MORPHOSTRATIGRAPHICAL CORRELATION OF RIVER TERRACES IN THE CENTRAL PART OF THE BOHEMIAN MASSIF WITH THE EUROPEAN STRATIGRAPHICAL CLASSIFICATION OF THE QUATERNARY

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ABSTRACT

The results of geomorphological research, focused on identification of larger remains of fluvial terrace sedimentary sequences in the Želivka, Sázava, Berounka, Vltava and Labe river-drainage basins in the Bohemian Massif, are presented. The terrace flights are characterised by a variable structure which is conditioned by the bedrock and drainage-network configuration created prior to the Pleistocene. They are formed by the specific hydrodynamic processes during the Quaternary. A series of transverse-valley profiles and longitudinal profiles have been constructed. This has enabled the differentiation of seven main terrace surfaces underlain by Quaternary fluvial sediments. However, the uppermost levels are underlain by Neogene-age deposits that comprise both fluvial and fluvio-lacustrine sediments at altitudes up to 135 m above the present valley floor. The Quaternary incision of the Sázava and Vltava valleys reaches an average depth of over 100 m. This was induced by neotectonic uplift of the Bohemian Massif. The terrace flights include incised meanders and bends, most of which formed during the Middle Pleistocene. Based on the currently accepted Quaternary chronostratigraphical scheme, the terrace system throughout the Bohemian Massif is mostly of Middle and Late Pleistocene age that is the period from the Cromerian Complex to the Weichselian stages of the NW European scheme. A marked erosional episode, that pre-dates the accumulation of terrace I sediments, occurred at the end of the Early Pleistocene Subseries. Older levels of fluvial sediments in the central part of the Bohemian Massif, occupying higher topographical positions, previously classified as of Pliocene age, are now considered to date from the Early Pleistocene.

Keywords: river terraces, morphostratigraphy, Quaternary, Bohemian Massif

1. Introduction

The flight of river terraces and related fluvial deposits in the Želivka, Sázava, Berounka, Vltava and Labe river valleys in the Bohemian Massif (Figure 1) has traditionally been used as a reference framework for the Quaternary stratigraphy of the region. It is also realised (e.g. Záruba et al. 1977; Tyráček et al. 2004, 2009; Balatka, Kalvoda 2010) that the terrace system, which is widespread along the major rivers, developed as a result of regional neotectonic uplift. Over the past years, the following procedure for studying the terrace system and evolution of river valleys has been adopted (Balatka, Kalvoda 1995, 2010; Balatka et al. 2010a, b): a) evaluation of existing regional literature, b) analysis of the longitudinal profiles of the modern river and valley floor, c) detailed geomorphological survey of the valley, d) reconstruction of river terrace surfaces and underlying deposits in both long profiles and cross-sections, e) connection of the established terrace system in individual valleys to the regional terrace system; f) an outline of the main stages of the valley evolution through the Quaternary. As a result of geomorphological research, the longitudinal profiles of fluvial terrace accumulations and Neogene sediment localities, the structure of valley cross-sections and the major occurrences of planation surfaces have been plotted (Balatka, Kalvoda 2008, 2010; Balatka et al. 2010a, b).

This method of characterising the terrace system and interpreting the valley evolution from it, builds strongly on the assumption that the terrace elements, i.e. the palaeo-thalweg and the surfaces of each major terrace level, maintained stable gradients that correspond to the longitudinal profiles and represent the so-called "equilibrium profile". In this state, the discharge and transport capacity at each position along the river channel is in equilibrium with upstream sediment delivery and, averaged over millenia, the river thus neither erodes nor accumulates sediment but applies all its energy to the transfer of transported material (Mackin 1948). This state may be disturbed, either in the direction of net erosion or in that of net accumulation, as a consequence of differential tectonic movements and changes in discharge regime and sediment supply. For example, increased water and sediment supply is associated with intensive cryogenic processes during the colder intervals in the Pleistocene. In these circumstances huge accumulations formed, altering the equilibrium profile to a new state over valley subreaches. This results in marked steps in the river gradient. The variations of the convex-concave gradient line in the longitudinal profiles represent the front to backwards erosion which proceeded upstream as a down-cutting phase that begins when the cryogenic sediment delivery stages ceases.

In this paper, the main features of the erosional and denudational history of the central part of the Bohemian Massif are discussed in relation to neotectonic and climato-morphogenetic processes during the late Cenozoic. The sedimentary and morphological records of the

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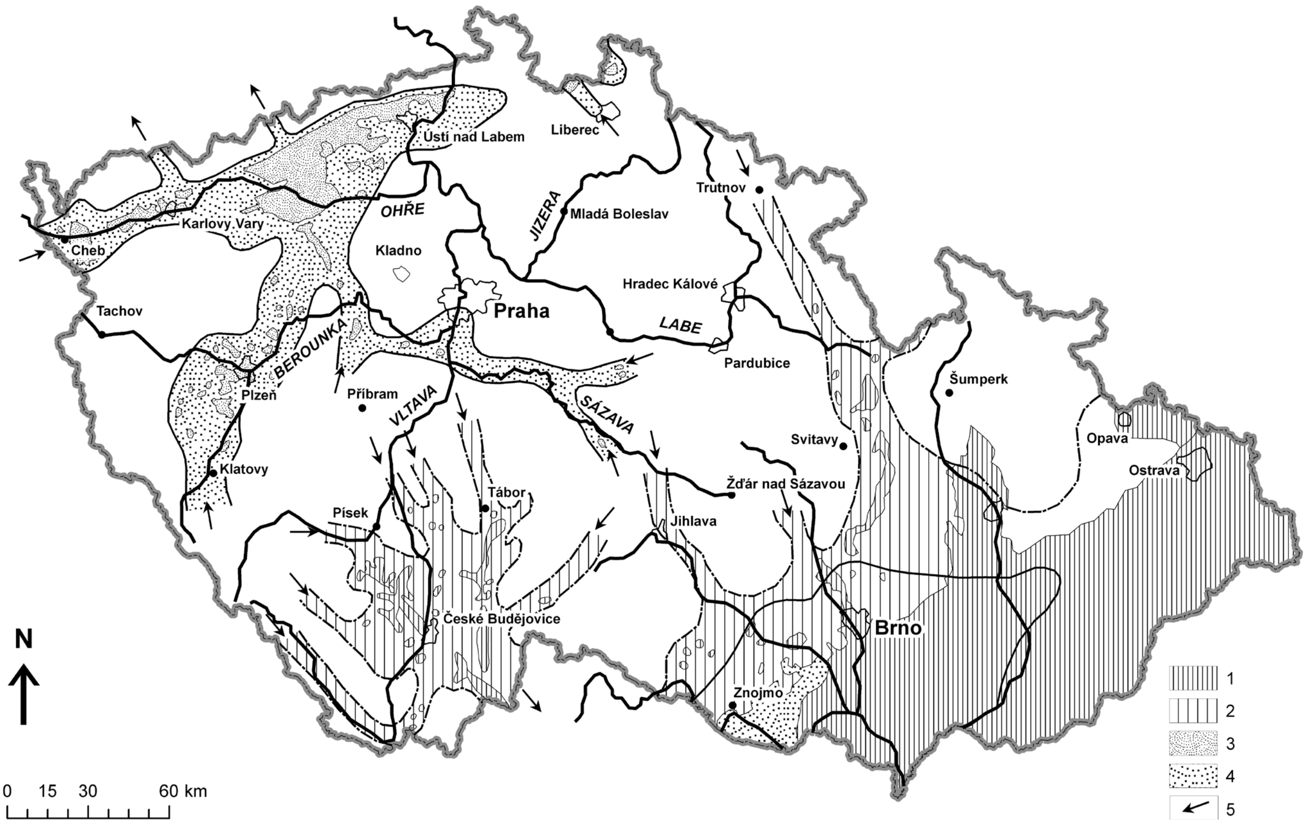

Fig. 1 Palaeogeographical position of Miocene sedimentary basins and present-day river network of the Bohemian Massif (adapted from Malkovský 1979 and Chlupáč et al. 2002). Key: 1–2 Middle and Upper Miocene sediments: 1 – preserved, 2 – assumed; 3–4 Lower Miocene sediments: 3 – preserved, 4 – assumed; 5 – directions of transport of Miocene sediments.

Quaternary evolution of antecedent valleys and river accumulation terraces in the central part of the Bohemian Massif are correlated with the European chronostratigraphical scheme for the Quaternary. The aims of the study are the comparison of diverse results of the river terraces exploration in major valleys of the region and their uniform morphostratigraphical interpretation.

2. Erosion and denudation processes in relation to the morphostructural evolution of the Bohemian Massif

River valleys and terraces originate in regions of variable tectonic activity combined with very specific climate-morphogenetic and hydrodynamic processes (Antoine et al. 2000; Bridgland, Westaway 2008; Gibbard, Lewin 2009). The palaeogeography of the central part of the Bohemian Massif (Figure 2) involved several morphogenetic events related to significant tectonic uplift. All the uplift episodes between the Cadomian and Alpine orogenesis were accompanied by rapid denudation under very variable climatic conditions (Malkovský 1975). For example, in the Upper Palaeozoic, some parts of the Bohemian Massif were deeply denuded and crystalline rocks from a depth of 15 km were exhumed exposing deep-seated granite massifs. The relief of the central part of the Bohemian Massif took the form of a post-Hercynian planation surface denuded under a semi-arid and very warm climate. From the Cretaceus Cenomanian to Santonian stages, marine sedimentation occurred in the Bohemian Cretaceous Basin. This marine transgression, during which both the exhumed crystalline rocks and the post-Hercynian planation surface, covered by kaolinic and lateritic regoliths formed on them were submerged for the first time since the Precambrian. This phase was terminated by epiplatform uplift during the Santonian (Chlupáč et al. 2002). The uplift of the Bohemian Massif at the end of the Santonian resulted from the ongoing Alpine and Carpathian orogenesis. This event marked the definitive retreat of the Upper Cretaceous epicontinental sea which significantly receded leaving an erosion foundation for the region.

The neotectonic rejuvenation of the Bohemian Massif occurred during the Laramide stage of the Alpine orogenesis some 65 million years ago. The Bohemian Massif was uplifted and a system of graben structures and diagonal tectono-volcanic zones were formed. At the beginning of the Tertiary, the climate in the Bohemian Massif was humid and tropical, with a mean annual temperature of up to 26 °C and a mean annual rainfall of 2000–3000 mm (Malkovský 1979). Lateritic and kaolinic weathering products were developing up to the beginning of the Oligocene, under warm and in some periods wet climate

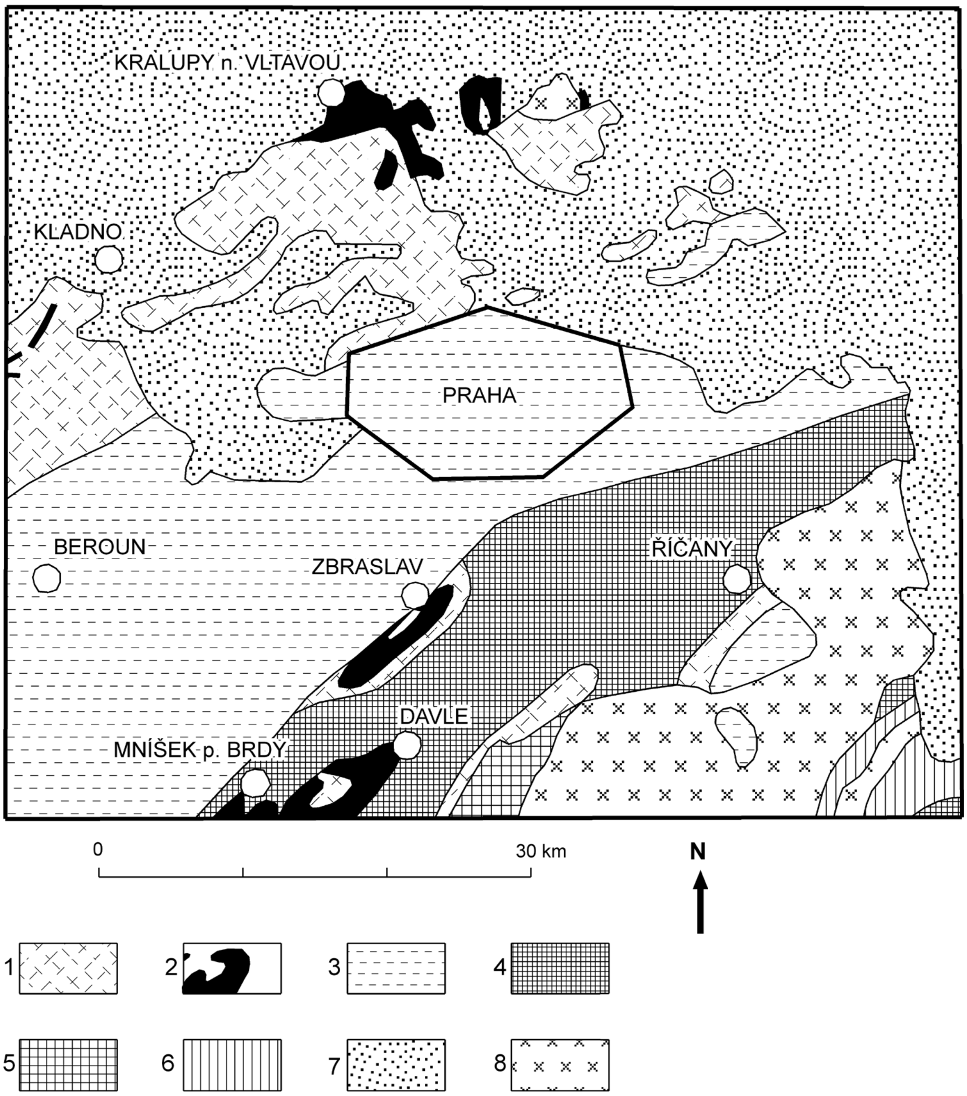

Fig. 2 Geological sketch of the central part of the Bohemian Massif (adapted from Chlupáč et al. 2002). Explanations: 1 – Proterozoic metamorphosed rocks of the Zbraslav and Kralupy units, 2 – Proterozoic volcanites, 3 – Cambrian to Devonian sediments and metamorphosed rocks of the Barrandian unit, 4 – Proterozoic rocks of the Štěchovice unit, 5 – metamorphosed subsilicic (alkaline) rocks, 6 – metamorphosed rocks of an uncertain age, 7 – Upper Carboniferous to Tertiary sediments, 8 – Variscan (Hercynian) granitic rocks.

conditions. The pre-Oligocene planation surface is indicated by duricrust relics in western and central Bohemia (Demek 2004). In the Oligocene the temperature fell to 16 °C under a savannah-type climate with dry winters, and the very dry climate prevailed also in the Middle Oligocene. The Upper Oligocene was characterised by a permanently wet and warm climate, with subtropical rain forests remaining until the Middle Miocene. Up to the end of the Palaeogene, streams ran through shallow, wide vale-shaped low gradient valleys. However, at the end of the Oligocene, planation processes of the Bohemian Massif were interrupted by tectonic movements (e.g. Malkovský 1979; Chlupáč et al. 2002), accompanied by volcanic activity in its western and northwestern part 35–17 million years ago.

In the Oligocene and Miocene, the main European watershed between the collection area of the epicontinental sea at the south-west and the basins of the Para-Tethys crossed the Bohemian Massif approximately along the north-western margin of the central Bohemian Pluton. It then turned to the northern part of the Českomoravská vrchovina Highlands. From there it continued to the north (Chlupáč et al. 2002). The initial impulse towards the morphographical distinctiveness of geomorphological units was initiated in the Lower Miocene (Aquitanian to Burdigalian), when tectonic disintegration of the planation surface occurred. The progressive depression of the southern and southeastern parts of the Bohemian Massif in the Middle Miocene enabled the sea to penetrate into these regions (Demek 2004). Depressions in the region of the Ohře rift and differential movements of the main fault zones in the Bohemian Massif were also morphotectonically significant. Moreover, the evolution of the relief of the Bohemian Massif was influenced by two neotectonic stages of volcanic activities in the Upper Miocene between 9.0 and 6.4 Ma, and from the Upper Pliocene to the Pleistocene, between 3.0 and 0.17 Ma ago (Ulrych et al. 2011). Morphostructural patterns of the Bohemian Massif, originated during the Miocene, determined the main elements of present-day river network (cf. Figures 3 and 4).

The oldest indices concerning the disposition and changes of the river network of the Bohemian Massif are preserved in the Miocene sedimentary record (Malkovský 1975, 1979; Kovanda et al. 2001). During the Lower

Fig. 3 Antecedent valley of the Labe river near Litoměřice town, partly infilled by fluvial and slope accumulations, is cut through an uplifted horst of crystalline rocks which is an underlier of neovolcanic rocks in the České středohoří Low mountain range.

Fig. 4 Deep valley of the Berounka river with a considerable fluvial accumulation terraces incised into Cambrian volcanic rocks of the Křivoklátská vrchovina Highland in the late Cenozoic.

Miocene, a tropical humid climate with dry periods prevailed in the Bohemian Massif. This later changed to a subtropical wet climate in the Upper Miocene. Periods of humid climate in the Neogene were characterised by very extensive erosion and denudation of the kaolinic and lateritic weathering mantle, down to the basal weathering surface. Since the intensive volcanic activity ceased at the end of the Lower Miocene a "post-volcanic" planation surface developed. It was being formed under warm and humid climatic conditions from the Middle Miocene, throughout the Pliocene (5.3 – 2.6 Ma) and continued into the lowermost Early Pleistocene (Chlupáč et al. 2002; Demek 2004). The morphostructural features and the internal differentiation of this Neogene planation surface were dependent on the rock resistance to weathering under a tropical or subtropical climate.

In the Middle and Upper Miocene, southern Bohemia was still drained towards the south (Tyráček 2001; Tyráček, Havlíček 2009). It is indicated both by relics of fluvial and lacustrine sediments and by secondary finds of river-transported moldavites (these tektites originated during the Rees Impact and are radiometrically dated at 14.3 million years) in the adjacent part of Austria. During the late Cenozoic, the regionally differentiated tectonic uplift and changes of the European climate were significantly represented in the evolution of the fluvial network of the Bohemian Massif. The granular character of the Pliocene river sediments is similar to those of Lower Pleistocene terrace deposits which indicate that the orographical situation of the Bohemian Massif was closely similar to that today (Kalvoda, Balatka 2006; Balatka 2007). Important changes in the fluvial network occurred at this time with significant manifestations of epigenetic and antecedent evolution of river valleys through rapid erosion (Figures 3 and 4), as well as ongoing reconstruction of the large area of sedimentation of transported material.

3. River terraces evolution in the central part of the Bohemian Massif during the Quaternary

3.1 Geomorphological position of river terraces related to tectonic uplift

The oldest river terrace accumulations in central Bohemia are situated above the margins of the canyon-like valleys of Vltava, Berounka, Sázava and Želivka Rivers (e.g. Záruba-Pfeffermann 1941, 1942; Záruba et al. 1977; Kovanda et al. 2001; Tyráček et al. 2004, 2009; Balatka, Kalvoda 2010). Relics of Miocene gravels and sands at the Sulava locality, near Radotín town have their surface lowered by erosion to 358 m a.s.l. and their base at 314 m a.s.l., i.e. 163 m or 119 m above the Berounka river level. Other relics of these Miocene and Pliocene-age sediments recorded from the neighbourhood of Slivenec, near Suchomasty and on Bílá Hora (380 m a.s.l.). The surface of Early Pleistocene sands and gravels, up to 40 m thick, between Kobylisy and Sedlec on the Zdibská plošina Plateau, occurs at 300 to 325 m a.s.l., i.e. 125 to 150 m above the Vltava river level, and 35–60 m below the Ládví touchstone ridge (359 m a.s.l.). They also include rounded pebbles and boulders of crystalline rocks derived from the regions of Kutná Hora, Říčany and Kouřim towns (Záruba-Pfeffermann 1941). Northwards from these Pliocene spreads on the Zdibská plošina Plateau, are sediments up to 20 m thick (with their surface 112 m above the Vltava river level). These sediments originated, within the so-called Lysolaje group of terraces, during the Middle Pleistocene (Table 1). In the Early Pleistocene, the Vltava and its tributaries were still freely meandering in

Tab. 1 Chronostratigraphical correlation of river terrace deposits in the central part of the Bohemian Massif related to North-West Europe stratigraphical stages of the Quaternary.

Regional stratigraphical stage/ substage divisions of the Quaternary (Gibbard et al. 2004, 2008, 2009)	SÁZAVA Balatka (2007), Balatka, Kalvoda (2010)	BEROUNKA Balatka, Loučková (1992)	VLTAVA – LABE confluence area Balatka, Sládek (1962)	VLTAVA Záruba at al. (1977)	VLTAVA and LABE system Tyráček (2001), Tyráček et al. (2004, 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)	Poříčí Terrace (VI)	Kazín Terrace (VI)	Mlčechvosty Terrace (VIa, b, c)	Veltrusy Terrace (VI)	Veltrusy Terrace (Warthe)
Middle Pleistocene Saalian (Drenthe)	Městečko Terrace (V)	Liblín Terrace (Va) Poučník Terrace (Vb)	Cítov Terrace (Va, Vb)	Dejvice Terrace (V)	Dejvice 1 and 2 Terrace (Drenthe)
Middle Pleistocene Saalian (Fuhne)	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		Zdiby Stadial (Pliocene)	Zdiby Terrace (Eburonian – Menapian)
Early Pleistocene Tiglian					Stříbrníky Terrace (upper Tiglian)
Neogene	Niveau A Bojiště	Niveau A		Klínec Stadial	

shallow and wide valleys formed on the Neogene planation surfaces.

Even as late as the beginning of the Middle Pleistocene, the basal boundary of which is the Matuyama / Brunhes palaeomagnetic boundary, dated at 780 ka, new terrace steps were being progressively formed (70 to 100 m above the present water courses), together with an epigenetic and antecedent deepening of the river network. For example, the Suchdol Terrace is situated up to 2 km west of, and 96 m above the Vltava valley floor. The Straškov (IIIb) Terrace of Balatka and Sládek (1962) is now ca. 70 m above the Vltava river near Račiněves in the neighbourhood of the Říp mountain. It is described by Tyráček (2001) as the Straškov 2 Terrace and is the equivalent of the Vinohrady Terrace in Prague (Table 1). During aggradation of the Straškov 2 Terrace, the Vltava flowed west of the Říp Oligocene – Miocene volcanic neck, subsequently diverting to its present-day position east of Říp. The fluvial deposits underlying the Straškov Terrace consist of a coarse lower and a finer upper unit (Tyráček et al. 2004). These sediments are overlain by loess and slope deposits that include palaeosols probably representing two warm interglacial stages. The 12–14 m thick lower fluvial units with stratified sands and gravels indicate a cold-climate braided-channel environment. The 0.5–2 m thick upper fluvial unit is composed of sand and fine sandy gravel, disturbed by cryoturbation. It has yielded thermophilous mammals, interglacial molluscs and Palaeolithic archaeological material (Tyráček 2001; Tyráček et al. 2004; Tyráček, Havlíček 2009).

The Vltava terrace sequence is subdivided longitudinally into two reaches. Downstream of its confluence with the Sázava river, the terraces are sub-parallel both to each other and to the modern channel gradient of ca. 0.4 m km^{-1}. Further upstream, the channel gradient is more variable, but typically steeper than the terraces, which thus converge towards the river's source (Balatka, Sládek 1962). An estimation of the values of the antecedent deepening of the Vltava river (stimulated by tectonic uplift), based on the position of relics of river accumulation terraces (Figure 5), is influenced by series of uncertainties such as terrace surfaces being irregularly lowered by erosion, destruction of their bases, a variable range and episodic rhythm of tectonic uplift. However, the results of the estimation are an example of the dynamics of the fluvial bedrock erosion and the transportation of weathered material in the region of central Bohemia during the late Cenozoic (Kalvoda, Balatka 2006; Kalvoda 2007): a) Middle Miocene to Pliocene: rate of deepening about 2–4 cm ka^{-1}, b) Early Pleistocene: 6–12 cm ka^{-1}, c) the younger part of the Middle Pleistocene: 6–8 cm 10 a^{-2}, d) a part of the Late Pleistocene (40 to 20 ka): 2–4 cm / cm ka^{-1}. During the Holocene are mostly recycling of gravels, sands and slope accumulations occurred in the valley bottom.

Deepening of the river network in the late Cenozoic is also indicated by landform evolution in the area of

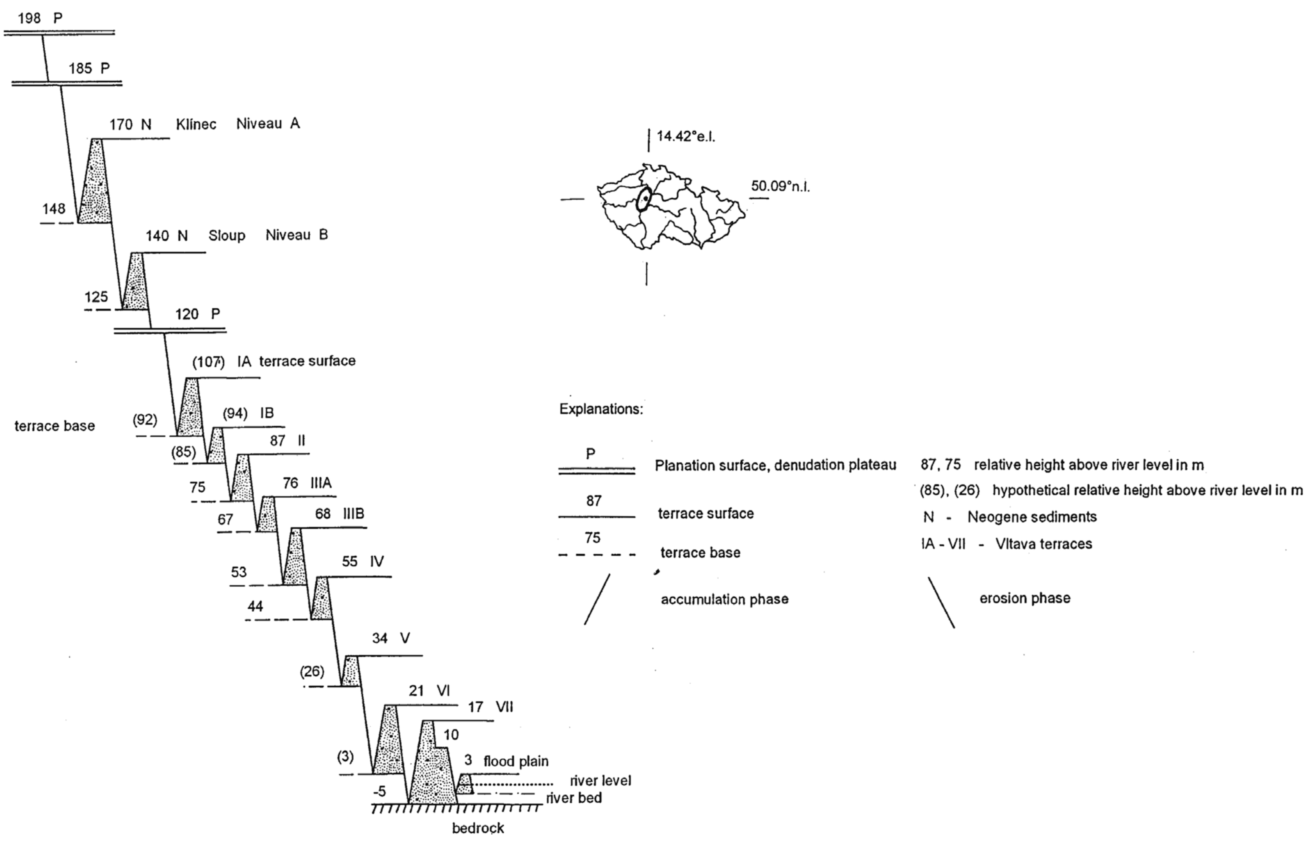

Fig. 5 River accumulation terraces in the Vltava valley between the mouths of the Sázava and Berounka rivers (modified after Balatka, Štěpančíková 2006 and Balatka, Kalvoda 2010). The stratigraphical correlation of river terraces is shown in Table 1.

the regional erosion base of the Bohemian Massif, i.e. in the Děčínská vrchovina Hilly Land. Between Děčín and Hřensko, erosion by the river Labe reached at least 50 m in the Pliocene and 180–200 m in the Quaternary (Balatka, Kalvoda 1995; Kalvoda, Balatka 1995). Besides the system of river accumulation terraces, wind-blown sands, loess loams and loess also provide valuable sedimentary evidence of Quaternary landscape evolution (e.g. Šibrava 1972; Záruba et al. 1977; Tyráček 2001; Balatka et al. 2010a, b). The deposits are maintained in a stratigraphically significant thickness in depressions or on lower plateaux of the Česká vysočina Highlands.

3.2 Discussion of key morphostratigraphical features of the river terraces

The river valleys of the region, and thus also their contained terrace flights, are the product of processes of hydrographical capturing from several Miocene individual catchments with different drainage directions. For example, the Sázava valley was probably initiated in the Pliocene as a result of tectonic movements of anticlinal and synclinal character, which interrupted the original Tertiary drainage of the basin to the north. If the Lower Miocene Sázava (with Želivka) already flowed from the Melechov ridge westwards, it captured the upper part of the valley to its course probably at the turn of the Miocene to the Pliocene. Relics of Miocene sediments are found in two areas on the planation surface, i.e. in morphostructural depressions of the Sázava – Želivka interfluve and the Sázava – Labe watershed (Figure 1). They are found at levels above the canyon-like valley cutting, with their surface at 110–135 m above the river (prevailing level A, Table 1). They represent relics of accumulation fills of old river channels as well as widespread denudational relic morphology. These fluvial to fluvial-lacustrine sediments are about 10 m thick. Their spatial distribution demonstrates either Sázava drainage from the Sázava town to the north, or, according to Malkovský (1975, 1979), Neogene drainage aligned towards the west, i.e. in the direction of the present course. Neogene sediments near Jesenice, south of Prague, filling deep channels near the Sázava – Vltava watershed (Kovanda et al. 2001). They indicate traces of drainage of the lower Sázava catchment to the north.

In the Sázava valley, seven main terrace surfaces with several secondary surface levels have been differentiated (Table 1). The genesis and structure of the terrace system and the valley evolution were influenced by two pronounced gradient steps in the river surface – one in the middle course and one in the lowermost course just before its confluence with the Vltava river. While in these reaches the mean gradient is 5.7‰ and 3.9‰ respectively, the 108 km long reach between both convex-concave gradient steps has a mean incline of only 0.88‰. These steps are associated with a huge fluvial accumulation in the lower reaches: the lower step mainly in the Vltava river valley, the upper step in the adjacent part of the middle course (Figure 6). A thick accumulation of sediments underlies the IIIrd (Chabeřice) terrace surface downstream of the later step, expressing an extraordinary thickness of about 25 m (Figure 7). A subsidiary level,

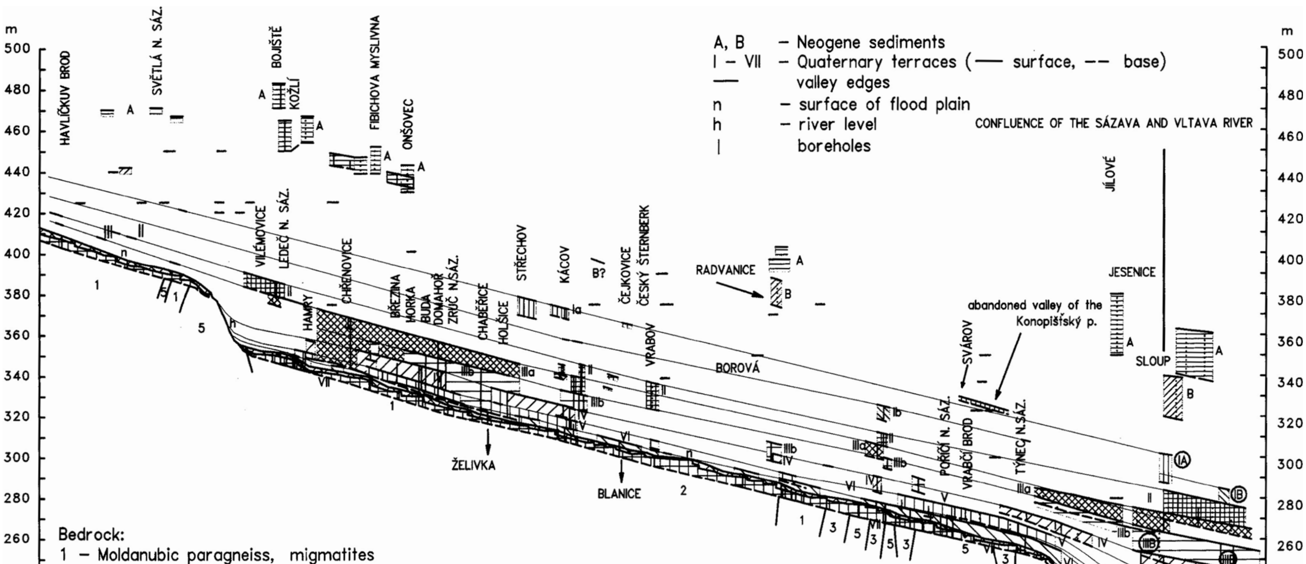

Fig. 6 The long profile of river terraces and Neogene sediments of the Sázava between Havlíčkův Brod and its confluence with the Vltava valley (exaggeration: × 300), with marked localities of planation surfaces (adapted from Balatka, Kalvoda 2008, 2010).

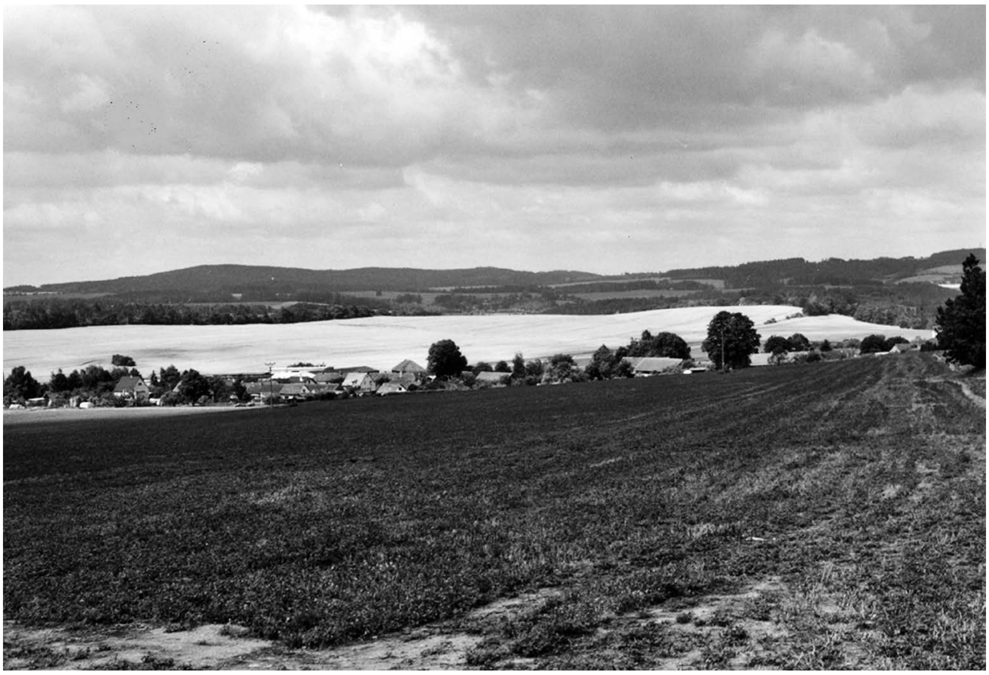

Fig. 7 Part of an abandoned valley of the Sázava river is near Chabeřice village infilled by sediments of terrace III up to 25 m thick.

terrace IIIb (Buda Terrace, Table 1), with its surface of about 8 m lower than that of terrace IIIa and 30 m above the water level, was formed in alluvial deposits of this Chabeřice Terrace.

The Sázava valley includes several geomorphologically remarkable characteristics (Balatka, Kalvoda 2010; Balatka et al. 2010a, b): a) reaches with closed transverse profile alternate with wider to vale parts; b) the highest planation surfaces of the etchplain and pediplain-type are situated mostly at 140–190 m above the river surface. Lower levels of denudational plateaux are situated at relative heights mostly between 90 and 130 m, and that in two to three height levels situated in the largely open-vale valley depression; c) margins of rare straight valley reaches displaying the levels of Quaternary downcutting are situated mostly at 60–85 m (rarely at 40 m) above the present river valley surface.

The beginning of the lower Želivka valley evolution began in the Neogene, mostly the Miocene, by sediment accumulations which are found in the area of the Želivka-Sázava interfluve as well as in the wider neighbourhood of Ledeč nad Sázavou and Zruč nad Sázavou. The main relicts of these Miocene sediments fill shallow depressions which follow the direction of the Želivka valley. The recent valley of the Želivka river was probably developed in the Pliocene as a wide vale-shaped depression. The intense erosional processes of the Želivka valley deepening occurred during the Quaternary. The processes themselves reached their highest activity in the erosional stage between the evolution of the IInd and IIIrd accumulation terraces when the valley was significantly deepened by about 25–30 m. The huge accumulation of the IIIrd (Soutice) Terrace, which is similar to the Chabeřice Terrace of the middle Sázava, was formed in the lower Želivka valley (Table 1).

During the erosional stage following the evolution of the IInd terrace the Želivka valley was deepened to a level of 5–8 m above the present water surface and in the following accumulation stage the river-bed was elevated by an aggradation of about 10–23 m above the base of the IIIrd terrace. The depressions of the pronounced valley meanders and bends were mainly filled by this aggradation. The depressions were formed in the period following the formation of the Ist and IInd terraces. These depressions are probably related to downward movements of tectonic origin in the area of the lower Želivka River in the wider neighbourhood of a morphostructural contact between the Českomoravská vrchovina Highland and the Středočeská pahorkatina Upland. The oldest, highest terraces in the central part of the Bohemian Massif are encountered only very sporadically in small patches, and above the margins of the valley incisions.

In the lowermost part of the Sázava course, the IIIrd terrace is encountered above the limit of valley margin. Here, the gradient line of the IIIa level is largely diverges from that of the modern river, from 30 m at the beginning of the gradient step to 75 m in the Sázava – Vltava confluence area downstream (Figure 6). The surface of the terrace has a constant gentle inclination and its thalweg in the lower course had probably an increased slope that was being progressively levelled by accumulation that progressed upstream from the Vltava valley. When the terrace was formed, more sediment must have filled the gorge reach of the present valley, but during following erosional stages these sediments were removed.

Reconstruction of the course of the IIIrd terrace in the longitudinal profile and the relation of this level to the Vltava terrace system has shown that the IIIrd terrace is the best-protected accumulation landform in the river valleys studied. Therefore, it has crucial significance for

Fig. 8 Cryoturbated weathered parts of Proterozoic greywacke slates in an erosional slope beneath the Sázava terrace III on the right bank near the confluence with the Vltava river.

understanding of the evolution of the Sázava and Želivka terrace system, as well as for its stratigraphical correlation with Quaternary landforms and sediments in the Bohemian Massif. It is suggested that the Chabeřice (IIIrd) Terrace is the stratigraphical equivalent of the Vltava terraces IIIA (Kralupy) and IIIB (Vinohrady, cf. Table 1), which also locally form an uniform accumulation. In comparison to the lower Vltava terraces, the sediments of the Chabeřice Terrace (IIIa) are more weathered (Figure 8) and thus undoubtedly older.

After the end of the accumulation of the IIIrd terrace, the valley bends and meanders were abandoned in several places (e.g. Figure 7), and a series of lower terraces developed as accumulations in alluvial reaches of the valleys during a significant stage of long-term erosional valley deepening. Some of these levels could be marked as erosional or incised features in the IIIrd terrace deposits (terrace IIIb, alternatively IVth terrace). River-bed dislocations and deep erosion were caused by changes in the local erosional base during highly variable denudation, erosion and accumulation processes. Changes in the intensity of these morphogenetic processes in the central part of the Bohemian Massif were related to neotectonic movements and differing resistance of the bedrock as well as with the changes of climatic conditions in the late Cenozoic.

Correlation of the sequences described here to the most recent global chronostratigraphical scheme for the Quaternary (i.e. Gibbard, Cohen 2008; Gibbard at al. 2004, 2009) demonstrates, that the entire terrace system in the central part of the Bohemian Massif corresponds in large part to the Middle and Late Pleistocene, from the "Cromerian Complex" to the Weichselian stages. The erosional interval before accumulation of the Ist terrace occurred at the end of the Early Pleistocene. Older levels of fluvial sediments, occupying in the studied region an even higher morphological position, and previously classified as Pliocene age, have thus been stratigraphically shifted to the Early Pleistocene time.

It is suggested that the dynamics of fluvial processes together with records about weathering, denudation and erosion, should be studied. These processes are connected with reconstruction of the large area of sedimentation of transported material.

4. Conclusions

The major features of the erosional and denudational history of the valleys in the central part of the Bohemian Massif are presented in relation to climate-morphogenetic and neotectonic processes during the Cenozoic. Fluvial sediments and related accumulation landforms in the Želivka, Sázava, Vltava, Berounka and Labe valleys are preserved as extensive river terrace systems. Geomorphological analysis of late Cenozoic fluvial sediments preserved in the central part of the Bohemian Massif confirm that in total seven main terrace accumulations with several secondary levels can be differentiated (Table 1). In the Early Pleistocene, the Vltava river and its tributaries were freely meandering in shallow valleys formed on Neogene planation surfaces. The relative height of the oldest fluvial terraces above the present-day bottom of river valleys in the central part of the Bohemian Massif exceeds 100 m which indicates the approximate depth of Quaternary erosion. Important changes in the fluvial network occurred with significant manifestations of epigenetic and antecedent evolution of river valleys through deep, lateral and backward erosion. An estimation of the values of the antecedent deepening of the river network in the late Cenozoic, based on the position of relics of fluvial accumulation terraces, suggests that the rate of downward erosion probably reached its maximum in the younger part of the Middle Pleistocene.

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RESUMÉ

Morfostratigrafická korelace říčních teras střední části Českého masivu s evropskou stratigrafickou klasifikací kvartéru

Říční terasy Želivky, Sázavy, Berounky, Vltavy a Labe mají ve střední části Českého masivu rozmanitou strukturu, která vznikala specifickými morfostrukturními a hydrodynamickými procesy při vývoji údolní sítě v mladším kenozoiku. Geomorfologický výzkum reliktů fluviálních sedimentů v těchto údolích umožnil rozlišit sedm kvartérních akumulačních teras (Tabulka 1) a dvě úrovně fluviálních a fluvio-lakustrinních sedimentů neogenního stáří. Relikty předkvarterních uloženin se vyskytují až 135 m nad současnými dny říčních údolí střední části Českého masivu. Erozivní zahloubení této antecedentní a epigenetické říční sítě bylo podmíněno neotektonickými zdvihy a během kvartéru dosáhlo více než 100 m. Charakteristické zakleslé meandry a ohyby říčních údolí vznikaly převážně ve středním pleistocénu. Podle současného statigrafického členění kvartéru se systém říčních akumulačních teras v údolích střední části Českého masivu vytvořil zejména ve středním a mladém pleistocénu, a to od Cromerského komplexu do Viselského období. Erozní procesy před vznikem říční akumulační terasy I probíhaly koncem staršího pleistocénu. Je také ukázáno, že dynamiku fluviálních procesů je vhodné studovat ve vztahu ke zvětrávání, denudaci, erozi a svahovým pohybům v kvartéru.

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