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Abstract	Landform evolution of the Prague area in the central part of the Bohemian Massif was controlled by the coupled occurrence of episodic tectonic uplift and variable climato-morphogenetic processes during the Cenozoic. Much older geological history of the region commenced in the Precambrian times and was very diverse in terms of transformations of the natural environment. Present-day landform patterns of the Prague area are determined by epigenetic and antecedent deepening of canyon-like valleys of the Vltava River and its tributaries to large planation surfaces during the Quaternary. These dynamic processes have led to the origin of river accumulation terraces as well as erosion and denudation slopes with weathered mantle of deposits. The extraordinary geodiversity and biodiversity of the landscape in the Prague area is associated with geomorphic hazards, including devastating floods and landslides. Prague is also faced to severe impact of modern urban development and related human activities on the architectural heritage.	
Keywords (separated by '-')	Landform evolution - Geomorphological processes - Environmental hazards - Prague	

5 The Geomorphological Evolution and Environmental Hazards of the Prague Area

Jan Kalvoda and Břetislav Balatka

Abstract

Landform evolution of the Prague area in the central part of the Bohemian Massif was controlled by the coupled occurrence of episodic tectonic uplift and variable climato-morphogenetic processes during the Cenozoic. Much older geological history of the region commenced in the Precambrian times and was very diverse in terms of transformations of the natural environment. Present-day landform patterns of the Prague area are determined by epigenetic and antecedent deepening of canyon-like valleys of the Vltava River and its tributaries to large planation surfaces during the Quaternary. These dynamic processes have led to the origin of river accumulation terraces as well as erosion and denudation slopes with weathered mantle of deposits. The extraordinary geodiversity and biodiversity of the landscape in the Prague area is associated with geomorphic hazards, including devastating floods and landslides. Prague is also faced to severe impact of modern urban development and related human activities on the architectural heritage.

Keywords

Landform evolution • Geomorphological processes • Environmental hazards • Prague

5.1 Introduction

Historical location of Prague has been substantially influenced by favourable natural conditions, including its extraordinary efficient geographical position in the central part of the Bohemian Massif. Archaeological findings give evidence that the Prague area has been occupied since 5 000 years B.P. and variable cultures of the Neolitic and Bronze Ages are also documented (Fridrichová et al. 1995; Fridrich 1997). The history of settlements continued in the pre-Christian centuries (Celts, Slavonic tribes, etc.) and thanks to an attractive combination of environmental, especially relief features, climatic and hydrological conditions (Hrdlička 1984; Kubíková et al. 2005), was not interrupted up to now. Even the present-day heritage evidences of multi-cultural urban patterns of ancient Prague (Fig. 5.1), represented, e.g. by variable architectural styles (especially Gothic, Renaissance and Baroque), have grown around a thousand years. Geological and geomorphic factors played an important role in the specific location and development of Prague, and historical evidence also shows many ways in which human activities have modified landform and environmental characteristics (Fig. 5.2). The aim of this study is to explain when and how the main rock assemblages and landform patterns of the Prague area have been evolved. Principal geomorphic events in palaeogeographical history of the area of Prague are emphasized, including the evolution of the Vltava River valley and its accumulation terraces during the Quaternary. Main recent geomorphic hazards are also illustrated as the topical evidence of relationships between natural and human processes in the environment of the Prague area.

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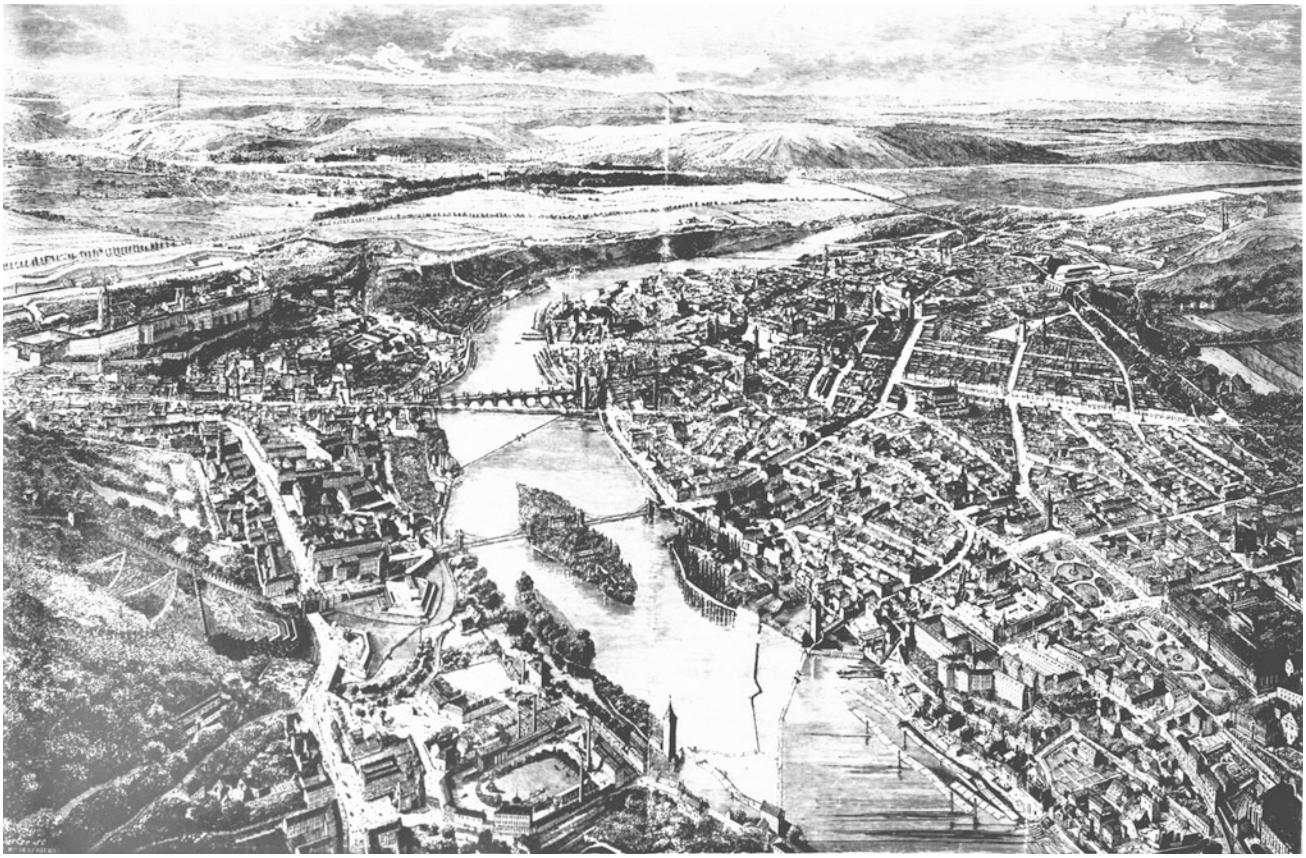

Fig. 5.1 Landscape of Prague in the middle of the nineteenth century drawn by an anonymous artist 150 years ago. The Prague Kettle with the oldest districts of the town is surrounded by flat plains and hills of the Prague Plateau. Painting shows the Vltava valley by a bird-eye view from the south to the north that is downstream. The Prague Castle (Hradčany) and the Lesser Town are situated on the left side and the Old Town and the New Town on the right side of the Vltava River valley (Reproduction of the lithography from the archives of the Map Collection of the Charles University in Prague.)

The geomorphological unit of the Prague Plateau and the adjacent areas (Figs. 5.1 and 5.3) which includes planation surfaces, slightly inclined (mainly) denudational slopes of different age and, by contrast, deeply incised fluvial valleys, including the Prague Kettle depression, has been formed since the beginning of the tertiary (Balatka 1985; Chlupáč 1999). The degree of uplift of the central part of the Bohemian Massif has been "masked" since that time by the concurrent action of differential tectonic movements and intensive erosion, denudation and transport of solid rock fragments and its weathered counterparts (Kalvoda and Balatka 2006). The current substantial height differences and relief contrasts have nevertheless developed only recently as in the late Cenozoic. Examples of maximal height differences in the Prague area are: (a) 225 m of total difference (a) plateau at 400 m a.s.l. westwards from Zličín and the Vltava level below Prague at 175 m a.s.l.), (b) the Bílá hora Hill (380 m a.s.l.) is situated only 6.5 km from the Vltava river, i.e. a difference is about 200 m, (c) the Na Vidouli Plateau (371 m a.s.l.) is situated at 4 km and the Petřín Hill (318 m) only at 750 m from the Vltava river valley floor at an altitude of 188 m (Fig. 5.2), the difference of relative heights being thus 183 and 130 m, respectively. Valley meanders and bends (Fig. 5.4), characteristic of the middle course of the Vltava River, were formed as bends on the bottom of the Pliocene wide valley with a low longitudinal channel gradient. The contemporary landforms appeared during the phase of valley deepening during the Quaternary, mainly by the development of larger bends with flights of river terraces inside the bends.

5.2 Principal Geomorphic Events in Palaeogeographical History of the Prague Area

Landform evolution in the Prague area was determined by neotectonic and climato-morphogenetic processes during the Cenozoic. However, main events in the geological history of the region are much older and very diverse in terms of

Fig. 5.2 Contemporary majestic view of the Prague city and its bridges (a view upstream) also shows susceptibility of the canyon-like Vltava valley to environmental problems associated with road traffic or other anthropogenic pollutions, floods and mass movements (*Photo* Michal Vitásek)

transformations of the natural environment. The oldest crystalline rocks of the central part of the Bohemian Massif (Fig. 5.5) have a complex past. The process of their origin commenced with sedimentation of transported material from the weathered mantle of the Precambrian continent into the epicontinental sea. Marine transgression penetrated the region during the Late Proterozoic and early Palaeozoic. Then, these marine sediments were metamorphosed to a different degree already during the early Palaeozoic (Chlupáč 1999; Kříž 1999). Strong uplift occurred during the Cadomian tectogenesis, whilst weaker uplift also occurred in the Early Ordovician and was followed by a very strong uplift in the Carboniferous. These uplift episodes were accompanied by erosion and denudation, which were particularly severe during the early Variscan times.

The position of this foundation of the central part of the Bohemian Massif at the end of the Ordovician was over 60° of southern latitude (Chlupáč et al. 2002). The Bohemian Massif, as the margin of the Gondwana ancient continent, shifted to that place from the northern temperate and equatorial zone during the Cadomian orogenesis in the Late Precambrian. The Caledonian folding of Gondwana in the early Palaeozoic occurred in the southern hemisphere and only as late as in the Carboniferous period did the Bohemian Massif return to the equatorial zone, i.e. in the period of the Hercynian (Variscan) orogenesis. These mountain building processes formed the Bohemian Massif as a structurally complex unit, the central part of which is formed by collision-deformed and metamorphosed crystalline rocks of the Moldanubicum (Fig. 5.5). As early as the Carboniferous, rapid denudation led to the unroofing of deeper parts of the crust. The Central Bohemian granitoid pluton, separating the Barrandien (Horný and Turek 1999) from the Moldanubicum block, is represented in its northern part by granitoids and by their mantle of contact-metamorphosed Proterozoic and Palaeozoic rocks.

Large granitoid intrusions occurred in extensional conditions in the mature stage of the Variscan orogenesis,

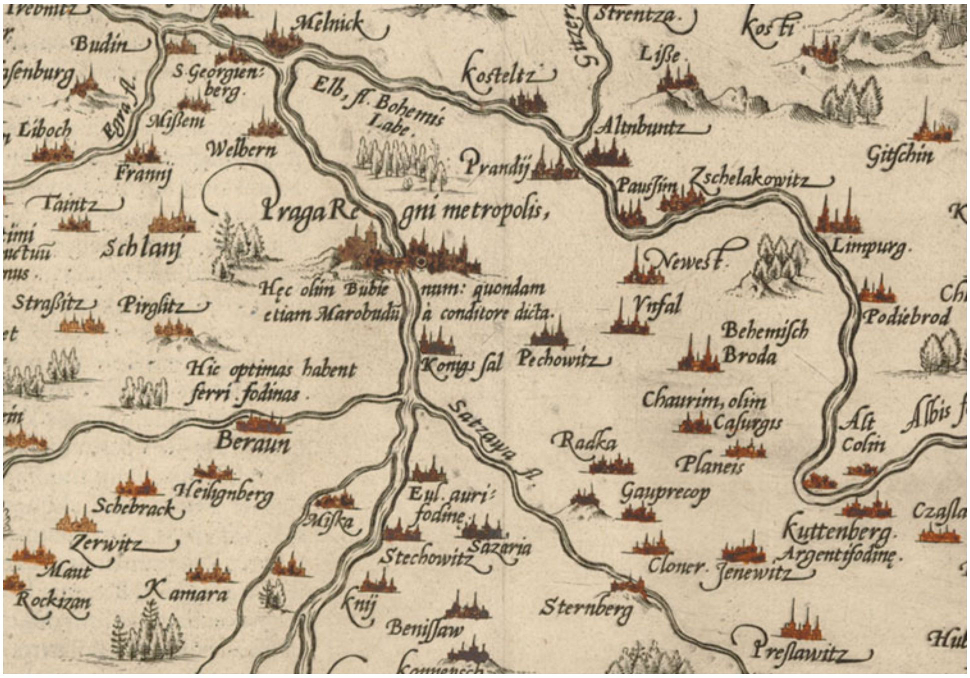

Fig. 5.3 Position of Prague (see locality “Praga regni metropolis”) as seen on the map “Regni Bohemiae descriptio”(Abraham Ortelius, Antwerp 1570). Remarkable is a lifelike sketch of the drainage patterns in the middle Bohemia. However, they are conspicuous errors in drawing the confluence areas of the Sázava, Vltava and Berounka Rivers in the S of Prague. This historical map is a part of many editions of the “Teatrum orbis terrarum” by Abraham Ortelius and it is based on the Johann Criginger´s map of Bohemia (1568). Dimensions of the sheet of map are 53 × 46 cm. (Reproduction of the original map from the archives of the Map Collection of the Charles University in Prague.)

followed during its final stage by horizontal sliding movements. In the Late Palaeozoic, some parts of the Central Bohemian Massif were deeply denuded and crystalline rocks from a depth of 15 km were exhumed exposing deep-seated granite massifs. The Prague region was dry land from the Late Permian to the Early Cretaceous and the Late Cretaceous transgression affected only the northern margin of this area. This period of tectonic stability saw the development of planation surfaces. The uplift of the Bohemian Massif at the end of the Santonian (some 65 million years ago) resulted from the ongoing Alpine and Carpathian orogenesis. These events marked the definitive retreat of the Late Cretaceous epicontinental sea which significantly receded leaving an erosional surface as a primary geomorphic surface for the region. The Bohemian Massif was also differentiated into a system of graben structures and tectono-volcanic zones.

At the beginning of the Tertiary, climate in the central part of the Bohemian Massif was humid and tropical, with a mean annual temperature of up to 26 °C and mean annual rainfall of 2 000–3 000 mm (Malkovský 1979). The occurrence of the pre-Oligocene planation surface is indicated by duricrust remnants in western and central Bohemia. In the Oligocene temperatures fell to 16 °C under savannah-type climate with dry winters, and a very dry climate prevailed also in the Middle Oligocene. The Late Oligocene was characterized by a permanently wet and warm climate, with subtropical rain forests remaining until the Middle Miocene (Malkovský 1975; Demek 2004). Up to the Palaeogene, streams ran through shallow, wide vale-shaped low gradient valleys. However, at the end of the Oligocene, planation processes in the Bohemian Massif were interrupted by tectonic movements (e.g. Malkovský 1979; Chlupáč et al. 2002), accompanied by volcanic activities in its western part 35–17 million years ago.

The highest and oldest planation surfaces of Palaeogene age are found westwards from Prague, at the present-day altitudes of 360–400 m, on Palaeozoic and Cretaceous rocks. They are slightly inclined to the north. According to the geomorphic position of Miocene river sediments, it was originally an early tertiary surface from which tropical regoliths were removed and the basal weathering surface was thus exposed during the Neogene. An example is the graded etchplain on Upper Cretaceous spongolites (argillites) at a locality west of Prague—at the Václav Havel Airport Prague.

Fig. 5.4 The location of Prague, dissected relief of its surroundings and a large incised meander of the Vltava River drawn by an anonymous artist as a part of *Ichnographia et orthographia metropolis Pragensis* (Reproduction of the cooper engraving (1740–1780) from the archives of the Map Collection of the Charles University in Prague)

During the Early Miocene, tropical humid climate with dry periods prevailed in the central part of the Bohemian Massif. This later changed to a subtropical wet climate in the Late Miocene. Periods of humid climate in the Neogene were characterised by very extensive erosion and denudation of the kaolinitic and lateritic weathering mantle, down to the basal weathering surface. The internal differentiation of this planation surface of Neogene age was dependent on rock resistance to weathering under tropical or subtropical climate. Moreover, the evolution of the relief of the Bohemian Massif was influenced by two stages of volcanic activities, in the Late Miocene between 9.0 and 6.4 Ma, and from the Late Pliocene to the Pleistocene, between 3.0 and 0.17 Ma ago (Ulrych et al. 2011). Morphostructural patterns of the Bohemian Massif, originating during the Miocene, determined the main elements of present-day river network.

The river valleys in the Central part of the Bohemian Massif (Fig. 5.3), and thus also their terrace flights, are the product of processes of hydrographical capturing of several Miocene individual catchments with different drainage directions. For example, Neogene sediments near Jesenice,

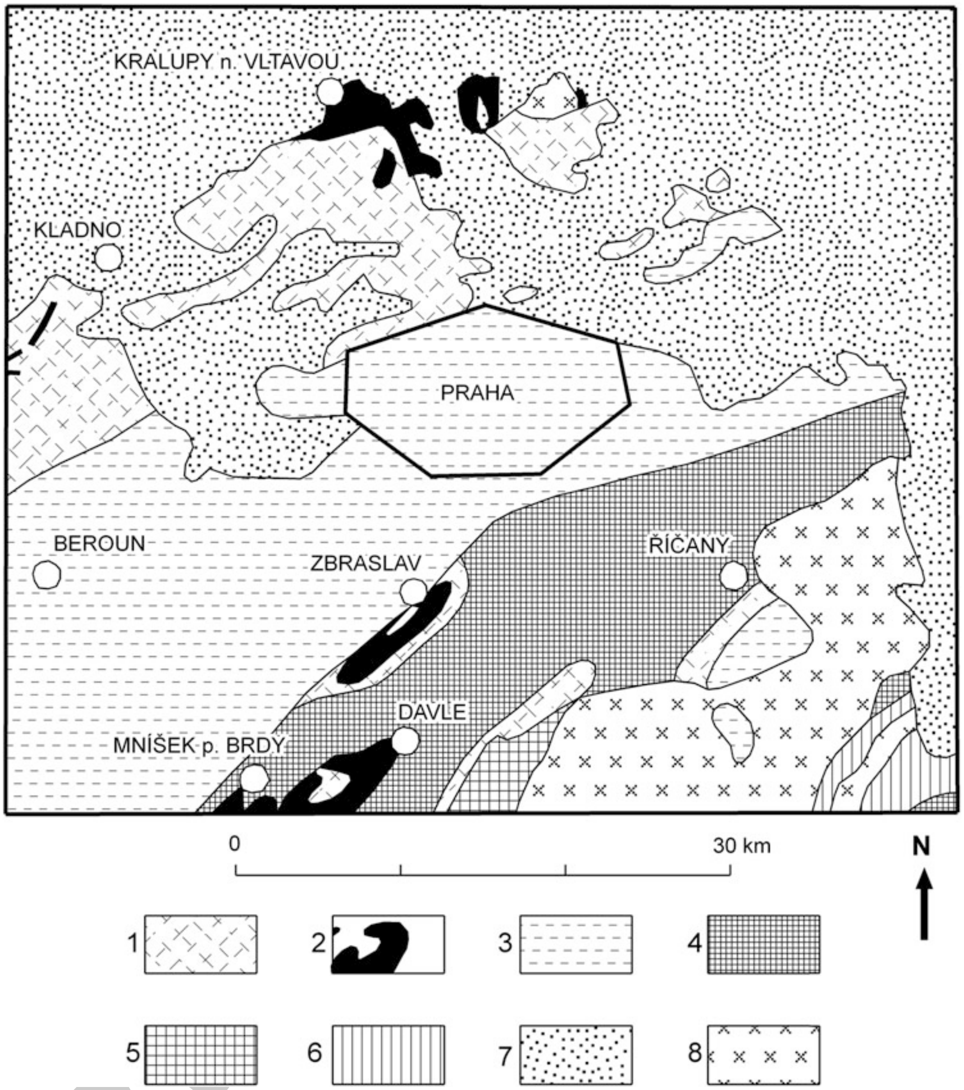

Fig. 5.5 Geological sketch of central Bohemia (Chlupáč et al. 2002). Explanations: *1* Proterozoic metamorphosed rocks of the Zbraslav and Kralupy units, *2* proterozoic volcanites, *3* cambrian to Devonian sediments and metamorphosed rocks of the Barrandian unit, *4* proterozoic rocks of the Štěchovice unit, *5* metamorphosed subsilicic rocks, *6* metamorphosed rocks of an uncertain age, *7* upper Carboniferous to Tertiary sediments, *8* variscan (Hercynian) granitic rocks

south of Prague, fill 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 Middle and Late Miocene, the substantial upper part of the Vltava catchment in the southern Bohemia was still drained towards the south (Tyráček 2001; Tyráček and Havlíček 2009). It is indicated by both relics of fluvial and lacustrine sediments and finds of river-transported moldavites (= specific rock types related to the meteorite impact) in the adjacent part of Austria. These tektites originated during the Ries Impact and are radiometrically dated at 14.3 million years.

The granular character of Pliocene river sediments is similar to those of Lower Pleistocene terrace deposits which indicate that the orographic situation of the central part of the Bohemian Massif was closely similar to one that occurs today (Balatka and Štěpančíková 2006; Kalvoda and Balatka 2006). The oldest and highest, mostly Early Pleistocene accumulation terraces survived only very sporadically and in small patches above the edges of the present-day valley incisions. Important changes in the fluvial network system occurred at that time with significant manifestations of epigenetic and antecedent evolution of river valleys through a rapid erosion.

5.3 River Terrace Evolution in the Prague Area During the Quaternary

The flight of fluvial deposits and related river terraces of the Sázava, Berounka, Vltava and Labe river valleys in the central part of the Bohemian Massif (Fig. 5.3) 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 and Kalvoda 2008, 2010) that the terrace system, widespread along the Vltava and other major rivers in the central part of the Bohemian Massif (Fig. 5.6), developed as a result of regional neotectonic uplift.

As a part of geomorphological research in the central part of the Bohemian Massif, the longitudinal profiles of fluvial terrace accumulations and Neogene sediment localities, the

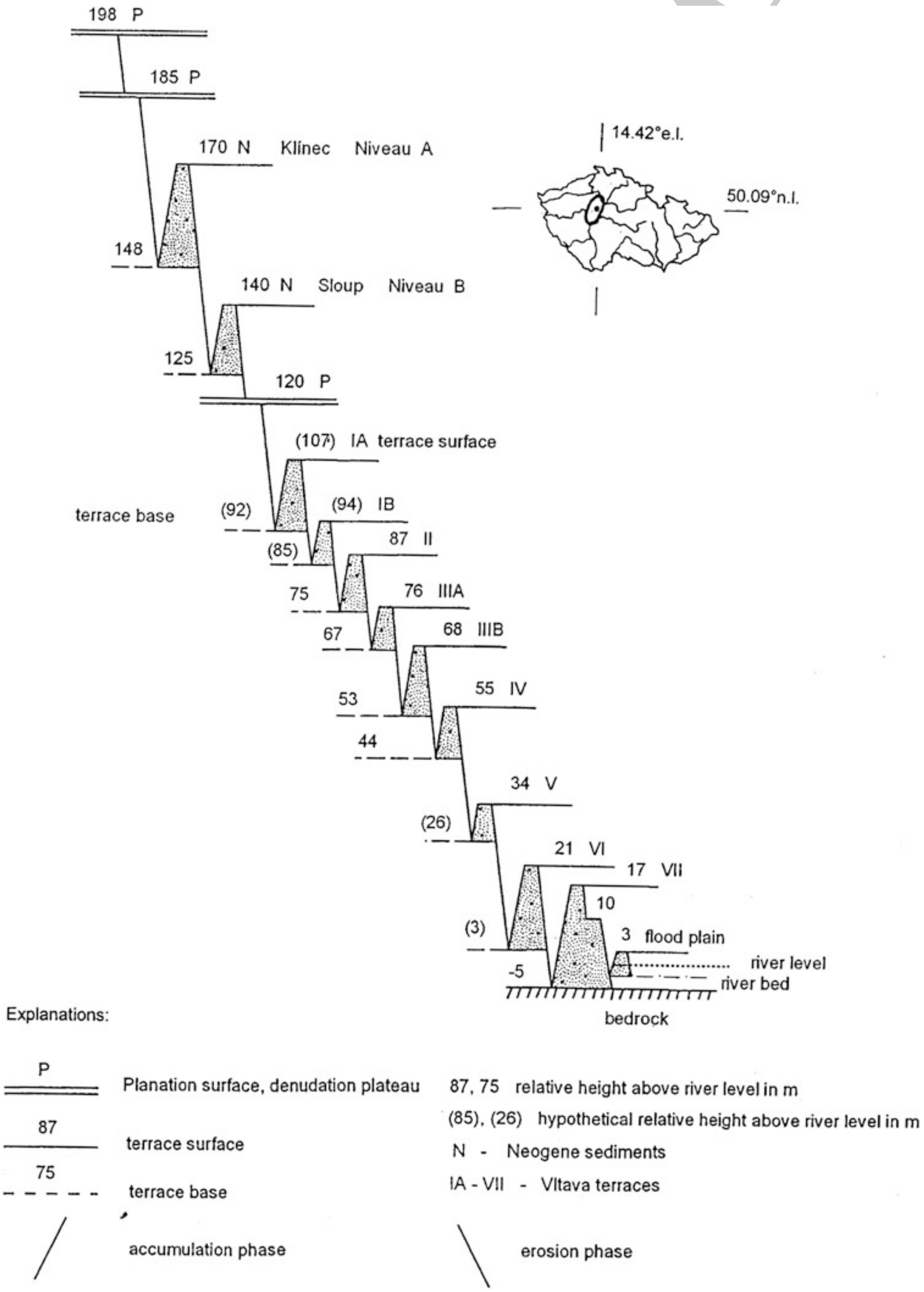

Fig. 5.6 Position of fluvial accumulation terraces in the Vltava valley between the mouths of the Sázava and Berounka Rivers south of Prague (Balatka and Štěpančíková 2006; Balatka and Kalvoda 2010). The chronostratigraphical correlation of accumulation terraces in the central part of the Bohemian Massif is demonstrated in Table 5.1

structure of valley cross-sections and the major occurrences of planation surfaces have been plotted (Balatka et al. 2010a, b; Balatka et al. in print). This method of interpreting the valley evolution builds strongly on the assumption that the palaeo-thalweg and the surfaces of each major terrace level maintained stable gradients that correspond to the contemporaneous longitudinal profiles. 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. 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/or climate changes influencing discharge regime and sediment supply. In the Vltava canyon-like valley (Fig. 5.7) and other major valleys of the Central part of the Bohemian Massif, increased water and sediment supply were associated with intensive cryogenic processes during the colder intervals in the Pleistocene. In these circumstances huge accumulation packages formed, altering the equilibrium profile to a new state over valley sub-reaches.

The sedimentary and morphological records of the 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 (Table 5.1).

Fig. 5.7 Very steep rocky slopes of the antecedent Vltava River valley near its confluence with the Berounka River, consisted of Palaeozoic calcareous sediments and metamorphosed rocks of the Barrandian unit, were modified by numerous anthropogenic changes as early as the nineteenth century. Historical drawing recorded the landscape of the southern periphery of Prague with an old railway and the St. John Church near the Chuchle area (Reproduction of the lithography (1887) from the archives of the Map Collection of the Charles University in Prague)

Table 5.1 Chronostratigraphical correlation of river terraces in the central part of the Bohemian Massif related to global stratigraphical scheme for the Quaternary (Balatka et al. 2010a, b)

Regional stratigraphical stage/substage divisions of the Quaternary (Gibbard and Cohen 2008, Gibbard et al. 2009)	SÁZAVA Balatka and Štěpančíková, (2006), Balatka (2007), Kalvoda (2007)	BEROUNKA Balatka and Loučková (1992)	VLTAVA—LABE confluence area Balatka and Sládek (1962)	VLTAVA in the Prague region Záruba et al. (1977)	VLTAVA and LABE system Tyráček (2001), Tyráček et al. (2004)
Late Pleistocene Weichselian	Pikovice Terrace (VII)	Lipence Terrace (VIIa)	Hostín Terrace (VIIa, b, c, d)	Maniny Terrace (VII)	Maniny Terrace (Weichselian)
		Dobřichovice Terrace (VIIb)			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)	Cítov Terrace (Va, Vb)	Dejvice Terrace (V)	Dejvice 1 and 2 Terrace (Drenthe)
		Poučník Terrace (Vb)			
Middle Pleistocene Saalian (Fuhne)	Týnec Terrace (IV)	Zbraslav Terrace (IVa)	Hněvice Hill Terrace (IV)	Letná Terrace (IV)	Letná Terrace (Fuhne)
		Hýskov Terrace (IVb)			
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)	Ledčice Terrace (II)	Pankrác Terrace (II)	Pankrác Terrace (Cromerian C)
		Hlince Terrace (IIb)			
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 Stadium (Pliocene)	Zdiby Terrace (Eburonian—Menapian)
Early Pleistocene Tiglian					Stříbrníky Terrace (upper Tiglian)
Neogene	Niveau A Bojiště	Niveau A		Klínec Stadium	

The oldest terrace accumulations in the Prague area are situated above the margins of the canyon-like valleys of Vltava, Berounka and Sázava rivers (e.g. Záruba-Pfeffermann 1941, 1942; Záruba et al. 1977; Kovanda et al. 2001; Tyráček et al. 2004, 2009; Balatka and Kalvoda 2008). Relics of Miocene gravels and sands at the Sulava lokality, near Radotín town have their surface lowered by erosion at 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. Other relics of sediments of Miocene and Pliocene age are 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 which are up to 40 m thick, between Kobylisy and Sedlec on the Zdibská plošina Plateau, is situated at 300–325 m a.s.l., i.e. 125–150 m above the Vltava level, and 35–60 m below the Ládví hill (359 m a.s.l.). Northwards from these Pliocene spreads on the Zdibská plošina Plateau are up to 20 m thick sediments 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 5.1). In the Early Pleistocene, the Vltava and its tributaries were still freely meandering in shallow and wide valleys (Fig. 5.4) formed on Neogene planation surfaces.

Even as late as the beginning of the Middle Pleistocene, the basal boundary of which is the Matuyama/Brunhes palaeomagnetic transition dated at 780 ka, new terrace steps in the valleys of the central part of the Bohemian Massif were progressively formed (70–100 m above the present water courses) together with a relatively rapid epigenetic and antecedent deepening of the river network. For example, the Suchdol Terrace (Fig. 5.8) in the Prague area 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 as an equivalent of the Vinohrady Terrace in Prague (Table 5.1). 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

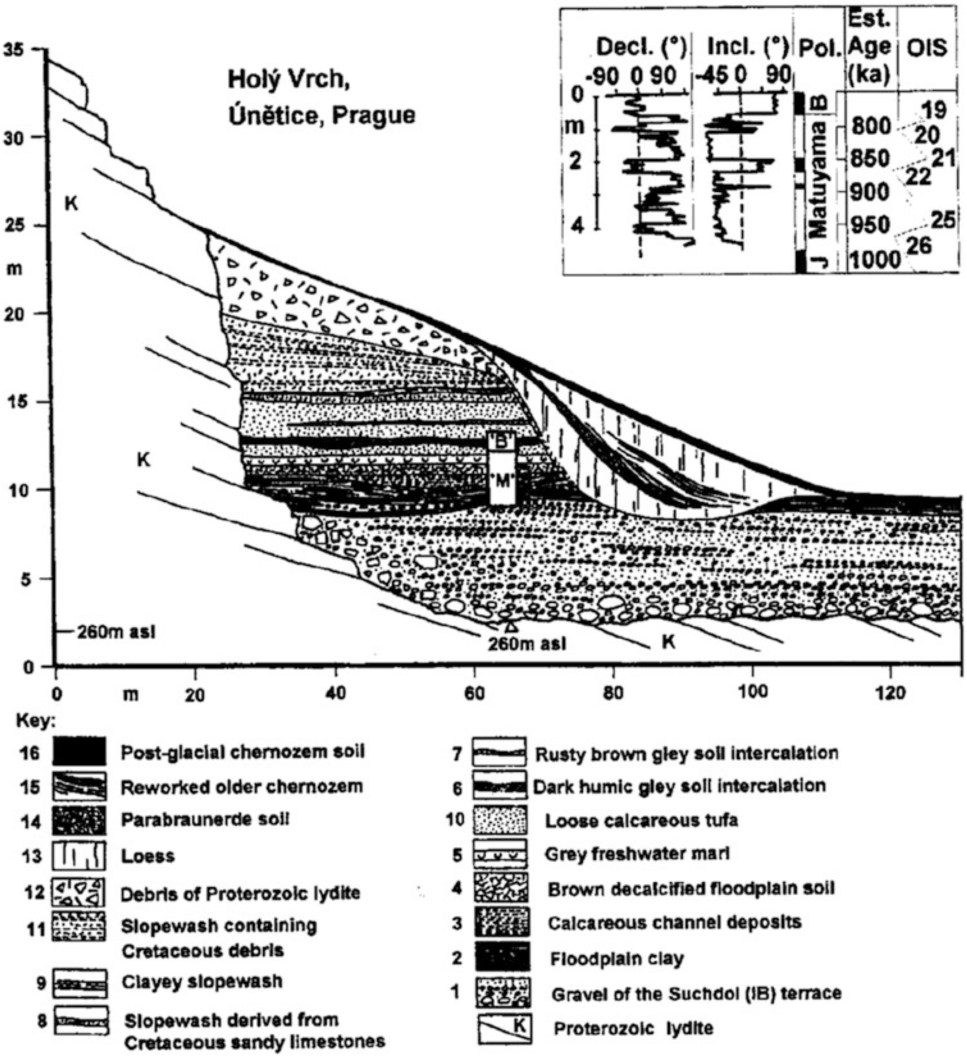

Fig. 5.8 Cross-section through the Suchdol Terrace of the Vltava River of the Middle Pleistocene age (Záruba et al. 1977; Tyráček et al. 2004). Oblong cut (B/M) in the middle part of the cross-section indicates a possible magnetostratigraphical boundary of Matuyama and Brunhes chrons

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 remnants of thermophilous mammals, interglacial molluscs and Paleolithic archaeological material.

After the end of the sediment accumulation of the IIIrd terrace in the Middle Pleistocene, the valley bends and meanders have been abandoned in several places, and a series of lower terraces developed as accumulation bodies in alluvial reaches of the valleys during a significant stage of long-term erosional valley deepening. River-bed dislocations and deep erosion (Figs. 5.7 and 5.9) were caused by the change in the local erosional base during highly variable erosional-denudational and accumulation processes. Changes in the intensity of these morphogenetic processes were related to neotectonic movements and non-uniform resistance of bedrock as well as to changes of climatic conditions in the late Cenozoic.

The values of the antecedent deepening of the Vltava River in the Prague area (stimulated by tectonic uplift), based on the position of remnants of river accumulation terraces (Fig. 5.6), are to be estimated with caution. Uncertainties include the possibility that terrace surfaces may have been irregularly lowered by erosion, and variability in the range and episodic rhythm of tectonic uplift. However, the results of the estimation provide data about the dynamics of fluvial bedrock erosion and transportation of weathered material in the region of Central Bohemia during the late Cenozoic (Kalvoda and Balatka 2006; Kalvoda 2007) and are as follows: (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^{-1}, (d) a part of the Late Pleistocene (40–20 ka): 2–4 cm ka^{-1}. During the Holocene are mostly recycling of gravels and sands occurred and new slope accumulations in the valley bottom originated. Besides of the system of river accumulation terraces, wind-blown sands, loess loams and loess (Fig. 5.8) also provide valuable sedimentary evidence

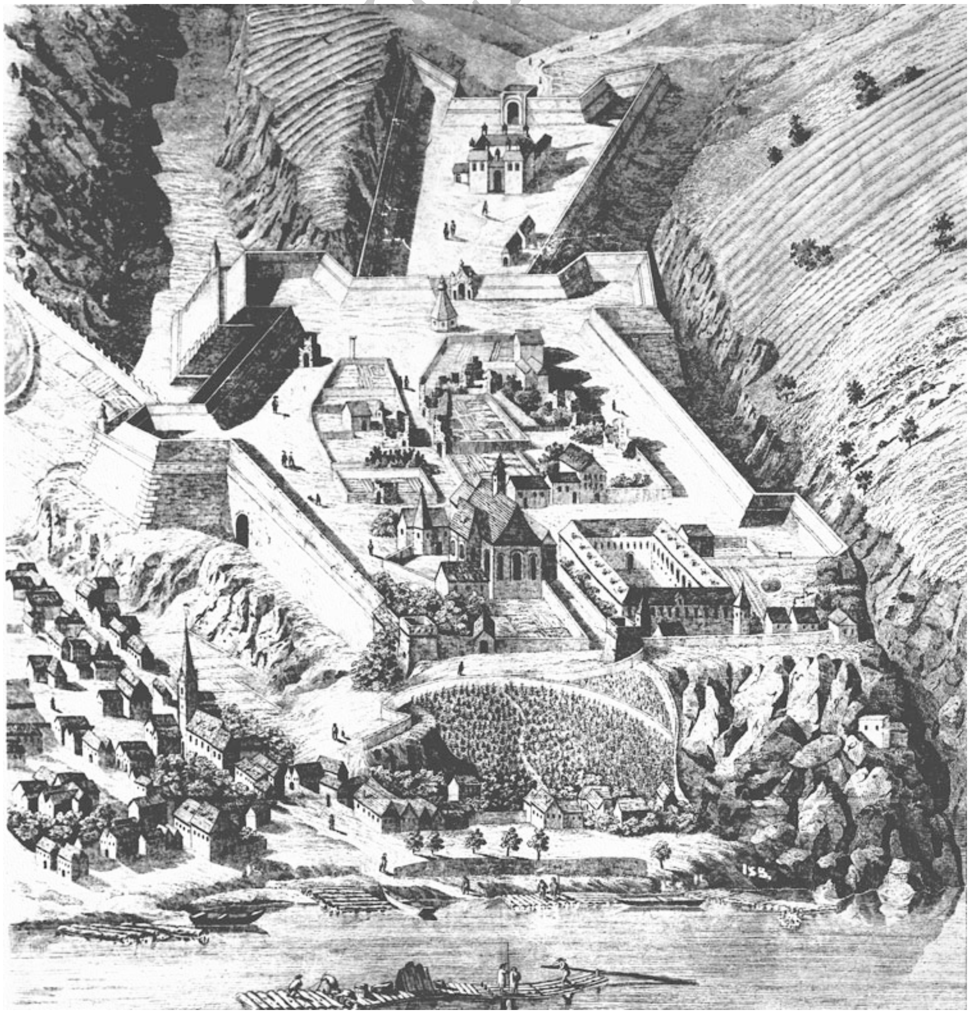

Fig. 5.9 The Vyšehrad Castle was built on a large rocky platform and slopes (build by sandstones, slates and metamorphic rocks of the Palaeozoic age) between two deeply incised erosion valleys of small right-side tributaries of the Vltava River. The painting records the Vyšehrad Castle with a new fortification (completed in the year 1668) as one of historical stages during permanent anthropogenic changes of relief in the Prague area (Reproduction of the lithography (1890–1910) archives of the Map Collection of the Charles University in Prague.)

of Quaternary landscape evolution (e.g. Šibrava 1972; Záruba et al. 1977; Tyráček 2001; Balatka et al. 2010a, b). These deposits are maintained in a significant thickness in depressions or on lower plateaux around Prague.

Geomorphological analysis of late Cenozoic fluvial sediments preserved in the Central part of the Bohemian Massif confirm that seven main terrace accumulations in total, with several secondary levels, can be differentiated (Table 5.1). The relative height of the oldest fluvial terraces above the present-day bottom of river valleys in the Prague area exceeds 100 m (Fig. 5.6) which indicates the approximate depth of Quaternary erosion. An estimation of the values of the antecedent deepening of the Vltava in the late Cenozoic, based on the position of remnants of river accumulation terraces, suggests that the rate of downward erosion of the Vltava reached its maximum in the younger part of the Middle Pleistocene.

5.4 Geomorphic and Environmental Hazards

The dynamics of fluvial processes in the Prague area was deeply influenced by weathering, denudation and mass movements during the late Quaternary (Figs. 5.10 and 5.11). Apparently, main patterns and/or relics of pre-historic favourable natural and life conditions have been sustained in present-day Prague. For example, in the Prague area the mean year temperatures 8–11 °C with mild winters and precipitations between 400–800 mm, including relatively dry summer, are typical. Remarkable geo- and biodiversity, many kilometres of streams as well as patches of fertile soils on plateaux around the city still exist. However, the city and its surroundings are exposed to permanent serious threats from a variety of geomorphic and environmental hazards (compare Figs. 5.7, 5.11 and 5.12). Steep slopes built of hard Palaeozoic rocks (e.g. lydite, quartzite and limestone) in

Fig. 5.10 The Hradčany Castle is surrounded by dissected relief with ancient as well recent features of rapid erosion and variable slope movements including landslides. Extraordinary graphical work from the first-half of the nineteenth century presents the eastern area of the Hradčany Castle, including the Deer Ditch valley and rocky walls consisted of sandstones and greywacke of the Palaeozoic age (Reproduction of the cooper engraving (1831) from the archives of the Map Collection of the Charles University in Prague)

deeply incised valleys of subsequent streams to the Vltava river emphasize picturesque landscape of the Prague area. At the same time, its dissected relief (e.g. Figs 5.9 and 5.10) is characteristic by different types of active slope processes, especially soil erosion and numerous mass movements, including rockfalls and very fast moving landslides.

The oldest reliable record of flooding in Prague is concerned with the disastrous flood in the year 1118 and more than 150 floods are mentioned in historical sources. Since the fifteenth century are some of them denoted by flood marks (e.g. near the Charles bridge) or recorded by flooding of buildings in the Old Town area of Prague. Main causes of the Vltava floods are extreme rainfall events a rapid thawing of snow in extensive watershed of the river. Before constructions of stone embankments and cascade of dams upstream was the area of Prague along the river also afflicted by floods with ice-jam effects. Substantial hazards are influences of extreme rainfall events to changes of groundwater flow systems, activity of landslides and flash-flood erosion and deposition. Actual research topics after two extreme events of 1997 and 2002 (Fig. 5.12) in the Czech Republic are concerned with quantifying feedbacks between climate variability and anthropogenic activities at various spacio-temporal scales. The challenge related to river management is the consideration of man-made floodplain modifications influencing the cross-section area and the hydraulic roughness significantly.

Prague is a city of great architectural and historic importance, but its ancient site and geomorphic position in deeply incised valleys and within dissected relief pose considerable problems in terms of environmental hazards and building foundation conditions. Many ancient buildings had been erected before ground conditions of valley side slopes and Quaternary deposits were understood (compare Figs. 5.10 and 5.12). Much of the valuable heritage of Prague is under threat, not only from changes of engineering-geological conditions (Píchal et al. 1979; Cílek 1995), but also from the present-day air pollution. There are many urban sources of particulates including traffic, combustion of fossil fuels and natural dust. Especially fine-grained particles pose health hazards and they contribute to soiling and damage to building, bridges, statues

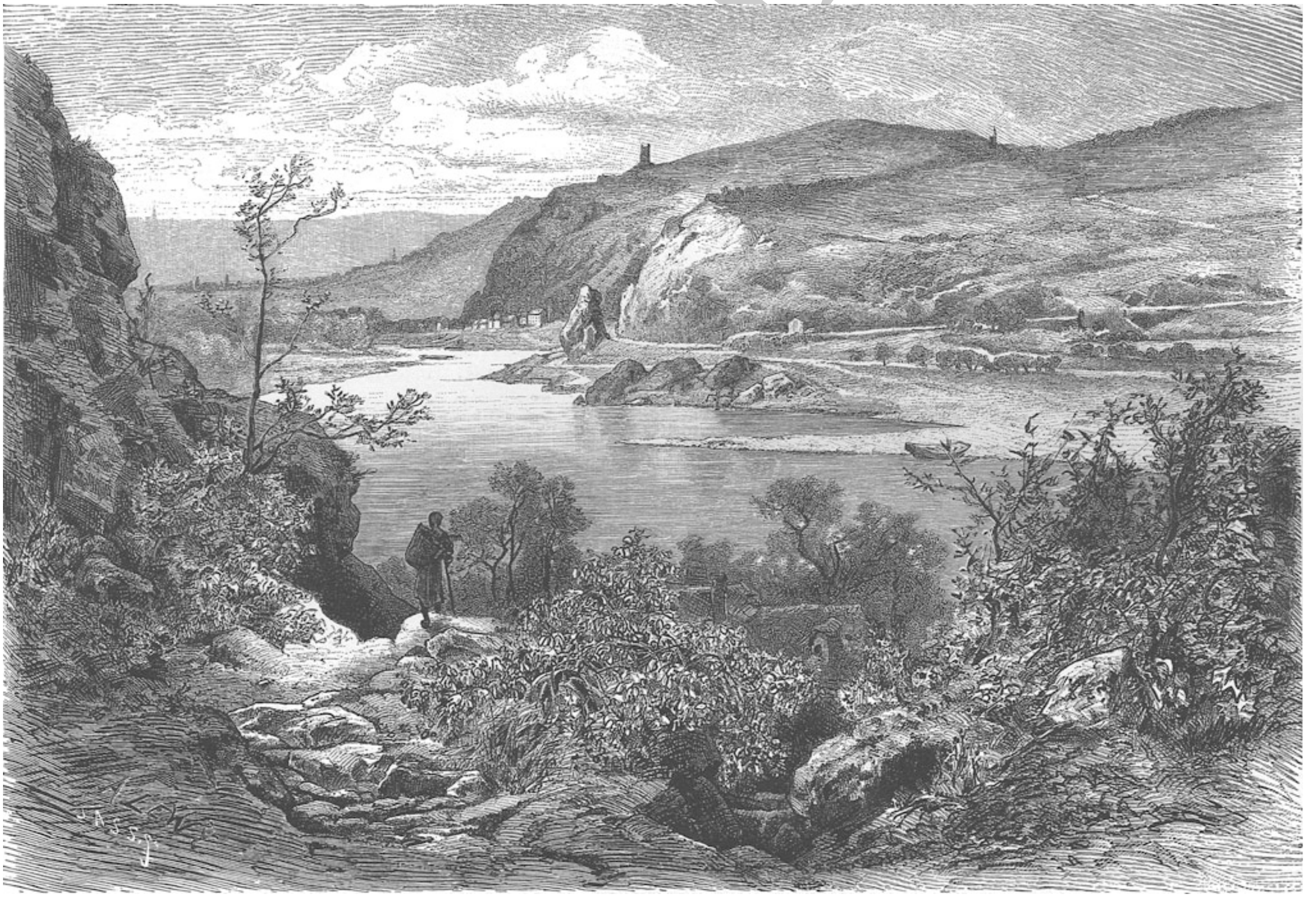

Fig. 5.11 Conspicuous canyon-like valley of the Vltava River at the northern periphery of Prague developed by rapid incision and lateral fluvial erosion of Upper Proterozoic rocks during the Quaternary. (Reproduction of the lithography (by A. Levý 1887) from the archives of the Map Collection of the Charles University in Prague.)

Fig. 5.12 Disastrous confirmation of an extent of floodplains in the Vltava valley passed in Prague during catastrophic summer floods in the year 2002. Aerial photography (14. 8. 2002, Raudenský and Dorazil 2002) displayed flooded areas around the National Theatre (down in the right) and a large part of the Lesser Town

and sculptures (Březinová et al. 1996). Profound changes in the urban development of Prague and a widespread industrial and agricultural activity throughout Central Europe have extremely severe impacts on historic and residential quarters of this beautiful city. Substantial reduction of risky co-existence of manifold environmental hazards in the Prague area is a topical challenge to heritage conservation endeavours supported by new applications of natural sciences.

5.5 Conclusion

Present-day landform patterns of the Prague area are determined by a long-term antecedent deepening of canyon-like valleys of the Vltava River and its tributaries to large planation surfaces of the central part of the Bohemian Massif during the Quaternary. The coupled occurrence of episodic tectonic uplift and variable climato-morphogenetic processes has led to the origin of stratigraphically significant river accumulation terraces as well as erosion and denudation slopes with weathered mantle of deposits. This extraordinary geodiversity and biodiversity of the landscape is, however, also associated with geomorphic hazards stimulated by human processes over the entire history of occupation of the Prague area, including devastating floods. During its centuries of history, the "golden and hundred-spire" Prague has become an architectural pearl of European and global significance. To effectively mitigate severe impact of modern urban development and related human activities on the architectural heritage of the city is the topical environmental issue in the Prague area. AQ1

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