also characteristic of the Bohemian Forest (Chap. 8), the most extensive forest landscape in Central Europe situated in the borderland with Bavaria (Germany). The area is strictly protected on both sides of the border via the Bohemian Forest National Park in the Czech Republic and Bavarian Forest in Germany. Due to considerable neotectonic uplift and survival of extensive summit plateaus reaching far above the Pleistocene snow line, this mountain range is one of the three regions in the Czech Republic that bear clear geomorphological markers of the existence of Pleistocene mountain glaciers.

Moving to the west, we can study geodynamically most active landscape in the country. It is evidenced by the occurrence of the youngest Pleistocene volcanoes and current seismicity in the area surrounding the Ohře/Eger rift (Chap. 9). Another morphostructural expression of this dramatic geodynamic setting is the area of the Krušné hory Mts, the longest mountain range with some of the most expressive fault scarps in the Czech Republic (Chap. 10). In the NE continuation of the Krušné hory Mts, we can observe a highly diverse landscape which originated as a result of intensive neotectonic movements and multi-stage Tertiary volcanic activity. It is a geological domain with pronounced rock control and presence of Late Cretaceous sandstones. One of the most valuable geomorphological landscapes of the Czech Republic is the area of the Elbe Sandstones (Chap. 11) involving the deeply incised valley of the Labe/Elbe River and sandstone “rock cities” in the Bohemian Switzerland National Park with some iconic sandstone landforms (e.g. Pravčická brána Arch). The nearby neovolcanic terrain of the České Středohoří Mts (Chap. 12) is another excellent demonstration of rock control in the landscape, but in this case it is connected with the exhumation of subvolcanic bodies, recently shaped by numerous large landslides. The Kokořín area (Chap. 13) is a much smaller unit, but it is a unique demonstration of how hydrothermal activity related to Tertiary volcanism affected lithological properties of Cretaceous sandstones and lead to the evolution of specific microforms such as mushroom rocks.

Jizerské hory Mts (Chap. 14) represent a true Sudetic landscape, typical of the northern borderland of the Czech Republic. High-elevation planation surfaces with numerous granite tors alternate with steep fault slopes hosting plenty of waterfalls and traces of active debris flow processes. Such features are even more noticeable in the Krkonoše Mts, the highest and formerly most glaciated mountain range of the Czech Republic (Chap. 15). Due to their extraordinary natural heritage, the Krkonoše Mts were established to be the first national park in the country in 1963. To the south of the Jizerské hory and Krkonoše Mts, a large exceptional landscape with several sandstone rock cities and neovolcanic bodies can be visited. Known as Bohemian Paradise (Chap. 16), it was included (as the only region in the Czech Republic) into the European Geopark Network due to its outstanding geological, geomorphological and historical heritage. The last region containing the phenomena of sandstone rock cities is the area of Adršpach–Teplice Rocks and Broumov Cliffs (Chap. 17), a system of elevated tablelands with characteristic mesas and cuestas, escarpments dissected by numerous rock columns, pillars, gorges and pseudokarst caves.

With the geomorphological landscape of the Žďárské vrchy Highland (Chap. 18), our book enters the territory of Moravia. Žďárské vrchy Highland represents a spectacular region at the main watershed between the Northern and Black Sea and gives a proof that in specific circumstances “rock cities” could develop even in crystalline rocks. Another landscape with a strong geomorphological imprint of crystalline rocks is the Dyje canyon-like valley, included in the Podyjí National Park just at the border with Austria (Chap. 19). It is one of famous deeply incised river valleys at the SE marginal slope of the Bohemian Massif with rock slopes and mysterious pseudokarst (“ice”) caves. Continuing to the NE, adjacent to the northern suburb of the Brno city (historical capital of Moravia), there is the most extensive karst landscape in the Czech Republic—the Moravian Karst (Chap. 20). With a complete list of exo- and endokarst phenomena on Devonian limestones, numerous examples of Early Cretaceous paleokarst and long tradition of geo-archaeological investigation connected especially with the name of K. Absolon (1877–1960), this territory is on the top from the point of view of the significance for the understanding of the long-term geomorphological history of the Czech Republic.

As for the Rychlebské hory Mts (Chap. 21), we have to move to the Sudetic north again. This landscape is spectacular for a high diversity of granite landforms, but what makes this region particularly valuable from the scientific point of view is the recent discovery of Late Pleistocene/Holocene tectonics along the Sudetic Marginal Fault. In this respect, tectonic landforms along the foot of the Rychlebské hory Mts are among the youngest ones in Central Europe and they demonstrate ongoing crustal deformations even in the domain of the old cratonised Bohemian Massif. The mountain region of the Hrubý Jeseník Mts (Chap. 22) represents the second highest range in the Czech Republic and despite its limited glaciation during the Pleistocene; by far, the most conspicuous geomorphological phenomena of this area are numerous periglacial features such as cryoplanation terraces, thufurs, sorted polygons and other microforms. Although nearby to the Hrubý Jeseník Mts, the region of Litovelské Pomoraví (Chap. 23) represents a completely different picture—alluvial landscape close to the outflow of the Morava River from a mountainous catchment. It is the only example of an anastomosing river pattern in the Czech Republic with excellent riparian habitats. Further to the east, the Nízký Jeseník upland (Chap. 24) forms a vast elevated plateau at the margin of the Bohemian Massif. It is marked by several Quaternary volcanoes and in many sites "penetrated" by large underground mines giving an insight into the interior of the rock massif formed by folded Carboniferous shales.

The remaining chapters describe the Western Carpathians—the youngest geological domain of the Czech Republic. The dirty mining landscape of the Ostrava-Karviná region (Chap. 25) is an example of drastic anthropogenic transformation of an originally agricultural landscape of the Carpathian Foredeep. This process lasted less than 200 years, but fortunately recent revitalisation of the devastated area has gradually been returning the nature back to this landscape. In comparison with this "black land", the stretches of the Odra River SW of the city of Ostrava (Chap. 26) looks like a pristine landscape. It is perhaps the best example of a meandering river belt in the Czech Republic as it survived decades of river training. The highest area of the Western Carpathians in the Czech Republic is represented by the Moravskoslezské Beskydy Mts and surrounding mountains (Chap. 27). Formed by folded and thrust flysch rocks, this region is especially prone to landslide activity, which represents a natural hazard, but it also tends to increase geodiversity of the landscape with numerous rock slopes, block fields and long pseudokarst/crevice-type caves. The southernmost part of the Czech Republic (Southern Moravia) is a domain of vast alluvial plains and rolling hills with vineyards, a landscape resembling Southern Europe. The most impressive alluvial plain here is situated along the lower course of the Morava River (Chap. 28). This is a semi-natural riverine landscape characterised by recent dynamic changes of channel morphology, but it also contains an exceptional sedimentary record of the Late Pleistocene-Holocene floodplain evolution. Nearby lowland covered by numerous Late Glacial sand dunes (often called "Moravian Sahara") is a unique example of aeolian landforms in the Czech Republic. Southernmost hilly landscape belonging to the Western Carpathians in the Czech Republic is represented by the Pavlov Hills (Chap. 29). These Jurassic limestone hills are a part of the "bridge" between Eastern Alps and Western Carpathians. The region provides excellent manifestations of rock control dominated by rigid limestone beds, but it also reveals good examples of tectonic landforms and contains some of the most important loess sequences in Europe.

The final chapters (Chaps. 30 and 31) provide to the readers the main aspects of geo-conservation and geotourism in the Czech Republic. They emphasize a long tradition of landscape protection in the country and also recent tendencies to prepare inventories of especially valuable landforms ("geomorphosites") as well as their inclusion in the network of protected areas. Some of the regions make use of their geoheritage in establishing geoparks which promote geodiversity and geoheritage to the public and accelerate tourism in particular areas.

We would like to express many thanks to Prof Piotr Migoń for offering us to participate in the editorial work of this volume and for his excellent supervision of this book series. We acknowledge the technical support of Dr. Veronika Kapustová and Dr. Jan Miklín. Many thanks belong to Monika Hradecká for her help with English corrections. We would like to warmly thank all contributors. It was a real pleasure to cooperate on such an exceptional book describing geomorphological and landscape beauties of our country.

References

Czudek T (2005) Vývoj reliéfu krajiny České republiky v kvartéru. Moravské zemské muzeum, Brno, 240 pp

Demek J, Mackovčín P, Balatka B, Buček A, Cibulková P, Culek M, Čermák P, Dobiáš D, Havlíček M, Hrádek M, Kirchner K, Lacina J, Pánek T, Slavík P, Vašátko J (2006) Hory a nížiny. Zeměpisný lexicon ČR. AOPK ČR, Brno, 582 pp

Part I

Physical Environment

Geology and Tectonic Development of the Czech Republic

2

Radomír Grygar

Abstract

Even if the Czech Republic occupies a small area in Central Europe, it is unique by the very interesting and varied geological and tectonic development that is recorded in the structure of the present-day Earth's crust, especially in the case of the Bohemian Massif. The Bohemian Massif can be interpreted as a heterogeneous unit composed of four separate regional domains. Each of them is defined especially by a specific stratigraphic content, tectomagmatic development and tectonic limitation in relation to its surroundings. The history of its development involves a long time period from the Paleoproterozoic to the recent period, i.e. about 2.1×10^9 years. Basic features of the Earth's crust structure, reflecting in geological maps, were however impressed on the area of the country only by relatively younger phases of Variscan orogeny and, to a lesser extent, Alpine orogeny that affected the eastern part of the country—the Western Carpathians. At the beginning of the Westphalian, the Bohemian Massif became part of the stabilised Variscan crust of the West European Platform, which in consequence meant that it began to act as a single unit, in which any mutual lateral displacement of units, metamorphosis and associated ductile deformation took place no longer. The Western Carpathians are one of partial branches of the vast orogenic belt of the Alpides created from the former Tethys Ocean. The development of the Western Carpathians already begins shortly after terminating the Variscan orogeny. At present, the Carpathians are divided from south to north into the Inner, Central and Outer Western Carpathians. The Central as well as the Inner Carpathians do not occur in the territory of the Czech Republic. The younger accretionary complex in the area of Moravia and Silesia is composed of the Pouzdřany, Ždánice, Subsilesian, Silesian and Fore-Magura Units.

Keywords

Bohemian Massif • Variscan orogeny • Epi-Variscan Platform • Alpine orogeny • Western Carpathians • Tectonic development

2.1 Introduction

The Czech Republic occupies a comparatively small area in Central Europe. In addition to other particularities, it is unique by the very interesting and varied geological development that is recorded in the structure of the present-day Earth's crust, especially in the central and western part of the territory—the Bohemian Massif. According to current knowledge, the history of its development involves a long time period from the Paleoproterozoic to the recent period, i.e. about 2.1×10^9 years. Basic features of the Earth's crust structure, shown on geological maps (Fig. 2.1), were however impressed on the area only by

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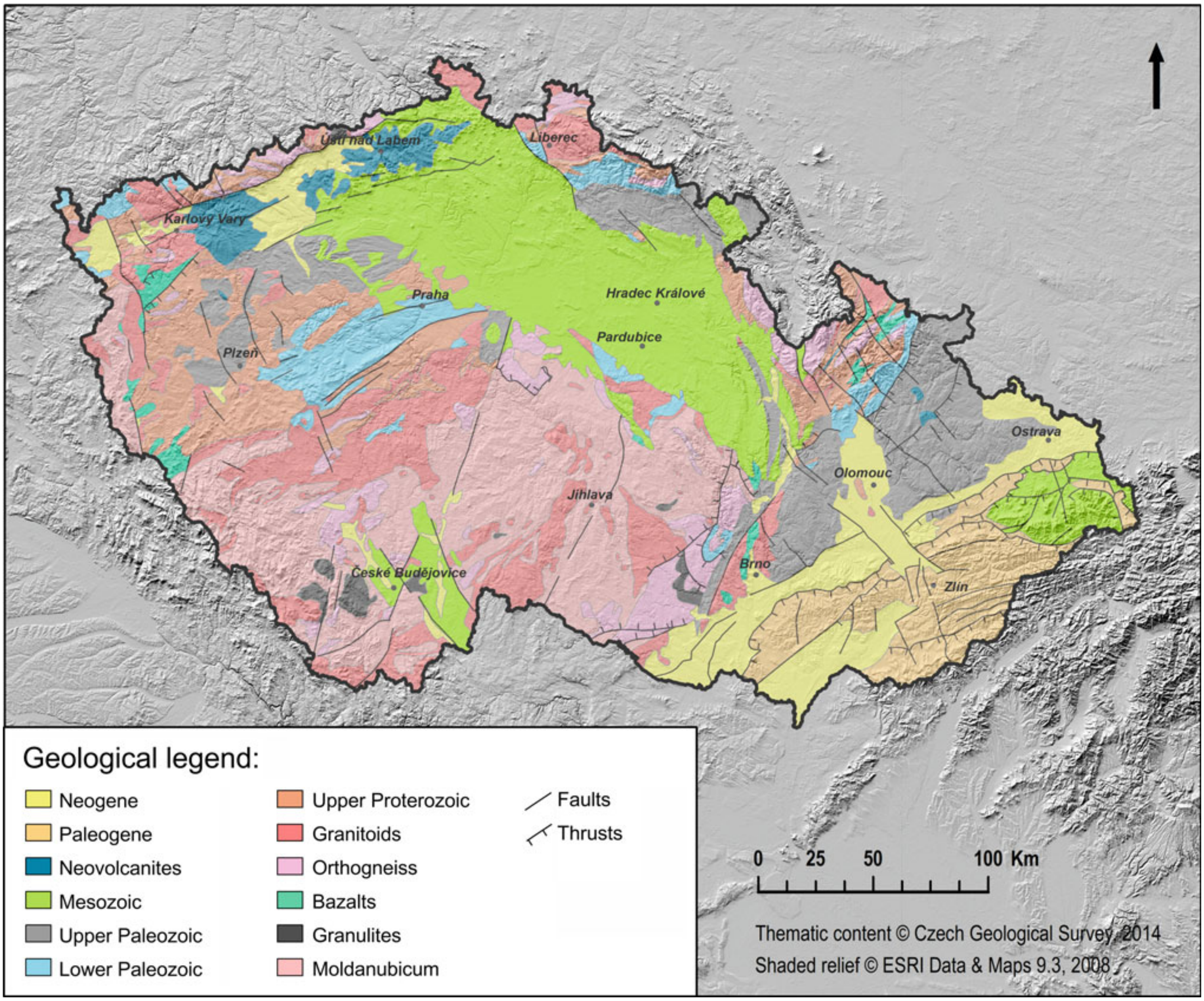

Fig. 2.1 Simplified geological map of Czech Republic draped over digital elevation model (Original made by Czech Geological Survey, courtesy of Lucie Kondrová)

relatively younger phases of geological development—Variscan orogeny and, to a lesser extent, Alpine orogeny that affected primarily the eastern part of the country—the Western Carpathians.

The territory of the Czech Republic is, besides its geographical and geopolitical position, a significant area in the geological pattern of Europe. In Moravia, two parts of Europe vastly different in age, geological development and geophysical parameters of the Earth's crust, meet. Bohemia and part of western Moravia and Silesia are a portion of the Bohemian Massif, one of the most significant and extensive fragments of the Variscan orogen formed during the Devonian and the Carboniferous (over the interval c. 380–320 Ma) by collision of the peri-Gondwana microcontinents (i.e. microcontinents situated in the early Paleozoic originally along the northern edge of the Gondwana continent) with Avalonia and Baltica (East European Platform).

The eastern part of Moravia and Silesia belong to the Western Carpathian orogen, which is one of sub-parts of the Alpine orogen—a vast mountain system of southern Europe. It was formed by collisions of continental fragments situated between the northern edge of Africa and the so-called Epi-Variscan Platform of Western Europe during the Mesozoic and the Tertiary.

The aim of the following chapter is thus to characterise the specific features of development and detailed division of both the above-mentioned different geological units constituting the territory of the Czech Republic.

2.2 The Bohemian Massif

The Bohemian Massif is one of the largest continuously outcropping fragments of the originally vast Variscan orogen that crops out from the basement of younger Epi-Variscan Platform sediments. The comparatively extensive Variscan orogen was formed gradually in the course of joining the peri-Gondwana fragments to (see Franke 1989; Franke et al. 2000; Matte et al. Laurussia1986, 1990, 1991; Winchester 2002; Ziegler 1982, 1984), i.e. to the more northerly situated continent created as the result of Caledonian convergence between Laurentia and Baltica.

Based on the current concepts of development of continents (Condie 1989), which start from the application of principles of plate tectonics, the Bohemian Massif can be interpreted as a heterogeneous unit composed of four separate regional domains. Each of them is defined especially by a specific stratigraphic content, tectomagmatic development and tectonic boundaries in relation to its surroundings.

According to the binding regional geological division of the Bohemian Massif (Commission 1994), the Bohemian Massif can be divided, based on the differences in structure and geological development, into four autonomous regions: Moldanubian Unit, Teplá-Barrandian Unit, Saxo-Thuringian Unit (subdivided by the younger Elbe Fault Zone into the Krušné hory Mountains Zone and the Lugicum = West Sudetic Zone) and Moravo–Silesian Unit (Fig. 2.2). This basic division reflects the existence of four independent

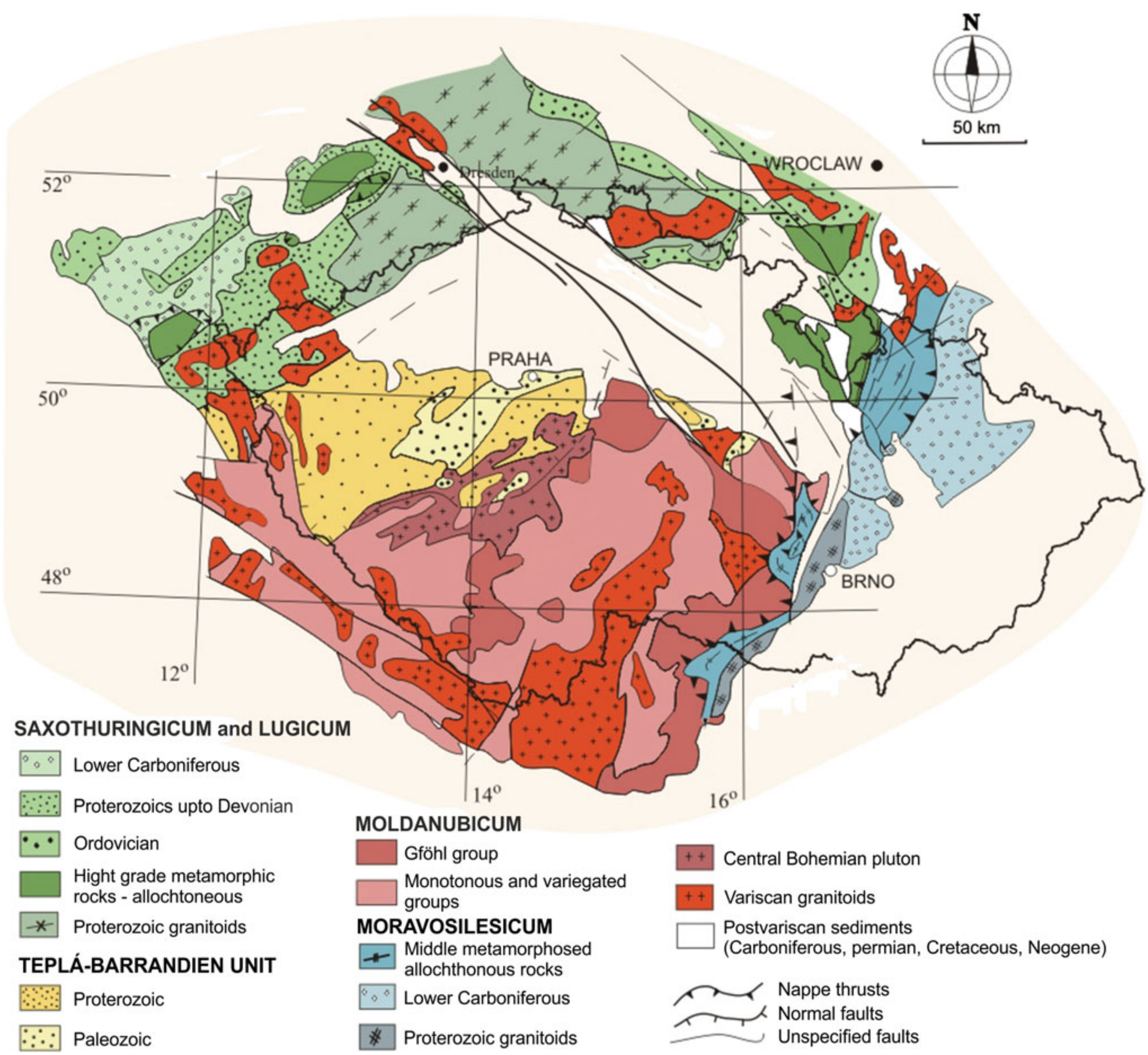

Fig. 2.2 Main Variscan regional units of the Bohemian Massif (Simplified according to Schulmann et al. 2005)

crustal fragments separated originally by oceanic domains, the traces of which are indicated today by the occurrences of ophiolite complexes and/or belts with high-pressure and mantle rocks (Mariánské Lázně complex, Letovice ophiolite complex, blueschists of Železný Brod crystalline complex and Rýchory ridge, high-temperature and high-pressure rocks of the Gföhl Unit). Paleomagnetic data (Krs et al. 2001; Tait et al. 2000), a number of common features in the development of the Cadomian basement, the presence of Cadomian calc–alkaline granitoids, formed by melting rocks above a subduction zone and flysch sequences deformed during the Cadomian orogeny, document that these units were part of a belt of island arcs and perhaps accretionary complexes on the northern edge of Gondwana. In the boundary period between the Proterozoic and the Paleozoic, this belt was situated in the area of low southern latitudes (Fig. 2.3).

It is the independence of the Moldanubian Unit that remains problematic. In comparison with the other units, the Moldanubian Unit has a different lithology, geophysical characteristics of the crust and the subcontinental mantle (Beránek and Dudek 1981; Beránek and Zátopek 1981; Babuška and Plomerová 2001), tectonic boundaries (with the Moravo–Silesian Unit and the Teplá-Barrandian Unit are quite evident) and above all different metamorphic development, given by the substantially deeper present-day denudation level.

In spite of the fact that the above-mentioned units are separated by significant sutures and tectonic zones, they have a number of common features related to the Neoproterozoic and, in part of them, also in the Cambro–Ordovician development; on the contrary, they differ markedly as far as the early stage of Paleozoic development during the Variscan orogeny is concerned.

After the end of the Variscan orogeny, the Bohemian Massif was gradually transformed into a platform unit. Paleomagnetic data for the Early Permian document that all western, central and northern Europe behaved as a single unit designated the North European Platform. It also included the Bohemian Massif. During the Carboniferous, it gradually became dry land. In the most of the area, with the exception of intramontane depressions, deep erosion of the Variscan basement took place. Erosion and continental sedimentation were interrupted only for a short time by a marine transgression over part of the area in the Jurassic, Cretaceous and Neogene Periods. In addition to the

Fig. 2.3 Proterozoic biotitic gneiss of Gföhl group of Moldanubicum. Locality Náměšť nad Oslavou (*Photo* R. Grygar)

deposition of sediments in the depressions, various types of volcanic bodies of Cretaceous to Quaternary age provided the finishing touches to the surface of the platform cover of the Bohemian Massif.

The basis of regional division of the Bohemian Massif is natural geological boundaries represented by significant sutures, and also other types of tectonic boundaries separating microcontinents (also smaller units, so-called terranes) with different paleogeographical provenances, lithologies and tectonometamorphic effects, ages of rock complexes, and maybe with different characters of magmatic manifestations.

The pre-Variscan geodynamic development of the units can be divided into two phases: Neoproterozoic and Paleoproterozoic. The Neoproterozoic development is evidenced best in the Teplá-Barrandian Unit (Fig. 2.4) and in the Saxo-Thuringian Unit reworked slightly by the Variscan orogeny. In a lithological record, a transition to the regime of active subduction in the upper part of the Neoproterozoic (Kralupy-Zbraslav Group), which was accompanied by the formation of island arcs and subsequently of an accretionary wedge of flysch sediments above the subducting oceanic lithosphere, is evident. During the Cambrian, the subduction

Fig. 2.4 Outcrops of Proterozoic silicites from Teplá-Barrandien region. Lokality Hudlice (*Photo* R. Grygar)

died away and the active margin was transformed to a passive margin. Parts consolidated by the pan-African orogeny began separating from the mother continent, Gondwana, in the Cambrian. A system of rifts was formed; along them, the comparatively continuous Avalonian-Cadomian belt of microcontinents was broken up.

The paleomagnetic, paleobiogeographical data and analysis of clastic micas and zircons show that East Avalonia and fragments outcropping on the eastern periphery of the Bohemian Massif separated first and at the fastest rate (Bruno-Vistulicum, Malopolska Massif and also Lysa Gora Unit of Holy Cross Mountains (Góry Swietokrzyskie)—e.g. Belka et al. 2002). The Malopolska Massif and the Bruno-Vistulicum came to direct contact already during the Cambrian.

Later, at the Cambrian–Ordovician boundary, the remaining Armorican microcontinents began separating as well. The separation of these microcontinents is also indicated, in addition to the paleomagnetic records, by extensive bimodal rift volcanism and magmatic activity, the beginning of which falls within the period from 520 to 480 Ma (i.e. Cambrian–Ordovician boundary). This magmatism is observable above all along the rims of gradually separating blocks in the whole area of the Armorican group of continents. Changes in tectonic regime at the Cambrian–Ordovician boundary caused that the Cambrian sedimentation cycle, connected partially with the Cadomian development, was sharply separated from the Ordovician–Devonian cycle in the Teplá-Barrandian Unit so as in the Saxo-Thuringian Unit. An acceleration of the expansion of the originally continental rifts then gradually led to the formation of the Rheic Ocean and, on the contrary, to the closure of the Tornquist Ocean.

From the paleomagnetic data and paleoclimatic indicators (Krs et al. 2001) it is obvious that, e.g. the Teplá-Barrandian Unit moved gradually from lower southern latitudes (about 40° South Latitude in the Ordovician, 20° South Latitude in the Silurian) to the northern hemisphere. In the Devonian, it was located in the tropical equatorial region; during the Early Devonian, it crossed the equator. The extensional regime in these continental fragments continued till the Early Devonian, when the tectonic regime began to change, with the onset of the Variscan orogeny, into compressional one. For this reason, the early Paleozoic sequences that deposited along the passive margins of these fragments in the majority of the units are largely continuous.

The Variscan orogeny was a result of collisions of the Armorican microcontinents and their final amalgamation to Avalonia and Bruno-Vistulicum. In the Bohemian Massif, it is a case of the collisions between the Teplá-Barrandian plate and the Moldanubicum and Saxo-Thuringicum, followed with the final amalgamation of the above-mentioned units to the Variscan foreland formed in N and NW by the block of

East Avalonia consolidated by the Caledonian orogeny and in NE by the Bruno-Vistulicum. Differences in the Variscan development of the four basic units of the Bohemian Massif are given by their different positions in the Armorican group of microcontinents, which entered to the processes of Variscan collisions at considerable intervals. The geometry of subduction zones determined, to a certain extent, even later processes of continental collisions, especially the vergence of overthrusting movements on the boundaries of colliding fragments. Sutures that controlled the processes of Variscan orogeny were as follows: Gföhl suture and its equivalents in the French Massif Central (south Brittany) and the Iberian Peninsula (Galician), Teplá suture (suture between the Teplá-Barrandian Unit and the Saxo-Thuringicum) and Rheic and Rheno-Hercynian sutures, between Avalonia and the northern margin of the Saxo-Thuringicum. First the Gföhl suture between the Moldanubian microblock and the Teplá-Barrandian microblock was closed (based on an analogy with the French Massif Central, this happened probably in the period from the Silurian till the Early Devonian). From the suture, metamorphic complexes mostly of Precambrian to Early Paleozoic age were thrust out towards the south and in the case of the Bohemian Massif towards the south-east. The thickened Moldanubian crust was strongly heated, which led to the origin of extensive granitoid bodies in the Early Carboniferous. A rapid exhumation of the thickened orogenic root caused its deep erosion up to the level of the middle crust. In consequence, less metamorphosed and unmetamorphosed supracrustal units are missing in the Moldanubicum.

The Teplá suture, forming the present-day geological boundary between the Teplá-Barrandian microblock and the Saxo-Thuringicum, was also closed in the Devonian; an obduction of high-pressure rocks took place at the end of the Middle Devonian (c. 380–370 Ma). Rocks from rather deep parts of the Saxo-Thuringian Ocean and both continental margins were thrust out towards NW over the Saxo-Thuringian autochthon. The outermost sutures of the Variscides are the Rheic and Rheno-Hercynian sutures. The older Rheic suture, which was closed already during the Devonian, is indicated by calc-alkaline volcanism and high-pressure low-temperature (HP–LT) metamorphism in the area of so-called Northern Phyllite Zone on the boundary of the Saxo-Thuringicum and the Rheno-Hercynicum. The equivalent of the Rheno-Hercynian suture in the Bohemian Massif is probably complexes on the boundary of the Bruno-Vistulicum and the Lugodanubicum, of which the Devonian–Carboniferous, mostly flysch complexes were thrust out towards E over the Bruno-Vistulian foreland.

The gradual migration of tectonic deformation in time and space from south to north together with different geometries of the main zones of shortening created the characteristic fan-like zonal structure of the Variscan orogen as defined already in classic papers (Suess 1926; Kossmat 1927; Stille 1951). Based on the age of protoliths of rocks of the basement and the Variscan mantle, main tectonic deformation phases, intensity of metamorphism, pre- and post-Variscan magmatic manifestations, the following zones can be defined from south to north: Moldanubian Zone, Saxo-Thuringian Unit, Rheno-Hercynian Zone and Subvariscan Foredeep; they can be observed in all the European Variscides (Cháb et al. 2010).

The Moldanubian Zone is characterised by an inverted internal metamorphic structure, high intensity of metamorphism, presence of HP–HT rocks (Fig. 2.3), which differ from similar rocks in other zones by higher temperatures and pressures of equilibration of high-pressure parageneses. The Teplá-Barrandian Unit, which represents together with the Armorican Massif the best preserved relic of the Cadomian crust, covered partly with discordantly laid unmetamorphosed Early Paleozoic sequences, was earlier regarded either as part of the Moldanubian Region (Kossmat 1927; Franke 1989), or as part of the Saxo-Thuringian Unit (Ellenberger and Tamain 1980; Mísař et al. 1983). It follows from the paleomagnetic data and well-documented suture lines, which delimit it, that these units have, in the framework of the orogen, independent positions. The termination of sedimentation in the Devonian and the main phase of deformation between the Givetian and the Fammenian make it different from the surrounding units, likewise the presence of the fundamental complex slightly reworked by the Variscan orogeny. The metamorphic development, in contrast with the Saxo-Thuringian Unit and the Moldanubian Region, is caused by Early Carboniferous subsidence along the extensive West Bohemian and Central Bohemian shear zones (Zulauf 1994).

The Saxo-Thuringian Unit is characterised, in comparison with the Teplá-Barrandinian Unit, by higher intensity of Variscan reworking of the Cadomian basement, by largely continuous unmetamorphosed to weakly metamorphosed sequences of the Paleozoic in the period from the Cambrian to the Lower Carboniferous (Fig. 2.5) and by Devonian to Carboniferous extension accompanied by intraplate volcanism. A characteristic feature is the presence of allochthonous relics that were thrust out from the Teplá suture and occupy the highest structural position, and the presence of granulite complexes underlying the Lower Carboniferous flysch units.

The Rheno-Hercynian Zone represents a predominantly Devonian–Carboniferous accretionary complex thrust out from the Rheno-Hercynian suture between Avalonia and the Saxo-Thuringicum. Older rock complexes crop out at the surface only rarely. The Zone is characterised by weak metamorphism and fold–thrust structure.

The Variscan Foredeep (Subvariscicum) represents a classical foreland basin formed by lithospheric flexure before the fronts of nappes of the Rheno-Hercynicum

Fig. 2.5 Outcrop of Ordovician quartzite belongs to allochtonian sequences of Krkonoše–Jizera units in the Lugicum region. Locality under the Ještěd Mt. (*Photo* R. Grygar)

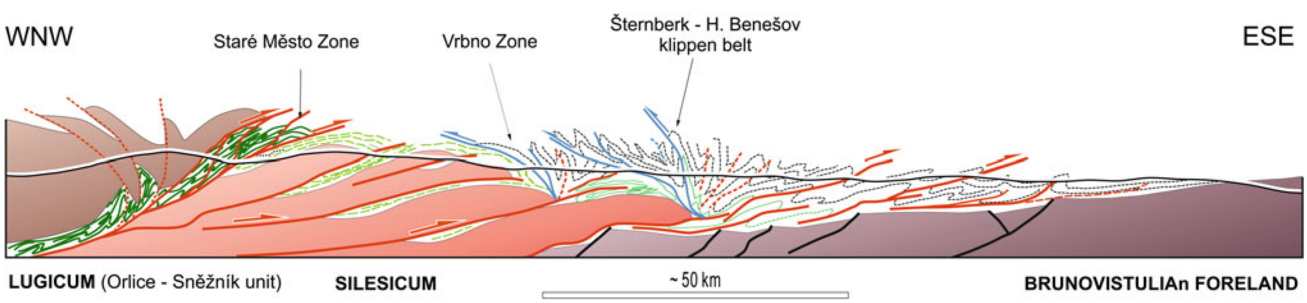

Fig. 2.6 Schematic structural cross section of the Variscan accretion wedge of the Moravo-Silesian unit. According to Grygar and Vavro 1995

finishing their thrust over the Avalon-Bruno-Vistulicum foreland (Figs. 2.6 and 2.7). The stratigraphic range of a molasse, first marine and later continental, is from the Namurian to the Westphalian. Variscan folds disappeared in the course of its filling. The character of fauna and flora shows that at that time oceanic barriers no longer existed in Europe and that newly created Variscan Europe formed one unit with the Gondwana.

2.3 *The Post-Orogenic—Platform Development of the Bohemian Massif*

Basic features of the structure of basement of the Bohemian Massif were formed during the Variscan orogeny. At the beginning of the Westphalian, the Bohemian Massif became part of the stabilized Variscan crust of the West European

Fig. 2.7 Fold and thrust structures of the Variscan flysh foredeep with eastward vergency. Locality Stará Ves near Bílovec (*Photo* R. Grygar)

Platform, which in consequence meant that it began to act as a single unit, in which any mutual lateral displacement of units, metamorphosis and associated ductile deformation no longer were taking place. The majority of later deformations are brittle, when vertical (largely in the order of several hundred metres to several kilometres) and/or lateral movements (in the order of kilometres to several tens of kilometres as a maximum) occured. Mostly it is the case of faults and tectonic zones, created by the Variscan orogeny and later reactivated, which reacted to changes in the stress regime in the lithosphere during the Mesozoic and the Tertiary in the course of so-called Saxonian tectonics due to deformations in the foreland of the Alpine orogen. The most significant lines are NW–SE faults (Sudetic direction), parallel to the Tornquist line, NE–SW faults (Krušné hory Mts. direction) and NNE–SSW faults (originated at the end of the Variscan phase as so-called furrows—Boskovice, Blansko, Jihlava). The Bohemian Massif is segmented by these faults into a series of blocks that show different characters of dominant movements in different phases. Platform sediments are only exceptionally affected by large-wavelength flat-lying folds, such as folds in the Cretaceous in the surroundings of the Orlice Basin, Hořice Ridge, etc.

A transition from the orogenic phase to the post-orogenic phase took place during the Westphalian (Late Carboniferous), in the course of which ductile deformations in the area of Variscan foreland basins terminated. After thickening the Variscan crust in the compressional phases of the Variscan orogeny, a gravitational collapse of the orogen happened. It was accompanied by the formation of asymmetrically bounded inner continental molasse basins (Fig. 2.8). The basins are often created by crustal subsidence along the originally compressional structures (Mattern 2001).

The Variscan molasse basins can be divided into two groups: the older group of intramontane basins of Namurian–Westphalian age is largely parallel to the major zones of the Variscan orogen. After a change in tectonic regime, when especially horizontal movements along the fault systems of Sudetic and NNE-SSW direction began to play their role, the other (i.e. younger) group of Stephanian–Permian basins, having often the character of narrow and deep asymmetric tectonic trenches, was formed. Already in the Early Permian (Saxonian) we can observe that subsidence slowed down and the area of the basins gradually decreased. In the Lugicum area, sedimentation of the Variscan molasse was terminated as late as in the Triassic.

The synconvergent granitoid magmatism, the culmination of which was recorded in the internal zones of the Variscides in the period from the Late Viséan to the Namurian (345–325 Ma), continued by intrusions of post-tectonic, mostly geochemically strongly differentiated granitoids till the Early Permian. As well, manifestations of the volcanic activity passed without interruption from the orogenic period to the post-orogenic molasse stage. In the Westphalian to the Lower Stephanian, explosive acid magmatism extended especially in the area of Central Bohemian and Western Bohemian basins. The final phase of subsequent intraplate magmatism falls to the period from the Stephanian to the Autunian. During this phase, in addition to the acidic members, alkaline members were also formed.

The termination of Triassic sedimentation can be regarded as the beginning of platform development of the Bohemian Massif. Almost for the whole remaining period of the Triassic and the Jurassic, it was exposed to extensive erosion and peneplanisation. In the Late Jurassic, only a narrow strip of the Massif along the Elbe Fault Zone was

Fig. 2.8 Tectonic contact in the zone of the Hronov–Poříčí thrust fault of Upper Cretaceous marine sediments (*left side*) with Permian continental red coloured sandstones (*right side*). Locality Malé Svatoňovice in the SW limb of the Lower Silesian basin (*Photo* R. Grygar)

flooded by the sea to form a channel connecting the North German Basin with the Tethyan area. After a short period, the sea again retreated from this area. The cover, which is more significant from the point of view of thickness, occurs in the south-east slopes of the Bohemian Massif, periodically reached by transgressions from the area of the western Tethys.

The long period of prevailing denudation of the Bohemian Massif was replaced, on a larger scale, by sedimentation only during the eustatic rise in the level of world's oceans in the Late Cretaceous, when part of the Bohemian Massif subsided along the faults of the Elbe Fault Zone and became a site of at first continental and later marine sedimentation in the Bohemian Cretaceous Basin. At the end of the Cretaceous and in the Paleogene, inversion of the Bohemian Cretaceous Basin occurred as a result of folding in the Alpine area. Some NW–SE faults that acted as normal faults or strike-slip faults in the course of deposition of Cretaceous sediments were used for shortening the basin in this stage. The best-known example of an inverted fault is the Lusatian Fault (reverse fault) (Adamovič and Coubal 1999).

In the Tertiary, continental basins of rather small extent were formed in the area of the Ohře/Eger Rift and in southern Bohemia. In the pre-rift stage, older depressions in relief were filled; the rift stage is connected with an increased rate of subsidence of the basin bottom and with sedimentation of several hundred metres of Miocene sediments (Fig. 2.9). In the course of sedimentation, extensive volcanic activity took place along the faults, especially those limiting the south-eastern margin of the rift (Doupov Mountains, Central Bohemian Uplands).

The Quaternary is a period when the Bohemian Massif was, after the regression of the sea of the Carpathian Foredeep in the Tertiary, solely dry land. It is a very short period in comparison with the duration of the other geological units (c. 1.6–1.8 Ma). In the Quaternary, the character of geological, especially exogenous processes was affected by the existence of vast ice sheets that covered considerable part of northern Europe.

Fig. 2.9 Open pit mine Družba in the Neogene Sokolov basin located in the Ohře/Eger graben. Coal seam outcropping along boundary normal falt. In the footwall (*right side*) weathered metamorphic rock of the Saxo-Thuringian zone of the Krušné Hory Mountains cropping out (*Photo* R. Grygar)

2.4 The Western Carpathians

The Western Carpathians are one of partial branches of the vast orogenic belt of the Alpides created from the former Tethys Ocean that extends from Spain to south-eastern Asia. In the territory of the Czech Republic, they occur merely in the easternmost areas of Moravia and Silesia. The development of the Western Carpathians already begins shortly after terminating the Variscan orogeny that gave rise to a huge supercontinent called Pangaea.

The beginnings of the origin of narrow rift basins, meaning the beginning of disintegration of Pangaea, are evident as early as in the Triassic. During the Jurassic and the Cretaceous, the broadening and differentiation of the basins occurred between Africa and Europe. However, at the end of the Jurassic, some of them began to close again, which led later even to continental collisions of partial microblocks that took place in the European area in three waves in the course of the Jurassic to the Early Cretaceous (c. 160–120 Ma), Late Cretaceous (110–80 Ma) and Paleogene to Neogene (45–12 Ma). The basement of the Mesozoic and Tertiary units, later folded during the Alpine cycle, with the exception of oceanic domains, is formed, both in the Alps and in the Carpathians, mostly by various parts of the crust formed by the Variscan orogeny.

In the Western Carpathians, migration of orogenic processes towards the north manifested itself in characteristic orogenic zonation that became the base for the inner zonation of the orogen. At present, the Carpathians are divided from south to north into the Inner, Central and Outer Western Carpathians. The Central as well as the Inner Carpathians do not occur in the territory of the Czech Republic.

In the area of eastern Moravia and Silesia, the Outer Carpathians are represented by two accretionary flysch complexes and the Carpathian Foredeep. The older accretionary complex is composed of Cretaceous but largely Paleogene siliciclastic complexes of the Magura Group of nappes immediately adjacent to the klippen zone interpreted earlier as part of the Outer Carpathians; at present, especially its inner parts are interpreted as part of the Late Cretaceous–Early Tertiary accretionary complex that occurs in the place of an assumed suture after the oceanic domain, the so-called Vahicum.

In the Magura Group of nappes in rhythmically bedded units, which are characteristic of flysch basins, sandy members predominate over claystones, siltstones and coarser-grained clastics. The total thickness of the sediments is several kilometres. The frontal parts of the nappes of this group reached comparatively far, as far as the Moravo–Silesian boundary, approximately the Hodonín–Valašské Meziříčí–Třinec line. They are partly overlain by sediments of the Vienna Basin and Late Miocene and Pliocene sediments of the filling of the Hornomoravský úval basin. This complex was shortened already during the Paleogene, but the thrust over the external group of nappes took place during the Miocene at the end of closure of flysch basins (42–23 Ma). The amplitude of overthrust is estimated at several tens of kilometres.

The younger accretionary complex in the area of Moravia and Silesia is composed of the Pouzdřany, Ždánice, Subsilesian, Silesian and Fore-Magura Units. In the Polish and