

Geomorphological estimates of orogenic uplift based on fluvial relief types in the Bohemian Massif

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ABSTRACT

This article presents research results regarding geomorphological topics investigated by the late RNDr. Břetislav Balatka, CSc. (1931–2025) and his colleagues in recent years. It primarily focuses on the classification of fluvial relief types and their relationship to the extent and rate of tectonic uplift of morphostructural units in the Bohemian Massif, Czechia.

The morphogenetic diversity of fluvial relief types of the Bohemian Massif is a consequence of the synergy between differential tectonic uplift induced by the ongoing Alpine orogeny and the variability of exogenous processes caused by pronounced climatic changes during the Cenozoic. The extent of vertical tectonic movements of morphostructural units in the Bohemian Massif, determined based on types of fluvial relief, reaches values on the order of 10^1 – 10^3 m over the Late Cenozoic. These represent minimum values for tectonic uplift in the Bohemian Massif. This approximate estimation is based on the substantial erosion and denudation of its landforms, including planation surfaces of various origins and age, and fluvial sediments of river terrace systems, under the influence of intensive climate-morphogenetic processes. Moreover, significant epigenetic and antecedent deepening of river valleys took place only from the late Middle Pleistocene. The fluvial sediments of river terraces I and II of the main streams were deposited during the Cromerian Complex period, while river terrace III was deposited during the Elsterian glaciation.

KEYWORDS

landform evolution; fluvial relief types; orogenic uplift; the Bohemian Massif; Late Cenozoic

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1. Introduction

1.1 Aims of the study

The study focuses on the results of research into one of the geomorphological topics that RNDr. Břetislav Balatka, CSc. (*11. 1. 1931 – †15. 2. 2025) and his colleagues have been working on in recent years. It mainly concerns determining the types of fluvial relief and their relationship to the extent of tectonic uplift of the morphostructural units in the Bohemian Massif. The solution consists in a combination of the created geomorphological division of the Bohemian Massif, the historical-genetic classification of its fluvial relief types, and research into the evolution of landforms in selected regions in Czechia. A comprehensive interpretation of the above-mentioned data sets and findings then enabled the preparation of a map showing the extent of tectonic uplift of morphostructural units in the Bohemian Massif in regions with fluvial relief types from the Upper Miocene to the present. By presenting this research work, we commemorate the creative spirit of Břetislav Balatka on the occasion of the 95th anniversary of his birth.

1.2 A brief reminder of the scientific work of Břetislav Balatka

The diverse trajectories of Břetislav Balatka's professional and personal life were closely connected with the Czech landscape. The results of his natural science research are a classic part of the intellectual wealth of Central European geography (Příbyl 2001; Kalvoda 2011, 2016 and Appendix 1). In the last period of his active work at the Department of Physical Geography and Geoecology of the Faculty of Science, Charles University, Břetislav Balatka focused primarily on the further development of selected thematic areas that are currently relevant in the international context of the development of geomorphology and physical geography.

He continued research on river terraces and the evolution of fluvial valleys in Czechia, as well as the study of methodological and morphogenetic aspects of regional geomorphological mapping. He also focused on the morphostructural and climate-morphogenetic evolution of specific types of georelief in the Bohemian Massif in the late Cenozoic. Břetislav Balatka contributed decisively to the conceptual framework and elaboration of the morphostructural regionalisation of the Czech part of the Bohemian Massif (according to the geomorphological terminology the Česká vysočina Highland; Balatka 2003; Balatka and Kalvoda 2006a), as well as to physical-geographical research in the central part of the Sázava River drainage basin and in the Prague area (Balatka 2007; Kalvoda and Balatka 2016). Furthermore, he continued the comprehensive interpretation of long-term geomorphological research in the Ohře (Eger) River drainage

basin (Balatka and Kalvoda 2018; Balatka et al. 2019). These regional studies were carried out with the aim of identifying signatures of the late Quaternary tectonic activity, slope movements, and related types of natural hazards.

Břetislav Balatka's fundamental achievement was the completion of a detailed classification of the georelief of the Bohemian Massif, presented in both text and cartographic form at a scale of 1:500,000 (Balatka and Kalvoda 2006a, 2006b), including the determination of morphographical and morphogenetic types of georelief. The catastrophic floods in the Czechia were, for Břetislav Balatka, one of the impulses for further extensive research of river accumulation terraces in Central Europe. Regional river terrace systems and the evolution of the Sázava and Želivka valleys were studied (e.g., Balatka and Štěpančíková 2006; Balatka 2007; Balatka and Kalvoda 2010a, 2010b), including their parallelisation with the river terrace systems of the Vltava and Labe rivers (Balatka and Kalvoda 2008, 2010c).

Břetislav Balatka devoted considerable attention to the current topic of the correlation between the morphostratigraphy of river accumulation terraces in the Bohemian Massif and the European sequence of the chronostratigraphic division of the Quaternary (Balatka et al. 2010a, 2010b, 2015, 2019). The original results of his research also testify to the fact that the Bohemian Massif is one of the key regions for understanding the interplay between orogenic activity and climate-morphogenetic processes during the evolution of the natural environment of Europe.

1.3 Motivation for the topic

In physical-geographical and geological publications, there is broad consensus and tradition that the current morphostructures of the Bohemian Massif were formed by neotectonic processes during the Cenozoic (e.g., Balatka et al. 1983; Chlupáč et al. 2002; Demek et al. 2007, 2009; Grygar 2016), predominantly during the Neogene phases of the Alpine orogeny and partly also in the Quaternary. The fundament of the current georelief of the Bohemian Massif was the Paleogene planation surface (Balatka 1968; Malkovský 1975, 1979; Král 1985; Kovanda et al. 2001), which was progressively broken up by differential tectonic movements, including subhorizontal displacements, uplift and subsidence. The long-term trend of differentiated tectonic uplift of the morphostructural units of the Bohemian Massif, whose boundaries are often defined by pronounced fault scarps, continues to prevail over relative subsidence even at present.

The geomorphology of the Czech lands is highly diverse, which is mainly caused by their location on the northern edge of the Alpine-Carpathian orogenic zone between the African and European continental plates (Pharaoh 1999; Chlupáč et al. 2002; Cháb et al. 2007, 2008). Morphostructural analyses of the

Hercynian crystalline rocks of the Bohemian Massif have shown (cf. Balatka and Kalvoda 2006a, 2010a; Demek et al. 2009; Pánek and Hradecký Eds. 2016) that its individual parts responded to Alpine orogenic processes in varied ways. Several phases of tectonic activity during the Tertiary led to the formation of the ridge and graben structure of the Bohemian Massif and to the uplift of its marginal mountain ranges (Ivan 1999; Ivan et al. 2000; Pánek and Kapustová 2016). Older planation surfaces were reshaped by neotectonic processes, uplifted to various elevations and simultaneously subjected to deep erosion and denudation. Substantial paleoclimatic changes during the Cenozoic (e.g., Příbyl 1972; Ložek 1973; Kopecký and Cílek 1998; Ložek et al. 2003; Hradecký and Brázdil 2016) further controlled the variability of exogenous geomorphological processes in Central Europe.

The Paleogene planation surface was mainly of an etchplain character (Král 1966, 1968; Demek 2004) with variously strong weathering of crystalline rocks, deep igneous rocks, and Mesozoic sediments of the Česká tabule Table. The fragmentation of the Paleogene planation surface probably increased from the area of today's central part of the Česká tabule Table toward the south and southwest. Collisional stresses associated with the Alpine orogeny on the Hercynian block of the Bohemian Massif caused undulation and flexural deformation of its originally flat surface, including the reactivation of older fault zones. As a result, neotectonic structures of the Bohemian Massif developed in the form of anticlines, synclines, escarpments, faults and tectonic trenches.

It should be noted that the morphostructural principles of the development of the Bohemian Massif had been already studied by Daneš (1913), Dědina (1914) and Moschelesová (1923, 1930), including the identification of fundamental tectonic zones trending NW–SE, SW–NE, and N–S. A more detailed arrangement of geomorphological units was subsequently established on these primary megastructures, usually in combinations of the above-mentioned main tectonic zones (Hrádek and Ivan 1972, 1974; Coubal 1989; Coubal and Adamovič 2000). Examples include the mosaic pattern of geomorphological units in the Šumava subprovince (Fig. 1), the alternation of anticlines and synclines within the Česká tabule Table and in the Brněnská vrchovina Hill Country, where horsts and grabens were formed.

The Sudeten direction of tectonic zones (NW–SE) (Cymerman 1999; Danišík et al. 2010, 2012) is particularly evident in the arrangement of morphostructural units of the Krkonoše-Jizera subprovince, the Šumava subprovince, in the northern part of the Českomoravská vrchovina Highland (e.g., Železné hory Mountains, Hornosvratecká vrchovina Hill Country), in the area of the so-called Central Bohemian Threshold and in the distinctive concave units of the Labe (Elbe) basins and South Bohemian basins (Fig. 1;

Balatka and Kalvoda 2006a). The Krušné hory Mountains direction of tectonic zones (SW–NE) prevails in the morphostructures of the Krušnohorská subprovince (Balatka and Sládek 1975; Vilímek 1993, 1997; Stolínová and Vilímek 2003), the Poberounská subprovince and in the Brněnská vrchovina Hill Country. The Jizera direction of tectonic lines (N–S) (Balatka 1958, 1966; Balatka and Sládek 1973; Zeman 1978; Balatka et al. 2000) is striking in the patterns of morphostructural units along the southeastern edge of the Česká tabule Table and in the southern part of the Českomoravská vrchovina Highland.

During the late Cenozoic, differential tectonic uplift and changes in climatic conditions significantly affected the development of the river network of the Bohemian Massif. Gradually, substantial changes of drainage pattern occurred, accompanied by intensive epigenetic and antecedent development of river valleys, as well as by the reworking of large areas of fluvial deposition (Kunský 1929, 1966; Balatka and Sládek 1962a, 1963, 1970, 1974; Balatka et al. 1964, 1966; Ložek et al. 2004). The grain-size characteristics of Pliocene fluvial sediments in the Bohemian Massif is similar to those of Lower Pleistocene deposits (cf. Kunský 1929, 1966; Záruba 1942; Záruba and Rybář 1961; Kovanda et al. 2001). This similarity suggests that the Bohemian Massif already had a similar orographic arrangement as it has today.

The synergistic action of climate-morphogenetic processes and tectonic uplift have created Quaternary systems of river accumulation terraces in the valleys of the main streams of the Bohemian Massif (e.g., Balatka and Sládek 1964, 1976; Balatka and Loučková 1992; Balatka et al. 2015, 2019). These fluvial sediments, together with other signatures of the antecedent development of river valleys (e.g., Mazáčová et al. 1963; Příbylová et al. 1967; Příbyl and Votýpka 1970; Balatka and Příbyl 1996, 1997), presents an important source of data on the history of the georelief of the Bohemian Massif. The briefly described paleogeographic aspects of the formation of morphostructural units are significantly reflected in the present-day orography of the Bohemian Massif. Consequently, they have traditionally provided a key impetus for development of geomorphological regionalisation schemes of landforms across the broader Central European region at the collisional contact of the Hercynian, Alpine and Carpathian orogens.

2. Methodology

2.1 Concept and types of geomorphological regionalisation

Geomorphological regionalisation involves the separation and delimitation of objectively existing territorial units of the Earth's surface relief according to defined criteria. In this analytical process, two

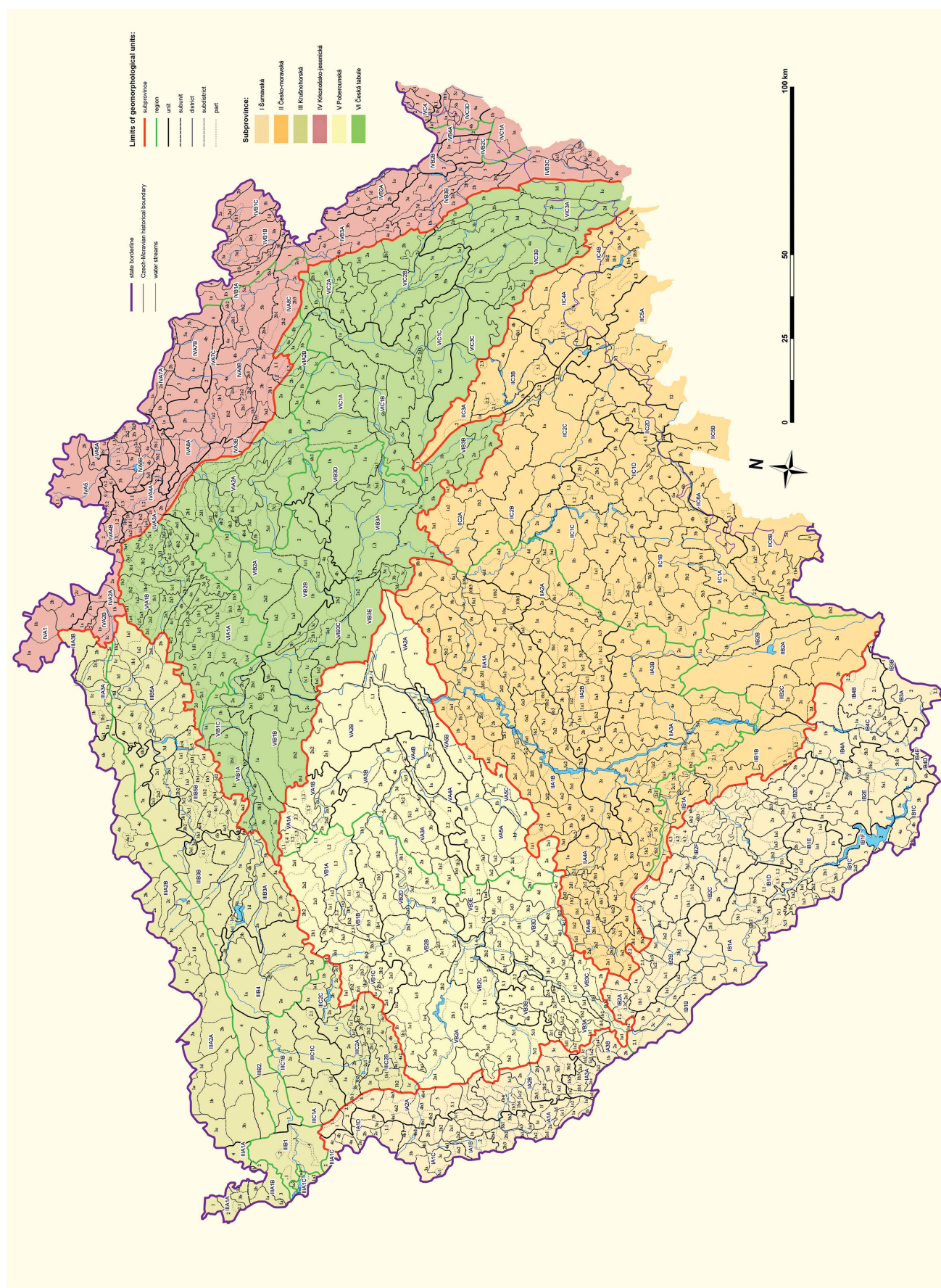


Fig. 1 Geomorphological units in the territory of Bohemian (Czech) part of the Bohemian Massif (the Česká vysočina Highland) ranging from subprovinces to subunits (adapted according to detailed maps and tables in Balatka and Kalvoda 2006a). Basic data on these geomorphological units are given in Tab. 1. Created by Břetislav Balatka, Jan Kalvoda and Tereza Steklá.

Tab. 1 Geomorphological regionalisation of the relief of Bohemia in the range from subprovince to subunit (modified after Balatka and Kalvoda 2006a).

Subprovince	Region	Unit	Subunit	Name of the geomorphological unit	Highest point [m a.s.l.]	Lowest point [m a.s.l.]	Amplitude span [m]
I				Šumavská subprovincie	1378	370	1008
I	A			Českoleská oblast	1042	370	672
I	A	1		Český les	1042	425	617
I	A	1	A	Čerchovský les	1042	425	617
I	A	1	B	Kateřinská kotlina	546	496	50
I	A	1	C	Přimdský les	894	450	444
I	A	1	D	Dyleňský les	940	470	470
I	A	2		Podčeskoleská pahorkatina	679	370	309
I	A	2	A	Tachovská brázda	679	420	259
I	A	2	B	Chodská pahorkatina	662	370	292
I	A	3		Všerubská vrchovina	751	405	346
I	A	3	A	Českokubická vrchovina	668	420	248
I	A	3	B	Jezvinecká vrchovina	751	405	346
I	B			Šumavská hornatina	1378	400	978
I	B	1		Šumava	1378	465	913
I	B	1	A	Šumavské pláně	1370	565	805
I	B	1	B	Železnorudská hornatina	1343	465	878
I	B	1	C	Trojmezská hornatina	1378	560	818
I	B	1	D	Boubínská hornatina	1362	600	762
I	B	1	E	Želnavská hornatina	1228	693	535
I	B	1	F	Vltavická brázda	845	711	134
I	B	2		Šumavské podhůří	1096	385	711
I	B	2	A	Strážovská vrchovina	770	415	355
I	B	2	B	Svatoborská vrchovina	989	450	539
I	B	2	C	Vimperská vrchovina	922	455	467
I	B	2	D	Prachatická hornatina	1096	430	666
I	B	2	E	Českokrumlovská vrchovina	1066	485	581
I	B	2	F	Bavorovská vrchovina	700	385	315
I	B	3		Novohradské hory	1072	485	587
I	B	3	A	Pohořská hornatina	1072	570	502
I	B	3	B	Jedlická vrchovina	832	485	347
I	B	4		Novohradské podhůří	870	400	470
I	B	4	A	Kaplická brázda	753	400	353
I	B	4	B	Stropnická pahorkatina	696	400	296
I	B	4	C	Soběnovská vrchovina	870	430	440
I	B	4	D	Hornodvořišská sníženina	721	555	166
I	B	4	E	Klopanovská vrchovina	824	648	176
II				Česko-moravská subprovincie	836	189	647
II	A			Středočeská pahorkatina	729	195	534
II	A	1		Benešovská pahorkatina	638	195	443
II	A	1	A	Dobříšská pahorkatina	546	195	351
II	A	1	B	Břežnická pahorkatina	638	250	388
II	A	2		Vlašimská pahorkatina	723	285	438
II	A	2	A	Mladovožická pahorkatina	635	285	350
II	A	2	B	Votická vrchovina	723	350	373
II	A	3		Táborská pahorkatina	633	295	338
II	A	3	A	Písecká pahorkatina	633	295	338
II	A	3	B	Soběslavská pahorkatina	545	370	175

Subprovince	Region	Unit	Subunit	Name of the geomorphological unit	Highest point [m a.s.l.]	Lowest point [m a.s.l.]	Amplitude span [m]
II	A	4		Blatenská pahorkatina	729	380	349
II	A	4	A	Horažďovická pahorkatina	596	380	216
II	A	4	B	Nepomucká vrchovina	729	405	324
II	B			Jihočeské pánev	583	360	223
II	B	1		Českobudějovická pánev	480	360	120
II	B	1	A	Putimská pánev	466	360	106
II	B	1	B	Blatská pánev	480	375	105
II	B	2		Třeboňská pánev	583	370	213
II	B	2	A	Lomnická pánev	525	405	120
II	B	2	B	Kardašovečická pahorkatina	514	400	114
II	B	2	C	Lišovský práh	583	370	213
II	C			Českomoravská vrchovina	836	198	638
II	C	1		Křemešnická vrchovina	765	325	440
II	C	1	A	Jindřichohradecká pahorkatina	665	440	225
II	C	1	B	Pacovská pahorkatina	760	410	350
II	C	1	C	Želivská pahorkatina	633	325	308
II	C	1	D	Humpolecká vrchovina	765	355	410
II	C	2		Hornosázavská pahorkatina	650	210	440
II	C	2	A	Kutnohorská plošina	525	210	315
II	C	2	B	Světelská pahorkatina	601	320	281
II	C	2	C	Havlíčkovobrodská pahorkatina	650	390	260
II	C	2	D	Jihlavsko-sázavská brázda	567	410	157
II	C	3		Železné hory	668	200	468
II	C	3	A	Chvaletická pahorkatina	450	200	250
II	C	3	B	Sečská vrchovina	668	270	398
II	C	4		Hornosvratecká vrchovina	836	340	496
II	C	4	A	Žďárské vrchy	836	340	496
II	C	4	B	Nedvědicke vrchovina	774	350	424
II	C	5		Křižanovská vrchovina	706	375	331
II	C	5	A	Bítešská vrchovina	706	375	331
II	C	5	B	Brtnická vrchovina	683	455	228
II	C	6		Javořická vrchovina	836	455	381
II	C	6	A	Jihlavské vrchy	836	515	321
II	C	6	B	Novobystřická vrchovina	738	455	283
III				Krušnohorská subprovincie	1244	116	1128
III	A			Krušnohorská hornatina	1244	116	1128
III	A	1		Smrčiny	758	430	328
III	A	1	A	Ašská vrchovina	758	490	268
III	A	1	B	Hazlovská vrchovina	744	443	301
III	A	1	C	Chebská pahorkatina	656	430	226
III	A	2		Krušné hory	1244	270	974
III	A	2	A	Klínovecká hornatina	1244	420	824
III	A	2	B	Loučenská hornatina	994	270	724
III	A	3		Děčínská vrchovina	723	116	607
III	A	3	A	Děčínské stěny	723	116	607
III	A	3	B	Jetřichovické stěny	495	120	375
III	B			Podkrušnohorská oblast	934	140	794
III	B	1		Chebská pánev	534	413	121
III	B	2		Sokolovská pánev	573	355	218
III	B	3		Mostecká pánev	460	140	320

Subprovince	Region	Unit	Subunit	Name of the geomorphological unit	Highest point [m a.s.l.]	Lowest point [m a.s.l.]	Amplitude span [m]
III	B	3	A	Žatecká pánev	395	185	210
III	B	3	B	Chomutovsko-teplická pánev	460	140	320
III	B	4		Doupovské hory	934	275	659
III	B	5		České středohoří	837	125	712
III	B	5	A	Verneřické středohoří	726	125	601
III	B	5	B	Milešovské středohoří	837	142	695
III	C			Karlovarská vrchovina	983	360	623
III	C	1		Slavkovský les	983	360	623
III	C	1	A	Kynžvartská vrchovina	983	420	563
III	C	1	B	Hornoslavkovská vrchovina	883	360	523
III	C	1	C	Bečovská vrchovina	817	450	367
III	C	2		Tepelská vrchovina	847	415	432
III	C	2	A	Toužimská plošina	847	555	292
III	C	2	B	Bezručická vrchovina	762	415	347
III	C	2	C	Žlutická vrchovina	734	445	289
IV				Krkonoško-jesenická subprovincie	1602	208	1394
IV	A			Krkonošská oblast	1602	208	1394
IV	A	1		Šluknovská pahorkatina	610	294	316
IV	A	2		Lužické hory	793	290	503
IV	A	2	A	Lužický hřbet	793	300	493
IV	A	2	B	Kytlická hornatina	760	290	470
IV	A	3		Ještědsko-kozákovský hřbet	1012	263	749
IV	A	3	A	Ještědský hřbet	1012	263	749
IV	A	3	B	Kozákovský hřbet	744	263	481
IV	A	4		Žitavská pánev	593	235	358
IV	A	4	A	Liberecká kotlina	593	312	281
IV	A	4	B	Hrádecká pánev	445	235	210
IV	A	5		Frýdlantská pahorkatina	572	209	363
IV	A	6		Jizerské hory	1124	280	844
IV	A	6	A	Smrčská hornatina	1124	400	724
IV	A	6	B	Jizerská hornatina	1122	280	842
IV	A	7		Krkonoše	1602	440	1162
IV	A	7	A	Krkonošské hřbety	1602	620	982
IV	A	7	B	Krkonošské rozsochy	1423	470	953
IV	A	7	C	Vrchlabská vrchovina	809	440	369
IV	A	8		Krkonošské podhůří	835	265	570
IV	A	8	A	Železnobrodská vrchovina	835	265	570
IV	A	8	B	Podkrkonošská pahorkatina	673	305	368
IV	A	8	C	Zvičinsko-kocleřovský hřbet	671	285	386
IV	B			Orlická oblast	1115	285	830
IV	B	1		Broumovská vrchovina	880	351	529
IV	B	1	A	Žacléřská vrchovina	880	365	515
IV	B	1	B	Polická vrchovina	828	375	453
IV	B	1	C	Meziměstská vrchovina	880	351	529
IV	B	2		Orlické hory	1115	419	696
IV	B	2	A	Dešenská hornatina	1115	546	569
IV	B	2	B	Mladkovská vrchovina	765	419	346
IV	B	2	C	Bukovohorská hornatina	995	440	555
IV	B	3		Podorlická pahorkatina	835	285	550
IV	B	3	A	Náchodská vrchovina	835	285	550

Subprovince	Region	Unit	Subunit	Name of the geomorphological unit	Highest point [m a.s.l.]	Lowest point [m a.s.l.]	Amplitude span [m]
IV	B	3	B	Žamberská pahorkatina	658	310	348
IV	B	3	C	Moravskotřebovská pahorkatina	626	305	321
IV	B	4		Kladská kotlina	610	434	176
IV	B	4	A	Králická brázda	610	434	176
IV	C			Jesenická oblast	1491	208	1283
IV	C	1		Zábřežská vrchovina	714	228	486
IV	C	1	A	Drozdovská vrchovina	714	287	427
IV	C	3		Hanušovická vrchovina	1003	236	767
IV	C	3	D	Branenská vrchovina	1003	320	683
IV	C	4		Králický Sněžník	1423	520	903
V				Poberounská subprovincie	865	170	695
V	A			Brdská oblast	865	170	695
V	A	1		Džbán	537	255	282
V	A	1	A	Ročovská vrchovina	536	255	281
V	A	1	B	Řevničovská pahorkatina	537	285	252
V	A	2		Pražská plošina	434	170	264
V	A	2	A	Říčanská plošina	410	180	230
V	A	2	B	Kladenská tabule	434	170	264
V	A	3		Křivoklátská vrchovina	721	220	501
V	A	3	A	Zbirožská vrchovina	721	220	501
V	A	3	B	Lánská pahorkatina	488	223	265
V	A	4		Hořovická pahorkatina	499	190	309
V	A	4	A	Hořovická brázda	490	190	300
V	A	4	B	Karlštejská vrchovina	499	210	289
V	A	5		Brdská vrchovina	865	192	673
V	A	5	A	Brdy	865	330	535
V	A	5	B	Hřebený	660	192	468
V	A	5	C	Příbramská pahorkatina	667	390	277
V	B			Plzeňská pahorkatina	773	230	543
V	B	1		Rakovnická pahorkatina	677	230	447
V	B	1	A	Kněževeská pahorkatina	462	230	232
V	B	1	B	Žihelská pahorkatina	633	340	293
V	B	1	C	Manětínská vrchovina	677	395	282
V	B	2		Plaská pahorkatina	704	240	464
V	B	2	A	Stříbrská pahorkatina	704	330	374
V	B	2	B	Kaznějovská pahorkatina	597	300	297
V	B	2	C	Plzeňská kotlina	430	300	130
V	B	2	D	Kralovická pahorkatina	537	240	297
V	B	3		Švihovská vrchovina	773	300	473
V	B	3	A	Chudenická vrchovina	773	360	413
V	B	3	B	Merklínská pahorkatina	536	335	201
V	B	3	C	Klatovská kotlina	590	385	205
V	B	3	D	Radyňská pahorkatina	673	310	363
V	B	3	E	Rokycanská pahorkatina	575	300	275
VI				Česká tabule	696	141	555
VI	A			Severočeská tabule	696	150	546
VI	A	1		Ralská pahorkatina	696	150	546
VI	A	1	A	Dokeská pahorkatina	614	150	464
VI	A	1	B	Zákupská pahorkatina	696	238	458
VI	A	2		Jičínská pahorkatina	562	205	357

Subprovince	Region	Unit	Subunit	Name of the geomorphological unit	Highest point [m a.s.l.]	Lowest point [m a.s.l.]	Amplitude span [m]
VI	A	2	A	Turnovská pahorkatina	562	205	357
VI	A	2	B	Bělohorská pahorkatina	525	260	265
VI	B			Středočeská tabule	461	141	320
VI	B	1		Dolnooharská tabule	461	141	320
VI	B	1	A	Hazmburská tabule	418	150	268
VI	B	1	B	Řipská tabule	461	150	311
VI	B	1	C	Terezínská kotlina	211	141	70
VI	B	2		Jizerská tabule	410	155	255
VI	B	2	A	Středožizerská tabule	410	195	215
VI	B	2	B	Dolnožizerská tabule	320	155	165
VI	B	3		Středolabská tabule	400	156	244
VI	B	3	A	Nymburská kotlina	285	175	110
VI	B	3	B	Čáslavská kotlina	340	195	145
VI	B	3	C	Mělnická kotlina	247	156	91
VI	B	3	D	Mrlinská tabule	278	190	88
VI	B	3	E	Českobrodská tabule	400	168	232
VI	C			Východočeská tabule	692	199	493
VI	C	1		Východolabská tabule	351	199	152
VI	C	1	A	Cidlinská tabule	329	219	110
VI	C	1	B	Chlumecká tabule	351	202	149
VI	C	1	C	Pardubická kotlina	294	199	95
VI	C	2		Orlická tabule	451	230	221
VI	C	2	A	Úpsko-metujská tabule	360	235	125
VI	C	2	B	Třebechovická tabule	451	230	221
VI	C	3		Svitavská pahorkatina	692	208	484
VI	C	3	A	Českořebovská vrchovina	692	270	422
VI	C	3	B	Loučenská tabule	657	248	409
VI	C	3	C	Chrudimská tabule	453	208	245

approaches are applied and combined, namely individual and typological regionalisation (see Balatka and Sládek 1989a, 1989b; Balatka and Kalvoda 2006a). Individual regionalisation represents a methodological approach that results in the determination of geomorphological units. Each unit has its individual characteristics, expressed, for example, by a name and code, which apply to a single territorial entity. In contrast, typological regionalisation applies a selected criterion to a larger number of units delimited on a map. The previously used orographic criteria considered only certain features of the Earth's surface, especially its topography and external appearance. A cartographic approach to the delimitation of orographical units was used especially by Kořistka (1885) and Kuchař (1955). By comparison, the geomorphological approach allows for the development of a comprehensive regionalisation of the georelief within the natural environment (Balatka and Sládek 1989a, 1989b).

The creation of geomorphological regionalisation of the Czech lands represents one of the traditional topics of Czech physical geography and cartography

(e.g., Kořistka 1885; Kuchař 1955; Hromádka 1956; Balatka and Sládek 1989a, 1989b). In this regard, several important map series were published during the second half of the 20th century, by Balatka et al. (1971a, 1971b, 1973, 1975), Kudrnovská 1975, Kudrnovská and Kousal (1971, 1975a, 1975b), Czudek et al. (1972) and Demek et al. (1987). Based on the publications of the above-mentioned expert teams, a map of the Higher Geomorphological Units of the Czech Republic (1996) was subsequently compiled.

The aim of the geomorphological regionalisation of the georelief of the Bohemian Massif in the 1990s and early 21st century at the Department of Physical Geography and Geoecology of the Faculty of Science, Charles University, was to develop a taxonomy system of geomorphological classification and its cartographic representation on the base map of the Czech Republic at a scale of 1:500,000 (Balatka and Kalvoda 2006a; Fig. 1). In addressing this topic, Břetislav Balatka's expert team followed up on the results of previous geomorphological and cartographic works by Hromádka (1956), Czudek et al. (1972), Balatka et al. (1973, 1975) and Demek et al. (1987). Methodological

inspiration was also taken from maps and related text summaries of conceptual papers on individual and typological regionalisation of the georelief of Slovakia prepared by Mazúr and Lukniš (1978, 1979) and Mazúr (1979).

This comprehensive geomorphological approach enabled the detailed individual regionalisation of the georelief of Bohemia into a ten-level classification system, comprising the following taxonomic levels (Balatka and Kalvoda 2006a): system, subsystem, province, subprovince, region, unit, subunit, district, subdistrict, and part. However, only one province (the Česká vysočina Highland) is represented in the territory of Bohemia, which is part of a single subsystem (the Hercynian Mountains) and therefore also of a single system (the Hercynian system). Given the role of georelief as the main factor among the components of the natural environment (e.g., Ložek 1973; Czudek 1997, 2005; Demek et al. 2009), geomorphological regionalisation represents the fundamental framework for the regionalisation of other components of the landscape and also for the possibility of the development of comprehensive physical-geographic regionalisation.

Typological classification of relief, as another basic form of geomorphological regionalisation, consists of the determination and cartographical delimitation of main relief types according to certain classification principles. A relief type is a territory with a homogeneous complex of landforms sharing the same morphographic features and similar genesis depending on the morphostructure with a similar paleogeographical history (Czudek et al. 1972; Balatka et al. 1975; Demek and Mackovčin Eds. 2006; Demek et al. 2007). The types of the georelief in the Bohemian Massif are primarily determined by the varying intensity of neotectonic movements as well as climate-morphogenetic processes during the Cenozoic. In orographic terms, these include mountains, highlands, hill countries, hills, plains in the form of plateaus or tables, and basins.

Higher mountains, characterised by stronger neotectonic uplift, reach altitudes of over 1,200 m a.s.l. in the Bohemian Massif, while the lower mountains mostly reach 900–1,200 m a.s.l. Mountains form a distinct border of the Česká vysočina Highland province in the Šumava, Krušnohorská and Krkonoše-Jizera subprovinces (Fig. 1), which is interrupted in the intermountain areas by the georelief of hill countries to hilly lands. The hill countries are characterised by a rugged relief with remnants of Neogene planation surfaces at altitudes of mostly 500–900 m (e.g., Král 1971, 1985; Votýpka 1975, 1997; Křížek 2001, 2006; Demek 2004). They were formed as relatively extensive foothills of mountains and occupy large areas in the central and upper parts of the Česká vysočina Highland province. Hilly lands are characterised by less undulation and more extensive Neogene planation surfaces at altitudes of up to 600 m

a.s.l. (Balatka and Příbyl 1996, 1997; Kuncová 2005; Bláhová and Křížek 2007). Plains, plateaus and tables occur mainly in the territory of the Česká tabule Table and surround the tectonically conditioned basins of the Česká vysočina Highland province (Balatka et al. 1959, 2019; Lochman 1971; Lipský 1980; Balatka and Příbyl 1997; Steklá and Kalvoda 2024). Morphostructurally controlled basins represent a specific type of relief at various elevations. These basins in the Bohemian Massif are characterised by relative tectonic subsidence and are usually filled with predominantly Tertiary sediments.

The course of the boundaries of the geomorphological units of the Czech part of the Bohemian Massif largely reflects the varying morphographic character of their georelief (Fig. 1; Tab. 1). In mountainous areas and most hill countries and basins, these boundaries follow the course of more or less distinct foothill lines. Morphographic boundaries can also be defined by river valleys, e.g., in the case of asymmetric valleys in terms of height and/or slope; however, the breakthrough river valleys should not be used as boundary lines (Balatka et al. 1975; Balatka and Sládek 1989b). In flat and poorly dissected units (hilly lands, tables and plains), morphographic boundary is often defined as median line within transition zones of variable width, where landforms of adjacent units gradually merge. In such cases, the boundary separates genetically different types of georelief without clear topographic differences.

2.2 The strategy and course of research work

The dynamics of geomorphological evolution of a certain area can only be assessed and stratigraphically interpreted through broader regional correlations. We therefore started to compare the geomorphological findings from different parts of the relatively large Bohemian Massif only after several decades of gaining experience in physical-geographical research, both in Europe and in orogenetically active regions of the High Asian mountains (e.g., Kalvoda 1992a, 1993, 1998b, 2020). Conceptually and methodologically, our work also benefited from geomorphological studies in the Alpine zone of Europe from the Pyrenees to the Caucasus, especially in the Alps, Vosges, Western Carpathians, and the mountains of the Balkan Peninsula.

The morphostructural development of the Czech part of the Bohemian Massif was briefly described in the study by Kalvoda and Balatka (2006) as a part of Břetislav Balatka's map and tabular work on the geomorphological regionalisation (Balatka and Kalvoda 2006a). A contribution to understanding the evolution of river terrace systems of the Bohemian Massif are provided by studies that followed the fundamental works of Balatka and Sládek (1962a, 1962b, 1962c, 1965, 1975), Záruba et al. (1977), Tyráček (2001a, 2001b, 2010), Tyráček et al. (2004), Tyráček and Havlíček (2009). These further developed in publications

by Kalvoda and Balatka (1995), Příbyl (1999), Balatka and Příbyl (2003), Balatka and Kalvoda (2008, 2010a, 2010b, 2018) and Balatka et al. (2010b, 2015, 2019).

Together with a number of colleagues, we also studied the evolution of landforms in the contact area of the Střibská pahorkatina Hills, Tepelská vrchovina Hill Country and Tachovská brázda Furrow (Kalvoda 1966, 1980), then especially in the High Tatras (Kalvoda 1970, 1974, 1994, 1998a), the Moravian-Silesian Beskydy Mountains (Prášek 1985, 1993; Kalvoda and Prášek 1987, 1996), the Děčínská vrchovina Hill Country (Balatka and Kalvoda 1995), the Krkonoše Mountains (Mercier et al. 2000, 2002; Carr et al. 2002, 2007; Engel and Kalvoda 2002a, 2002b; Mercier et al. 2003; Bourlés et al. 2004; Braucher et al. 2006), the Orlické hory Mountains (Vaníčková 2004; Vaníčková and Kalvoda 2006a, 2006b), the Česká tabule Table (Engel and Kalvoda 2002a; Steklá and Kalvoda 2024) and in the Sázava River area (Štěpančíková 2003; Kalvoda 2005, 2007a; Balatka 2007; Balatka and Kalvoda 2010a, 2010b; Balatka et al. 2010a).

We have continuously applied the above geomorphological studies during engineering geological research of landslides and other types of slope movements (e.g., Kalvoda and Zvelebil 1983a, 1983b, 1989; Kalvoda et al. 1997; Rybář et al. 2000; Hartvich and Vilímek 2008; Vilímek et al. 2010) and with interpretation of geodetic and geophysical measurements of the Earth's surface movements. Geomorphological procedures could be used to address several topics: a) determination of the causes of movements of the Earth's surface detected by repeated geodetic measurements (e.g., Kalvoda and Pašek 1975; Kalvoda and Zeman 1979, 1982, 1983; Kalvoda 1995a, 1995b, 1996a, 1996b; Kalvoda et al. 1990, 1994; Vilímek 1995; Vilímek et al. 2021); b) monitoring of movements in fault zones of the near-surface part of the rock massif, including seismic activity (Kalvoda and Košťák 1984; Kalvoda Ed. 1995a, 1995b; Košťák et al. 2000; Stemberk et al. 2000, 2010; Štěpančíková et al. 2008, 2010, 2018, 2019; Štěpančíková and Stemberk 2016); c) geomorphological aspects of Earth dynamics monitored by methods of space geodesy and geophysics (Kalvoda et al. 2004, 2013; Kostelecký et al. 2005; Klokočník et al. 2014).

We also gained valuable experience and knowledge during our teaching activities and geographical research in selected localities of the Bohemian Massif and the Western Carpathians, which we conducted with students and doctoral candidates of the Faculty of Science, Charles University. With regard to the topics of this paper, we refer, for example, to regional geomorphological studies by Šust (1981), Pánková (1995), Tomeček (2007), Hasenkopfová (2002), Soukupová (2008), Steklá (2012) and Halžová (2017) and studies on the development of fluvial landforms by Průša (1993), Čtyroký (1996), Lachmanová (1996), Novotná (1998), Hartvich (2002, 2008) and Mikisková (2009). References to other (published)

research results by graduates in physical geography are provided throughout the present paper.

3. Results concerning orogenic uplift of the Česká vysočina Highland

3.1 The determination of the types of fluvial relief

An important geomorphological record of fluvial processes in the Bohemian Massif is provided by the extent and structure of river accumulation terraces. Therefore, alongside his research work on the historical-genetic geomorphological regionalisation of the Bohemian Massif (Balatka and Kalvoda 2006a), Břetislav Balatka prepared graphic manuscripts of two additional maps of this type, focused on the fluvial landforms. These original maps of fluvial relief types, river terraces, and erosion in relation to the morphostructures of the Bohemian Massif at a scale of 1:500,000 (Balatka 2006) represent a pilot solution to the current geomorphological topic. They depict varied regions classified by structure of fluvial sediments, their position in the longitudinal river profiles and the areal distribution of river accumulation terraces.

The main criterion is the extent of the river terrace system in the georelief of the Bohemian Massif, which provides a basis for understanding relationships to other landforms (Balatka and Kalvoda 2006b for details) and shows the intensity of erosion and denudation. From the above-mentioned manuscript maps by Břetislav Balatka, we have prepared the resulting map of fluvial relief types in relation to the morphostructures of the Bohemian Massif (Fig. 2). This thematic map also served as one of the key foundations for the subsequent stage of research, namely in creating a primary map of the extent of differential tectonic uplift of morphostructural units in the Bohemian Massif in the Late Cenozoic (Chapter 3.2).

The basis for the typification of the fluvial relief of the Bohemian Massif was the regional division into lower geomorphological units, down to the level of subunits (Fig. 1; Tab. 1). These units are morphostructurally and, to a certain extent, morphogenetically homogeneous areas that have been classified according to a defined typological legend. The classification criteria for fluvial relief types include ten morphogenetically specific regions, which are shown in Fig. 2 as coloured areas with Roman numerals. From a morphostructural point of view, the specified regions of fluvial relief types can be considered homogeneous units (Balatka 2006). These regions include both areas where river accumulation terraces are the dominant landforms, and erosion-denudation areas in which river terraces are limited to small localities or, except for valley floodplains, are completely absent. When evaluating the georelief of the Bohemian Massif according to the types of river terraces, their complete

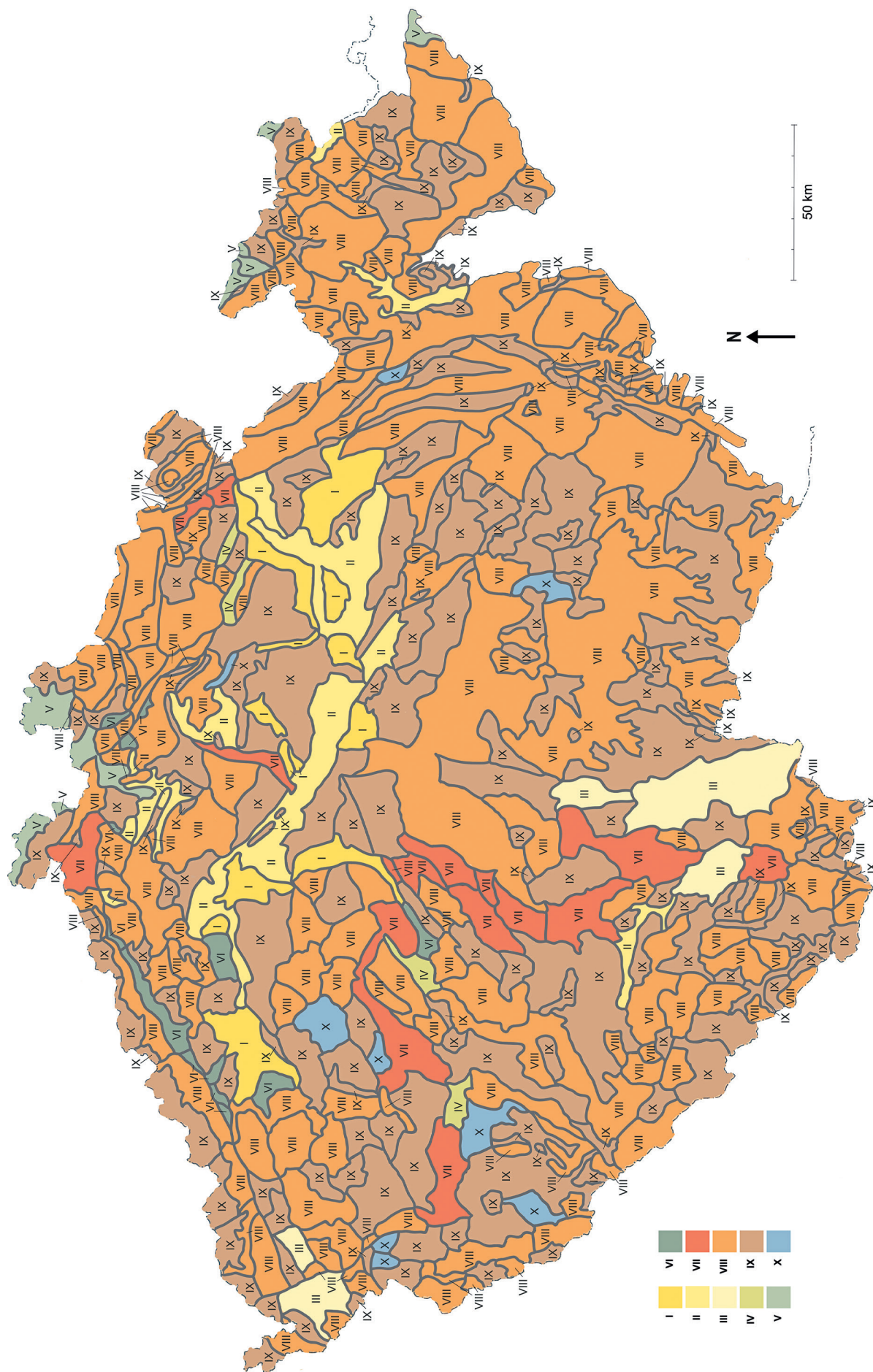




Fig. 3 Neovolcanic hill of Říp (461 m) is formed by a selectively denuded nephelinitic diatreme. The hill is surrounded by the Quaternary system of river accumulation terraces near the confluence area of the Labe (Elbe) and Vltava rivers. Photo Břetislav Balatka.

system was considered including relics of the oldest levels developed during the Lower Pleistocene.

The determination of the types of fluvial relief of the Bohemian Massif could be clearly represented cartographically (in the original scale of 1:500,000) only based on detailed research by Břetislav Balatka and his collaborators (Chapters 1.2 and 2.2). From a conceptual point of view, the papers of Balatka (1960, 1961, 2003), Balatka and Sládek (1962a, 1962b, 1975), Balatka et al. (1964, 1966), Balatka and Loučková (1992), Balatka and Kalvoda (1995, 2006a) should be mentioned. Morphogenetically, the most significant is Region I of the fluvial relief (Fig. 2), which includes an area with extensive Quaternary river terraces, with relative heights of their highest levels of 90–110 m above the present-day valley floors.

The territories classified as Region I have a fluvial relief with the best-developed (and preserved) river accumulation terraces in the lower tabular and basin morpho-structural units of the northern part of the Bohemian Massif (e.g., Fig. 3). These are mainly the Východolabská, Středolabská, Dolnooherská, Orlická tabule Tables, as well as the Mostecká pánev Basin, the southern part of the Pražská plošina Plateau and the adjacent area of the Hořovická brázda Furrow (Balatka 2006; Balatka and Kalvoda 2006a).

Region II corresponds to the distribution of lower river terraces of predominantly Middle Pleistocene and Upper Pleistocene age (mostly up to a relative height of 20–25 m) and extensive valley floodplains. These landforms are preserved mainly in the basins of the Česká tabule Table (Terežinská,

Fig. 2 Types of fluvial relief in relation to morphostructures of the Bohemian Massif. The working scale of this thematic map is 1:500,000. According to the original manuscript maps and documentation of Břetislav Balatka (2006) adapted and drawn by Jan Kalvoda and Tereza Steklá. Regions of fluvial erosion and accumulation relief: Region I (deep yellow colour): Lowlands, lower plateaus and hilly lands with accumulation-erosion relief of extensive river terraces of a complete system with relative heights of up to 90–110 m. Region II (yellow): Lowlands with accumulation-erosion relief of mainly Middle and Upper Pleistocene river terraces up to a relative height of 20–25 m and extensive valley floodplains. Region III (orange): Higher-lying basins with accumulation-erosion to erosion-accumulation relief of river terraces up to a relative height of mostly 30–40 m and extensive valley floodplains. Region IV (light green): Basins with denudation and erosion-accumulation relief of less extensive river terraces up to a relative height of mostly 30–40 m. Region V (light blue): Lower hilly lands and basins influenced by continental glaciation with erosion-denudation relief including Middle and Upper Pleistocene river terraces to a relative height of mainly 30 m. Region VI (green): Basins with accumulation relief of extensive proluvial and fluvial cones, commonly incorporated into river terraces. Region VII (orange): Hills and hilly lands with erosion-denudation relief, with deeply incised valleys, and spatially limited river terraces up to a relative height of 50–90 m, diverging downstream. Region VIII (light orange): Erosion-denudation relief of tables, hilly lands, hill countries and mountains with deeply incised valleys without river terraces, or only with small relics of fluvial sediments. Region IX (brown): Erosion-denudation relief of tables, hilly lands, hill countries and mountains with shallow or widely open valleys, without river terraces or with only limited remnants of low-level terraces. Region X (deep blue): Lowlands and hilly lands with erosion-denudation relief and extensive occurrences of Neogene fluvial or limnic-fluvial sediments.

Mělnická, Nymburská, Čáslavská, Pardubická, Českolipská, Jestřebská, Mnichovo-hradištská and Mladoboleslavská pánev Basins). Region II is occasionally represented in some other depressions, e.g., in the north-western headland of the Českobudějovická pánev Basin, the Děčínská pánev Basin, the Mohelnická brázda Furrow, and in the Opavická niva Floodplain and the Albrechtická kotlina Basin in the Jindřichovická pahorkatina Hills in Silesia (Balatka 2006).

Region III consists of fluvial relief with Pleistocene river terraces reaching a relative height of mostly 30–40 m and extensive valley floodplains in Tertiary and Cretaceous basins (with the exception of the Mostecká pánev Basin), namely in the Chebská and Sokolovská pánev Basins (Svatavská pánev Basin), in the central part of the Českobudějovická pánev Basin (Blatská pánev Basin) and in the Třeboňská pánev Basin. The Pleistocene river terraces of Region IV are in a similar position in the territory of some other depressions of structural origin. These are the northern part of the Plzeňská pánev Basin (Touškovská pánev Basin), the central part of the Hořovická brázda Furrow (Zdícká brázda Furrow) and the Miletínský úval Graben and the Královédvorská pánev Basin (Balatka and Kalvoda 2006a, 2006b).

Region V corresponds to areas affected by or influenced by continental glaciation during the Quaternary. River accumulation terraces of Pleistocene age are developed here at lower relative heights, in two stages: a) up to 40 m (mainly from the Elsterian glaciation), b) up to 10–20 m (from the Saalian glaciation). These include the Šluknovská and Frýdlantská pahorkatina Hilly Land, the Hrádecká pánev Basin, the central part of the Zákupská pahorkatina Hilly Land, the Vidnavská nížina Lowland, part of the Žulovská nížina Lowland and the Osoblažská nížina Lowland.

Region VI includes areas with extensive Pleistocene proluvial and fluvial cones of various ages (Balatka 2006), which in places transition into river

terraces at relative heights from several meters to several tens of meters. These are mainly the areas of the Chomutovsko-Teplická pánev Basin at the foot of the Krušné hory Mountains, the Pětipeská pánev Basin, the western part of the Liberecká pánev Basin, the Hostimická pánev Basin at the northern foot of the Hřebený Hill Country, parts of the Podještědská and Českodubská pahorkatina Hilly Land at the foot of the Ještědský hřbet Ridge and the Klapská tabule Table between the České středohoří Mountains and the Ohře (Eger) River valley.

Region VII is characterised by the limited occurrence of river accumulation terraces of Pleistocene age at various relative heights, in places up to 90 m, often well expressed morphologically in deeply incised valleys of the hilly lands and hill countries. This region occupies striking strips along larger streams, namely along the Vltava in the Středočeská pahorkatina Hilly Land and in the southern parts of the Pražská plošina Plateau, as well as along the Mže River in the Stříbrská pahorkatina Hilly Land, along the Berounka River between Pilsen and Řevnice, along the lower Lužnice, Otava and Sázava rivers in the Středočeská pahorkatina Hilly Land, along the Jizera River in the Jizera tabule Table and along the Úpa River in the Krkonoše Mts. foothills (Balatka 2006; Balatka and Kalvoda 2006b).

Region VIII is represented by tectonically more strongly uplifted areas without river terraces or with sporadic relics of fluvial sediments. These are mainly geomorphological units with deeply incised valleys in the mountains, highlands and hilly lands, including the sandstone areas of the Česká tabule Table. Region IX represents tectonically less uplifted area with sporadic occurrence of fluvial sediments in shallow and widely open valleys of hilly lands, tables and basins or in hill countries and mountains with extensive relics of Tertiary planation surfaces (Fig. 4).

Region X is characterised by areas with substantial relics of Neogene fluvial and limnic sediments, located



Fig. 4 Part of an abandoned valley of the Sázava river near Chabeřice, infilled by fluvial sediments of the III. river terrace up to 25 m thick. Photo Břetislav Balatka.

in shallow valleys with low levels of river accumulation terraces. These include, for example, parts of the Podčeskoleská and Plzeňská pahorkatina Hilly Lands, as well as the Jihlavsko-sázavská brázda Furrow, the Čeremenská pahorkatina Hilly Land near Lanškroun, and the Velišský hřbet Ridge in the Turnovská pahorkatina Hilly Land.

A specific aspect of determining the types of fluvial relief of the Bohemian Massif, as expressed in the maps of Balatka (2006), is the possibility of deriving the approximate intensity of erosion and denudation during the Late Cenozoic. Balatka (2006) classified the extent of this reduction of the georelief on a scale from very strong intensity (exceeding 200 m) to very weak intensity (below 50 m) of the effects of erosion-denudation processes. However, the values given should be considered indicative only (Balatka and Kalvoda 2006b), because the maximum intensity of erosion and denudation in the defined morphostructural units of the Bohemian Massif is often restricted to narrow strips of territory along larger watercourses and to the lower reaches of their tributaries. On the contrary, in neighbouring areas (e.g., watershed zones), the values of erosion and denudation of the georelief estimated using this approach are significantly lower.

3.2 The extent of the vertical component of tectonic movements

The evaluation of the pattern of fluvial relief types in the Bohemian Massif (Fig. 2) and the relevant professional literature show that, mainly due to the influence of neotectonic movements, significant changes occurred in the structure of the river network, the courses of watersheds of various orders, and the deepening of valleys during the Late Cenozoic. Therefore, we focused on comparing the river terrace systems of the main streams (especially) in the central part of the Bohemian Massif and specifying their stratigraphical position in the current Quaternary subdivision (International Commission on Stratigraphy 2007; Gibbard et al. 2008, 2010). The results of these regional research efforts are collected in a series of studies by Balatka and Kalvoda (2008, 2010a, 2010b, 2010c, 2018), Balatka et al. (2010a, 2010b, 2015, 2019) and Steklá and Kalvoda (2024). The gradually acquired palaeogeographical knowledge was the basis for identifying the geomorphological record of differential tectonic uplift and (relative) subsidence of the main morphostructural units in the Bohemian Massif. In the subsequent stage of research, following up on the determination of fluvial relief types within the morphostructures of the Bohemian Massif (Fig. 2), we focused on identifying and graphically expressing the extent of the vertical component of tectonic movements during the Late Cenozoic.

When classifying the morphostructural units of the Bohemian Massif (to the level of subunits; Tab. 1) into

the categories by the extent of tectonic uplift, we evaluated the geomorphological conditions of these areas, including the current elevation of planation surfaces of various types and ages (cf. Fig. 5 and Fig. 6). Their gradual development and long-term transformation by weathering and denudation processes represent a period of relative tectonic stability in the paleogeographical history of the Bohemian Massif (e.g., Král 1985; Demek 2004; Kalvoda and Balatka 2006a). Morphometrical data were obtained from topographical maps mostly of the scale 1:50 000. The approximate extent of the reduction in the thickness of the weathered material and rock assemblages was derived from data on the relative height of the relics of the oldest river terraces (e.g., Fig. 5), as well as from the elevation of the Upper Miocene planation surface and the surface of Neogene sediments.

It should be noted that the process of exhumation of crystalline rocks of the deeper part of the Earth's crust and the planation surfaces of the Bohemian Massif of various origins and ages has received considerable attention in the geomorphological and geological literature (e.g., Demek et al. 1965; Král 1968, 1971, 1985; Migoň 1999; Danišík et al. 2010, 2012). The current valley network of Bohemian rivers is incised into the Upper Miocene planation surface to an extent that largely corresponds to differential neotectonic movements (Balatka and Kalvoda 2006b). This tectonic activity, with a predominance of spatially and temporally varied uplift (Fig. 6), together with the regimen of the streams, amount of transported material and the lithology of the bedrock, controlled the intensity of erosion and denudation processes during the Late Cenozoic.

We illustrated the extent of tectonic uplift of morphostructural units of the Bohemian Massif in regions of fluvial relief types from the Upper Miocene to the present on a thematic map (Fig. 7). The interpretation of the above-defined geomorphological data and the described methodological procedures for determining the extent of the vertical component of tectonic movements in the last ca. 10^7 years of the palaeogeographical history of the Bohemian Massif can, however, provide only an approximate quantitative estimate of the phenomenon under investigation. For this reason, we have distinguished only five classification levels on the thematic map (Fig. 7), representing areas with different intensities of neotectonic uplift. The extent of very strong tectonic uplift in the demarcated territories during the indicated period is approximately 900–1,200 m, while in areas with minor tectonic uplift it is only 50–150 m.

When determining the extent of tectonic uplift of morphostructural units of the Bohemian Massif, we relied on the depth of the Quaternary incision of river valleys (which is mostly 30–60 m, but often exceeds these values; Fig. 8) relative to the current elevation level of the originally Upper Miocene planation surface. However, we also assumed a certain

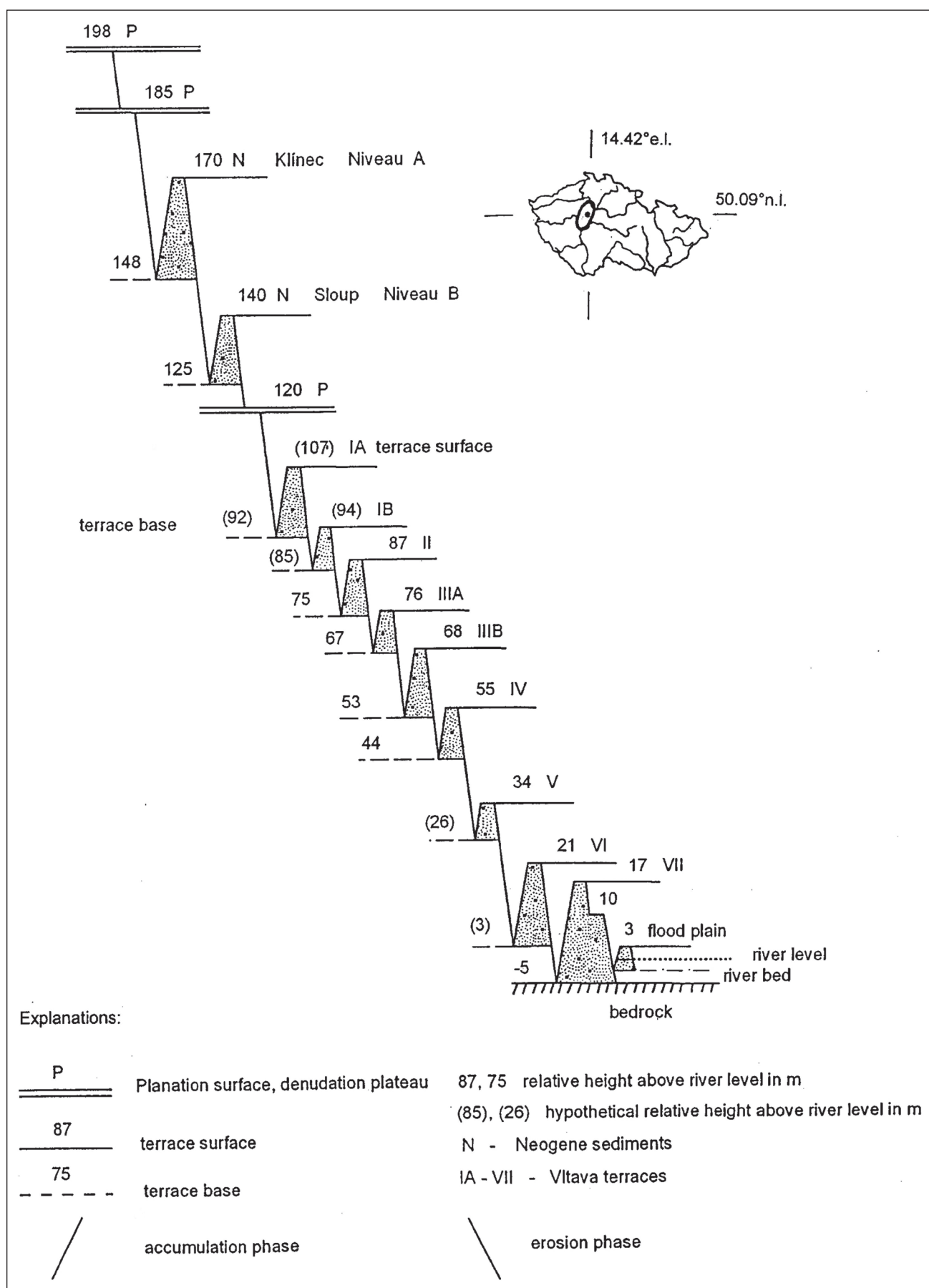


Fig. 5 River accumulation terraces in the Vltava valley between the mouths of the Sázava and Berounka rivers (modified after Balatka and Štěpančíková 2006; Balatka and Kalvoda 2010a). The morphostratigraphical correlation of river terraces is presented in Tab. 2.

reduction of this planation surface, by up to several tens of metres, which was preserved in a less disturbed form especially in the watershed areas. Regions with the highest intensity of tectonic uplift during the Late Cenozoic (red and brown colours in Fig. 7) should, under the above assumptions, correspond to both some of the most elevated areas (mountains and highlands) and areas with deeply incised valleys

of larger watercourses in hill countries. Regions with less intense and weak tectonic uplift (green and yellow colours in Fig. 7) are typically lower-lying basins and furrows, structural tables and hilly lands. We emphasise that areas classified especially within categories characterised by weaker tectonic uplift may, in fact, have the character of relative subsidence due to the stronger uplift of adjacent morphostructural units.

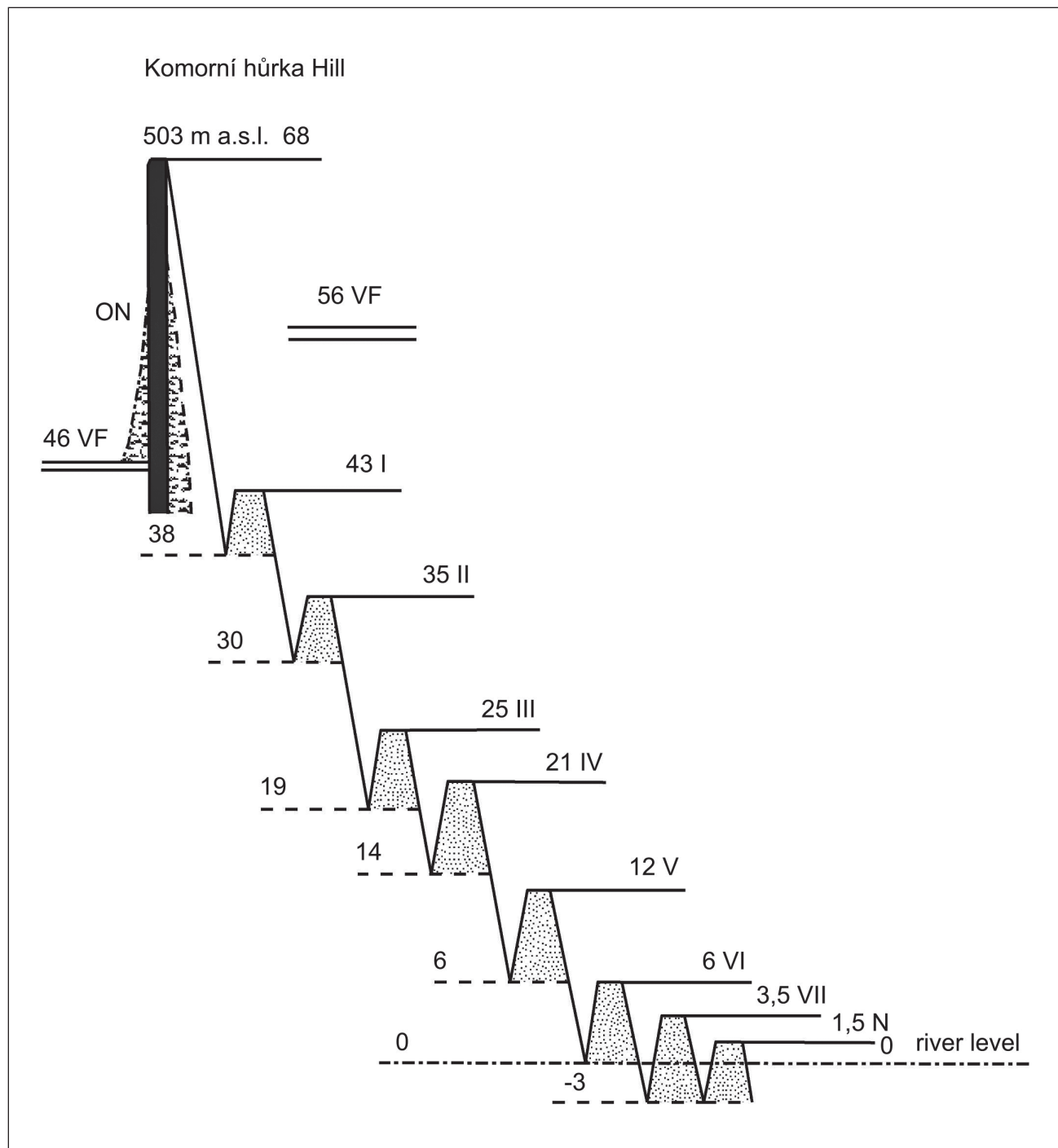


Fig. 6 Graphical scheme of successive incision of the river during the Ohře (Eger) valley evolution in the western part of the Chebská pánev Basin, river km 245–237 (Balatka and Kalvoda 2018; Balatka et al. 2019). Explanations: ON – olivine nephelinite and pyroclastic rocks of the Komorní hůrka Hill (with dated activity between 0.85 up to 0.26 Ma; Wagner et al. 1998); VF – the Vildštejn Formation: quartz micaschists, clay sand and gravel of the Upper Pliocene – Lower Pleistocene age; I–VII – Pleistocene river accumulation terraces; N – alluvium (floodplain); 8, 13, ... – relative height above river level in metres. Graphical explanations are presented in Fig. 5.

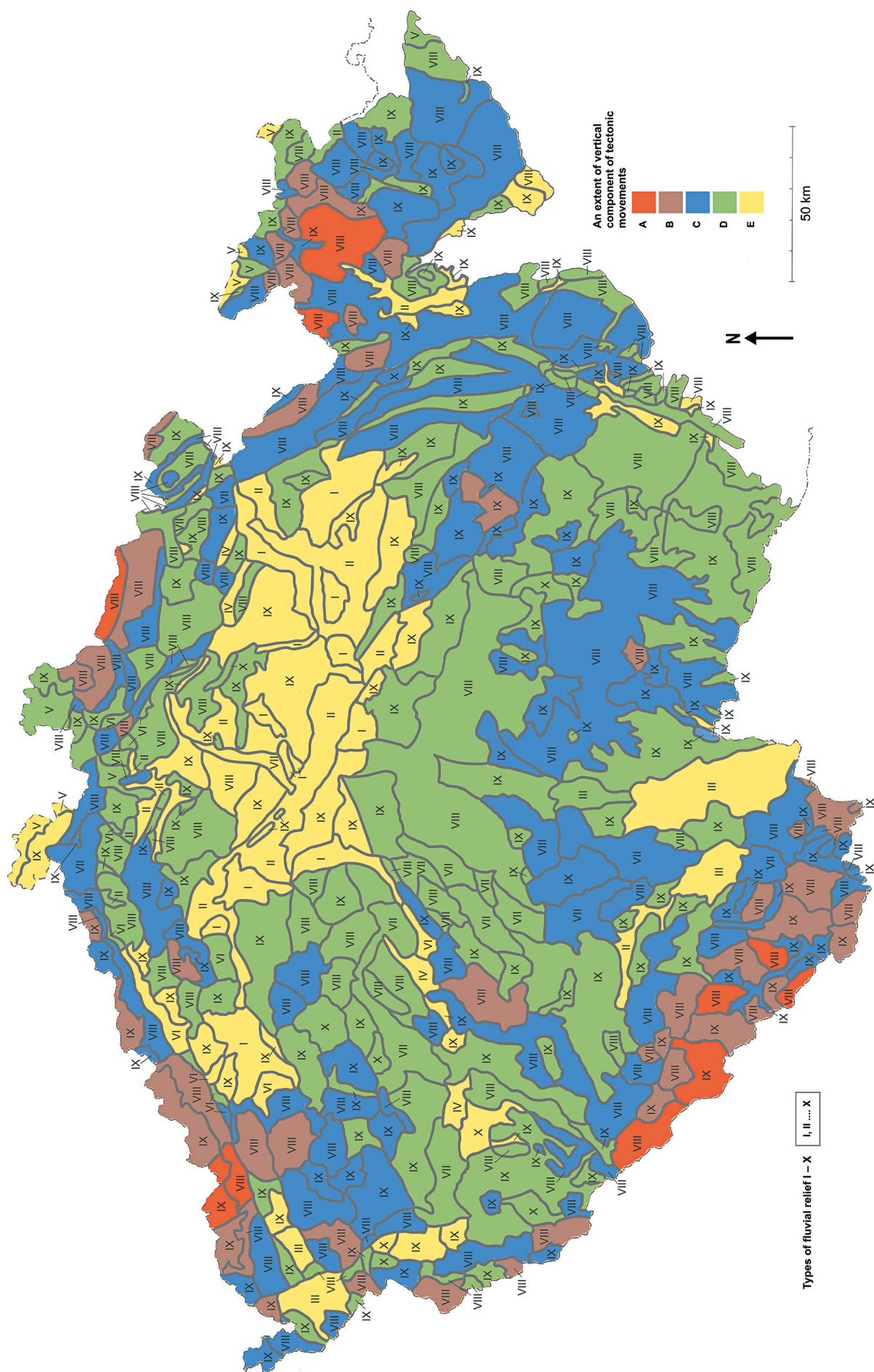




Fig. 8 The Labe (Elbe) River canyon developed in the Upper Cretaceous sandstones of the Děčínská vrchovina Highland during the Quaternary. Photo Jan Kalvoda.

The long-term trend of tectonic uplift of the Bohemian Massif is primarily a manifestation of the youngest Alpine collisional orogeny in Central Europe. The differentiation of morphostructural units of the Bohemian Massif took place in several phases, which significantly influenced the evolution of river valleys (Balatka and Kalvoda 2008; Balatka et al. 2015, 2019). For example, a comparison of the terrace systems of the Sázava, Vltava, Berounka and Labe (Elbe) rivers in the central part of Bohemia shows (Tab. 2) that significant epigenetic and antecedent deepening of the valleys took place as late as in the younger Middle Pleistocene (Balatka and Kalvoda 2008, 2010a; Tyráček and Havlíček 2009; Balatka et al. 2015). The fluvial sediments of river terraces I and II were formed during the Cromerian Complex, while terrace III was deposited during the Elsterian glaciation (Tab. 2).

It is important to note that the rate of tectonic uplift is not directly related to the conform rate of river incision. Deep erosion processes and the related bedrock valley development are determined by varied

environmental changes of valley gradient, bed erodibility, catchment sediment production and discharge conditions. These factors include, in particular, valley slope, the resistance of bedrock to erosion, the quantity and lithological properties of weathered material and the nature of its transport, the hydrological regime, and precipitation-runoff conditions throughout the catchment area. Of these environmental factors, only an increased valley gradient may occur directly as a consequence of tectonic activity through regional uplift, flexuring, and faulting. As an example, the repeatedly increased incision of rivers can also be attributed to the increased intensity of periglacial processes during glacial stages in the Quaternary, namely frost weathering of rocks, regelation, solifluction phenomena, and related coarse detrital sediment supply. These climate-induced changes in the natural environment led to a significantly higher amount of material being carried by rivers and to a higher rate of subsequent fluvial sediment deposition. Given the combined effects of valley gradient, flow regime, bed

Fig. 7 The extent of tectonic uplift from the Upper Miocene to the present in regions of fluvial relief types of the Bohemian Massif. The working scale of the thematic map, till this time unpublished, is 1:500,000. Created by Břetislav Balatka, Jan Kalvoda and Tereza Steklá. Explanations: The extent of the vertical component of tectonic movements: A – area with very strong tectonic uplift (900–1,200 m); B – area with strong tectonic uplift (500–900 m); C – area with medium tectonic uplift (300–500 m); D – area with weak tectonic uplift (150–300 m); E – area with minor tectonic uplift (up to 150 m), or with relative tectonic subsidence. The types of fluvial relief in regions I–X are described in the explanations to Fig. 2.

Tab. 2 Chronostratigraphical correlation of river terrace deposits in the central part of the Česká vysočina Highland related to North-West European stratigraphical stages of the Quaternary (modified after Balatka et al. 2015).

Regional stratigraphical stage/substage divisions of the Quaternary (Gibbard et al. 2004, 2008, 2010)	SÁZAVA Balatka (2007), Balatka and Kalvoda (2010a)	BEROUNKA Balatka and Loučková (1992)	VLTAVA – LABE confluence area Balatka and Sládek (1962b)	VLTAVA Záruba et al. (1977)	VLTAVA and LABE system Tyráček (2001a, 2001b); Tyráček et al. (2004); Tyráček and Havlíček (2009)
Late Pleistocene Weichselian	Pikovice Terrace (VII)	Lipence Terrace (VIIa) Dobřichovice Terrace (VIIb)	Hostín Terrace (VIIa, b, c, d)	Maniny Terrace (VII)	Maniny Terrace (Weichselian) Hostín 1 Terrace
Middle Pleistocene Saalian (Warthe Stadial)	Poříčí Terrace (VI)	Kazín Terrace (VI)	Mlčechvosty Terrace (VIa, b, c)	Veltrusy Terrace (VI)	Veltrusy Terrace (Warthe)
Middle Pleistocene Saalian (Drenthe Sadial)	Městečko Terrace (V)	Liblín Terrace (Va) Poučnick Terrace (Vb)	Cítov Terrace (a, Vb)	Dejvice Terrace (V)	Dejvice 1 and 2 Terrace (Drenthe)
Middle Pleistocene Saalian (Fuhne Stadial)	Týnec Terrace (IV)	Zbraslav Terrace (IVa) Hýskov Terrace (IVb)	Hněvice Hill Terrace (IV)	Letná Terrace (IV)	Letná Terrace (Fuhne)
Middle Pleistocene Elsterian	Buda Terrace (IIIb)	Srbsko Terrace (IIIb)	Straškov Terrace (IIIb)	Vinohrady Terrace (IIIB)	Vinohrady Terrace (Elster)
Middle Pleistocene Cromerian Complex (glacial c)	Chabeřice Terrace (IIIa)	Tetín Terrace (IIIa)	(IIIa)	Kralupy Terrace (IIIA)	Kralupy Terrace (Cromerian C)
Middle Pleistocene Cromerian Complex (Glacial c)	Český Šternberk Terrace (II)	Pohořelec Terrace (IIa) Hlince Terrace (IIb)	Ledčice Terrace (II)	Pankrác Terrace (II)	Pankrác Terrace (Cromerian C)
Middle Pleistocene Cromerian Complex (Glacial b)	Hvězdonice Terrace (Ib)	Řevnice Terrace (Ib)		Suchdol Terrace (IB)	Suchdol Terrace (Cromerian B)
Middle Pleistocene Cromerian Complex (Glacial a)	Střechov Terrace (Ia)	Skryje Terrace (Ia)	Krabčice Terrace (I)	Lysolaje Terrace (IA)	Lysolaje Terrace (Cromerian A)
Early Pleistocene Bavelian (Dorst) Menapian			Rovné Terrace		Rovné Terrace (Dorst) Vráž Terrace (Menapian)
Early Pleistocene Eburonian – Menapian	Niveau B Radvanice	Niveau B		Zdíby Stadial (Pliocene)	Zdíby Terrace (Eburonian – Menapian)
Early Pleistocene Tiglian					Stříbrníky Terrace (upper Tiglian)
Neogene	Niveau A Bojiště	Niveau A		Klínec Stadial	

material load, bedrock exposure and erodibility, the formation and structure of river terrace systems give evidence to the evolutionary complexity and diversity of the natural environment.

The comparison of river terrace systems from different parts of the Bohemian Massif shows that the major rivers respond sensitively and therefore diversely to the local character and changes in morphostructural and climate-morphogenetic conditions (Balatka et al. 1964, 2010a, 2010b, 2015, 2019; Balatka and Sládek 1976; Balatka and Kalvoda 1995, 2008, 2018; Bridgland 2000; Tyráček et al. 2004; Tyráček

and Havlíček 2009). However, stratigraphically significant indicators of large-scale (possibly global) changes in the environment during the Quaternary are very similar in their palaeogeographical record.

4. Discussion

The main current approaches to research into the geomorphological record of tectonic movements and related phenomena in the Bohemian Massif, carried out by several generations of physical geographers

and Quaternary geologists, can be described in the methodological context as follows:

Morphostructural, morphographical and morphogenetic analysis of planation surfaces of various genesis and age, their typological classification, determination of age and distribution, assessment of the effects of tectonic movements in their present-day elevation, and their relationship to the development of the valley system and palaeohydrological changes in the Late Cenozoic.

Geomorphological research of terrace systems of major Bohemian rivers, especially using the reconstruction method, and their integration into the continuously evolving international stratigraphical system of the Quaternary. This research includes, for example, geomorphological analysis of anomalies in the course of river accumulation terraces along longitudinal and transverse profiles, aimed at identifying the extent of discontinuities of the near-surface part of the Earth's crust caused by tectonic movements, and the influence of the bedrock lithology. It is also essential to address the relationship of fluvial relief to the relics of landforms of Quaternary continental and mountain glaciation. These topics have already been addressed in the Czech Republic by Šibrava (1972, 1979), Macoun and Králík (1975), Macoun (1985), Králík (1987), Engel (1996, 2004), Nývlt (1998, 1999, 2003, 2008), Růžicka (2004), Engel et al. (2010) and Štor et al. (2019).

A comprehensive study of morphostructural signatures of neotectonic activity through the delineation of typologically homogeneous regions and the determination of historical-genetic relationships of planation surfaces and fluvial landforms in the Bohemian Massif. The described and presented geomorphological procedures can mainly detect tectonic uplift and subsidence. However, tectonic differentiation of morphostructural units in Central Europe, which gradually evolved from the Miocene up to the Quaternary, is one of manifestations of the latest phase of alpine orogeny. Geological structure of the Eastern Alps and the Western Carpathian systems gives evidence that sub-horizontal tectonic movements prevailed during main phases of the collisional orogeny in the Cenozoic. The extension and course of related horizontal tectonic movements in the Bohemian Massif was studied, e.g., by Coubal (1989), Kopecký (1996), Coubal and Adamovič (2000), Štěpančíková and Stemberk (2004), Stemberk et al. (2010) and Štěpančíková et al. (2018, 2019).

Geomorphological analysis and monitoring of selected geodynamic processes and phenomena are significant trends in research on global changes in geographical systems. Special attention is paid to recent tectonic movements of the near-surface part of the Earth's crust and to the dynamics of current climate-morphogenetic processes, including natural hazards and risks. The nature of research in Earth sciences and the current needs of society suggest that these investigations in the Central Europe should be

evaluated in relation to current knowledge about: 1) the state and development of European landscape and society, and 2) trends in global environmental changes (Kalvoda Ed. 2003; Drbohlav et al. 2004a, 2004b). Geomorphological research aims both at understanding the principles of dynamic behaviour of natural systems (Goudie and Kalvoda 1997, 2007a, 2007b), and at the necessary diagnosis of natural hazards, the prediction of catastrophic events, and the mitigation of risk situations such as rapid soil erosion, landslides, floods, and seismic phenomena (Kalvoda and Rosenfeld Eds. 1998; Demek et al. 2006; Langhammer Ed. 2008; Kalvoda and Novotná 2024).

The multidisciplinary study of tectonic movements in the Bohemian Massif during the Quaternary, including current tectonic activity (e.g., Hejl et al. 1997; Štěpančíková et al. 2008, 2010, 2018, 2019, 2022; Steklá et al. 2017; Stemberk Jb. 2021), is a very topical theme of geodynamic research of orogenic processes and phenomena in Central Europe. Various approaches to assessing the extent of tectonic movements in the Bohemian Massif were described, e.g., in earlier studies by Kopecký (1970a, 1970b, 1972, 1973, 1983, 1986, 1989a, 1989b, 1996), Vyskočil (1975, 1984, 1988), Kalvoda and Pašek (1975), Kalvoda and Prášek (1987), Kalvoda and Zeman (1979, 1982, 1983), Kalvoda et al. (1990, 1994). Recent comprehensive approaches to the topic can be demonstrated, for example, by papers of Mrlina (2000), Bankwitz et al. (2003), Schenk et al. (2003), Hartvich (2005), Balatka and Kalvoda (2006, 2008), Stemberk et al. (2010, 2017) or Balatka et al. (2015, 2019).

The systematic efforts of expert teams to link research on the long-term development of landforms with current geomorphological processes and phenomena is continuously applied in the identification of geomorphological hazards and risks during the construction and operation of large engineering works (Kalvoda 1978, 1996a, 1996b, 1998a, 2007b; Zvelebil 1989; Stemberk 1994; Kalvoda and Mercier Eds. 1996; Demek et al. 2006; Kalvoda and Balatka 2016). In this regard, geomorphological studies focused on selected nuclear power plant sites in Central Europe have become again highly relevant (e.g., Kalvoda and Demek 1991; Demek and Kalvoda 1991, 1992; Kalvoda 1992b; Kalvoda and Stemberk 1993).

Currently, thematic emphases in projects focused on natural hazards are shifting from primary research into risk processes, their detection, monitoring and predicting (e.g., Štěpančíková and Stemberk 2004; Štěpančíková et al. 2008; Raška and Emmer 2014) toward efforts aimed at the controlled reduction or even elimination of environmental hazards and risks. This primarily involves prevention and development of resilient society, creating expert early-warning systems and the rapid deployment of rescue capacities when required. Furthermore, emphasis is placed on the essential importance of controlled mitigation of

cascading effects and understanding the variability of long-term impacts of catastrophic events on society.

5. Conclusions

The morphogenetic diversity of fluvial relief types in the Bohemian Massif (Fig. 2) is a consequence of the synergy between differential tectonic uplift induced by the continuing Alpine orogeny and the variability of exogenous processes caused by pronounced climatic changes during the Cenozoic. The extent of the vertical component of tectonic movements of morphostructural units of the Bohemian Massif, determined by means of fluvial relief types, reaches values in the order of 10^1 – 10^3 m (Fig. 7). We consider these values to be the lower limit of the extent of differential tectonic uplift in the Bohemian Massif. The reason why this estimation is only approximate is incomplete geomorphological record of the substantial erosion and denudation of its georelief, including planation surfaces of different origin and age as well as fluvial sediments of river terrace systems, under the influence of intensive climate-morphogenetic processes.

Geomorphological research in the central part of the Bohemian Massif indicates that significant epigenetic and antecedent deepening of river valleys took place only from the late part of the Middle Pleistocene (Table 2). The fluvial sediments of river terraces I and II of the main streams were deposited during the Cromerian Complex period and river terrace III during the Elsterian glaciation.

Substantial progress in methods of geomorphological analysis, numerical and physical dating of landform evolution, and monitoring of the intensity and causes of recent movements of the Earth's surface provides a comprehensive knowledge for morphostratigraphical interpretations of the dynamic evolution of the georelief in the Bohemian Massif. These regional geomorphological investigations also offer effective applications in determining serious natural hazards and risks, including their link to ongoing changes in the European landscape environment.

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Appendix 1

In memory of RNDr. Břetislav Balatka, CSc.

(*11. 1. 1931 – †15. 2. 2025)

(Jan Kalvoda)

January 2026 marked 95 years since the birth of the prominent Czech geographer RNDr. Břetislav Balatka, CSc. He was born in Benešov near Semily on 11 January 1931, graduated with honours from the grammar school in Planá near Mariánské Lázně (1950) and completed his university studies at the Faculty of Geology and Geography (Natural Sciences) of Charles University in Prague in 1954. Břetislav Balatka then became a research assistant at the Geology and Geography Section of the Czechoslovak Academy of Sciences, where his supervisor was Professor RNDr. Josef Kinský, DrSc., a corresponding member of the Czechoslovak Academy of Sciences. From 1957, Břetislav Balatka worked at the Geomorphological Department of the Czechoslovak Academy of Sciences

and in 1963 he became a researcher at the Institute of Geography of the Czechoslovak Academy of Sciences, where he worked for more than 30 years. He obtained his Candidate of Geographical Sciences (CSc.) degree (a PhD-equivalent academic research degree) in 1963 and in 1966 he received the title of Doctor of Natural Sciences (RNDr.) at Charles University in Prague. In 1993, Břetislav Balatka became a senior researcher and lecturer at the Department of Physical Geography and Geoecology, Faculty of Science, Charles University.

A detailed biography and professional focus of Břetislav Balatka was subject of an article by doc. RNDr. Václav Příbyl, CSc., published on the occasion of his seventieth birthday (Příbyl 2001). The article also includes a list of Břetislav Balatka's works from 1956–2001. A selection of his publications from the 21st century is then presented in articles by Kalvoda (2011, 2016). Lists of Břetislav Balatka's publications

include over 40 books, more than 80 original professional articles, around 25 thematic maps and 90 research reports, as well as over 100 popular papers and dozens of conference contributions and studies. Moreover, his teaching, editing and reviewing activities were also very extensive.

Břetislav Balatka and his main collaborators, PhDr. Jaroslav Sládek, CSc. and RNDr. Jaroslava Loučková, CSc., are prominent researchers in Czech physical geography and geomorphology. It was not possible to freely implement their excellent professional work in the international scientific context due to the unfortunate (or, more accurately, tragic) history of Czech society in the years 1948–1989. Therefore, they were unable to systematically participate in addressing and correlating geographical topics in the wider European region.

From Břetislav Balatka's extensive geographical work, it is particularly worth highlighting his geomorphological research focused on the development of the river network and fluvial relief in the Czech lands, as well as his physical-geographical work on selected regions of the Bohemian Massif. His professional experience in researching geomorphological, climatic, and hydrological processes and phenomena, as well as nature protection and natural hazards, allowed Břetislav Balatka to deepen and update the solutions to varied geomorphological problems in Czechia.

Břetislav Balatka's encyclopaedic knowledge in several Earth science disciplines and his extraordinary teaching skills were put to good use in university lectures, seminars, field excursions and during the education of undergraduate and postgraduate students. It should be noted that Břetislav Balatka, in addition to the fluvial geomorphology of the Czech lands, also investigated in detail the evolution of the landforms of the Czech Cretaceous Table, including its unique sandstone relief. He paid considerable attention to the evolution of the Ohře (Eger) valley, the main stages of which are associated with both substantial changes in climatic and morphogenetic processes and neotectonic activity in the Late Quaternary. His other favourite topics were pseudokarst

phenomena on neovolcanic rocks and crystalline rocks, as well as the significant phenomenon of slope movements in the Czech landscape. Břetislav Balatka and Jaroslav Sládek also focused on the very current issue of precipitation and runoff conditions in relation to changes in the water content of Czech rivers, including extraordinary events of this kind.

For a long time, Břetislav Balatka, together with colleagues from the Institute of Geography of the Czechoslovak Academy of Sciences, worked on the concept of various methods of geomorphological mapping, including the creation of their legends, as well as updates to the orographic subdivisions and the characteristics of historical-genetic types of georelief of the Czech lands. In the first decade of the 21st century, this classic figure in Czech physical and regional geography significantly contributed to the successful work of the Center for Earth Dynamics Research. Břetislav Balatka was a key member of the expert team that dealt with dynamic and evolutionary geomorphology. Systematic measurements and monitoring of geodynamic processes and phenomena using geodetic, geological and geophysical methods, including remote sensing, must be consistently integrated with their geomorphological and physical-geographical interpretations. This methodologically and knowledge-intensive comprehensive approach allows to identify evolutionary features of Earth dynamics in the palaeogeographical and/or prognostic context of global and regional changes in the natural environment.

Břetislav Balatka's dedication to scientific and pedagogical work was combined with his refined intuition for capturing the essential features of the observed natural processes and phenomena and at the same time with his creative ability to combine analytical and comprehensive approaches to the geographical topics he addressed. For these rare qualities, as well as his admirable diligence, modesty and very kind approach to colleagues and students, Dr. Břetislav Balatka became a shining example of a noble person and researcher for the current and upcoming generation of Czech geographers.