# Morphostructural evolution of the Labe and Jizera rivers confluence area (the Bohemian Massif, Czechia)

Tereza Steklá*, Jan Kalvoda

Department of Physical Geography and Geoecology, Faculty of Science, Charles University, Czechia
* Corresponding author: tereza.stekla@natur.cuni.cz

**ABSTRACT**

This article investigates the morphostructural evolution of the Labe and Jizera rivers confluence area in the Bohemian Massif of Czechia. The main stages of morphostructural evolution are identified and related landform patterns are described. The lithological and tectonic character of this contact area between the Barrandian and the Bohemian Cretaceous Basin has been gradually evolving since the Early Palaeozoic. Tectonic subsidence of the northeastern part of the Bohemian Massif and the Cretaceous transgression of the sea caused extensive marine sedimentation, which covered the pre-Cenomanian relief. The uplift of the Bohemian Massif during the Santonian initiated a widespread erosion and denudation in the Tertiary. The Labe River valley constitutes a remarkable boundary between the morphostructural plateaus in the south and the system of river accumulation terraces of the Labe and Jizera in the north. The originally extensive and currently considerably eroded III. river terrace of the Labe was formed in the Elsterian glacial period (Cromerian complex c). The conspicuous Jizera alluvial fan developed during the aggradation phase of the VII. river terrace in the Upper Pleistocene. Subsidence along the NW-SE-trending Labe Fault zone, deciphered from the vertical throw of the VII. terrace rock bases of Labe as well as related paleochannels of its local tributaries, which caused the current asymmetry of the Labe valley, reached up to 14 meters prior to the Holocene. The different rock resistance to weathering, arrangement of fault structures and neotectonic movements that took place even during the late Quaternary significantly influenced the intensity of varied climate-morphogenetic processes.

**KEYWORDS**

morphostructural evolution; landform changes; Labe (Elbe) and Jizera rivers confluence; Mělnická kotlina Basin; Českobrodská tabule Table

Received: 2 January 2024
Accepted: 10 April 2024

Steklá, T., Kalvoda, J. (2024): Morphostructural evolution of the Labe and Jizera rivers confluence area (the Bohemian Massif, Czechia). AUC Geographica 59(1), 35–59
https://doi.org/10.14712/23361980.2024.3

# 1. Introduction

## 1.1 Topics and objectives

The study area is situated in the Central Bohemia (Czechia) and it is represented by the confluence of the Labe (Elbe) and Jizera rivers. It is in a territory of natural and archaeological importance on the contact area between the south-eastern edge of the Bohemian Cretaceous Basin and the north-eastern Barrandian region. The main aim of the present paper is to decipher morphostructural evolution of the area. The landforms are studied as part of the relic record of the palaeogeographic evolution of the natural environment. This geomorphological topic about one of the historically unique areas in the Czech part of the Labe basin was chosen because of an extraordinary informative value of its landforms of different development and age. The analytical data on the geomorphological development in the Labe and Jizera confluence area is continuously interpreted in the context of the knowledge about the central part of the Bohemian Massif and the main stages of the development of its river network during the late Cenozoic.

According to the geomorphological classification of the Bohemian Massif (Balatka and Kalvoda 2006), the Labe and Jizera confluence area belongs to the morphostructural unit of the Středolabská tabule Table within the sub-province of the Česká tabule Table and the area of the Středočeská tabule Table. This

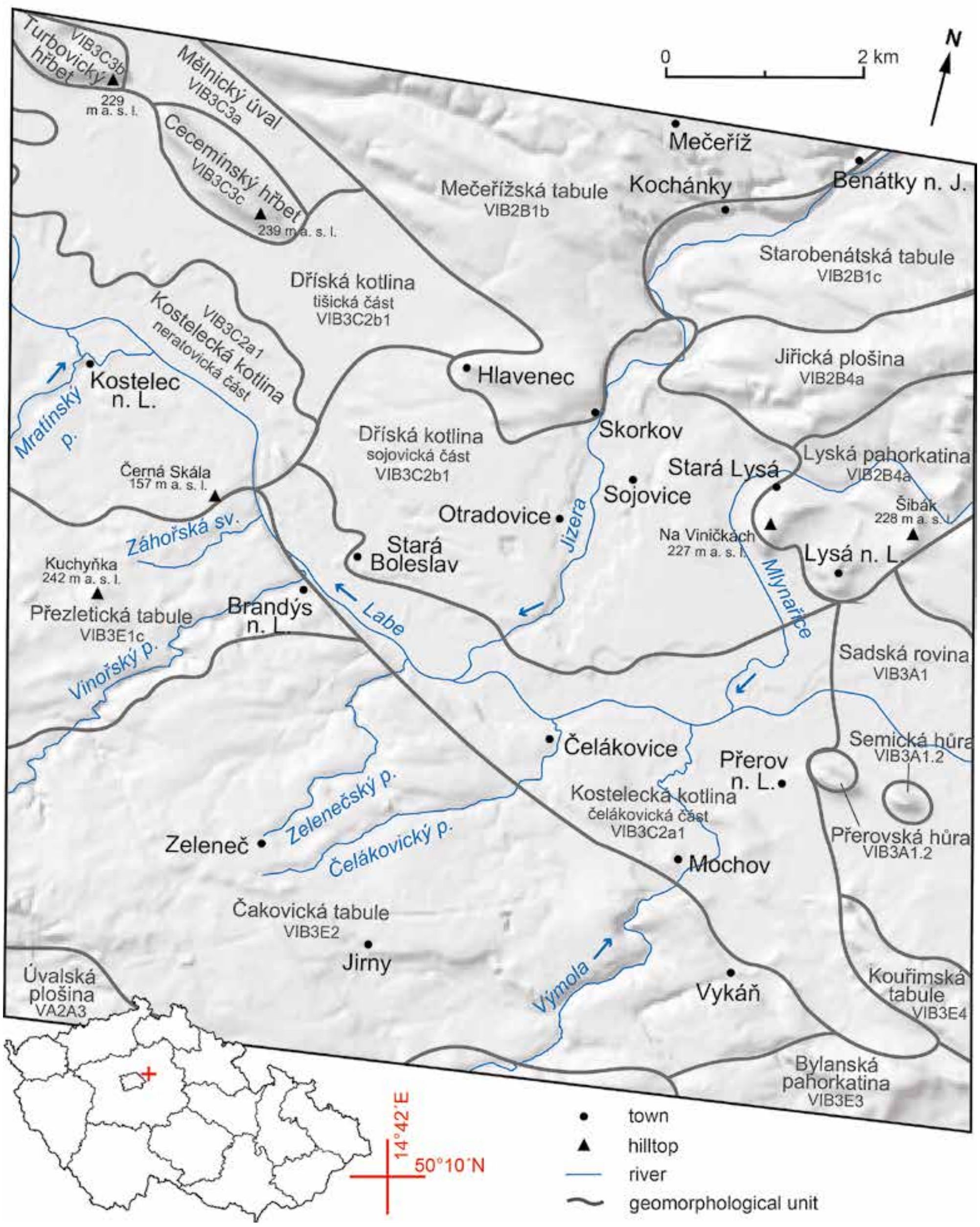

Fig. 1 Geomorphological units in the Labe and Jizera confluence area (169 m a.s.l.; 50°10′21″ N, 14°42′ 56″ E), situated at the morphostructural contact of the Českobrodská tabule Table and Mělnická kotlina Basin (Source: Balatka and Kalvoda 2006; DEM by Czech Office for Surveying, Mapping and Cadastre 2019).

geomorphic division conforms with morphostructures of the 2nd and 3rd order in the Bohemian Massif according to Demek et al. (2009). It concerns block morphostructures on the basement with upland and hilly land as well as complex systems of basin-and-range relief of the Central Bohemia Terrane.

The flat to flat-hilly character of the Středolabská tabule Table is divided by tectonic zones, which determined the formation of the morphologically different subunits of the Mělnická kotlina Basin and Českobrodská tabule Table (Fig. 1). The morphostructural boundary between these subunits runs across the studied area in the SE–NW direction and mostly follows the fault system of the Labe Fault zone (Fig. 2). Differential tectonic movements during the younger Cenozoic also determined other orographic features of the Středolabská tabule Table (Tyráček et al. 2004; Coubal 2010; Grygar 2016). In the neotectonically conditioned depression of the Staroboleslavská kotlina Basin, a flat erosion-accumulation relief was formed, which is bounded in the north both tectonically (Cecemínský and Turbovický Ridges) and in terms of erosion and denudation (Dolnojizerská tabule Table). The flat relief of the Českobrodská tabule Table passes into the hilly terrain at the Kojetický hřbet Ridge and the Bylanská pahorkatina Hilly land (Fig. 1). The higher elevation differences of the relief here were caused by neotectonic movements and varying bedrock resistance to erosion and denudation.

The morphostructural features of the contact area between the Barrandian and the Bohemian Cretaceous Basin have been gradually evolving since the Austrian phase of the Alpine orogeny. During this period of tectonic activity, the subsidence of the northeastern part of the Bohemian Massif accompanied by the Cenomanian and Santonian Sea transgression took place, causing sedimentary processes in the Bohemian Cretaceous Basin (Chlupáč et al. 2002). This ended a palaeo-climatically variable period of erosion and denudation of the pre-Cenomanian planation surface. Triassic terrigenous deposits of the Bohemian Massif are of a kaolinic type, produced by the intensive weathering of exhumed rocks in a humid tropical climate, which took place up until the Lower Cretaceous.

The varied relief in the Labe and Jizera confluence area is a result of the specific geological structure of the southwestern part of the Bohemian Cretaceous

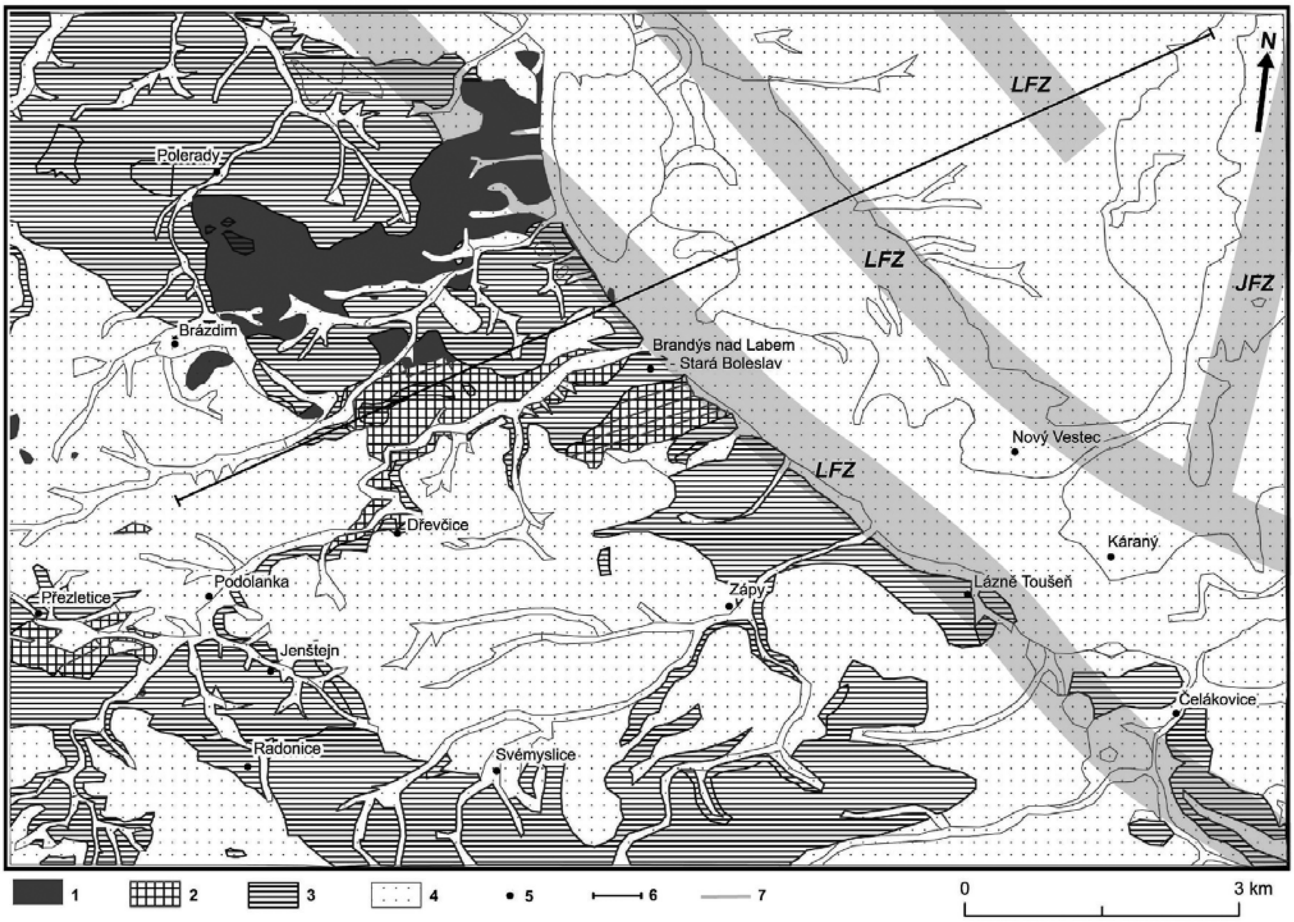

**Fig. 2** Scheme of the geological structure in the contact area between the north-eastern zone of the Barrandian and the south-eastern margin of the Bohemian Cretaceous Basin. Key: 1 – Proterozoic (mainly wacke, siltstones and phyllitic schists), 2 – Ordovician (conglomerates, sandstones, clay and sand shales, quartzites), 3 – Cretaceous (quartzose and calcareous sandstones, varied relics of marine and freshwater sediments), 4 – Quaternary (fluvial, slope and aeolian deposits), 5 – town, 6 – geological cross-profile (Fig. 9), 7 – fault zone, LFZ – Labe fault zone, JFZ – Jizera fault zone. Source: Czech Geological Survey: Map applications, version 1B.2, 2019; Uličný et al. 2009; Coubal 2010.

**Fig. 3** Boulder conglomerates of the littoral breaker facie of the Korycany layers at the Kuchyňka elevation (242 m a.s.l.), which was created by marine abrasion during the Upper Cenomanian, are unique evidence of the activity of palaeo-morphogenetic processes in the region of the Labe and Jizera confluence. Source: Žítt et al. 1998.

Basin (Fig. 2). In the exhumed part of the basin, Cretaceous and Tertiary platform sediments cover Proterozoic and Palaeozoic rocks of the northeastern zone of the Barrandian complex (Volšan et al. 1990; Holásek et al. 2005). The oldest relics of morphogenetic processes originated in the Upper Cenomanian, when some of the Barrandian Proterozoic outcrops protruded above sea level in the form of cliffs or were affected by abrasion as shallowly submerged elevations (Žítt and Nekovařík 2001). These relics of palaeo-morphogenetic processes were identified mainly on the rock exposures west of Brandýs nad Labem (Fig. 3).

In this paper, we deal with the morphostructural evolution of the Labe and Jizera rivers confluence area. It is based on complex interpretation of our own field data and particulars collected from earlier valuable works. A variety of natural processes during the palaeogeographic history of the contact area between the Barrandian and the Bohemian Cretaceous Basin allowed for an assessment of the main stages of the morphostructural landform evolution (Chapter 2) and an identification of their recent patterns in the Labe and Jizera confluence area (Chapter 3). Furthermore, significant periods of geomorphological changes during the Quaternary (Chapter 4) were verified and/or identified in this area and the main types and intensity of recent morphogenetic processes and phenomena were determined.

## 1.2 Research methods

The current knowledge of the palaeogeographic development of the central part of the Bohemian Massif is based on remarkable tradition of more than hundred years of natural science research in this area. The systematic evaluation, correlation, and integration of the results of these works are the methodological and knowledge base of recently completed or ongoing research. Extensive and inspiring sets of field and laboratory data, map series and documentary holdings enable both the preparation of comprehensive monographs (e.g., Kovanda et al. 2001; Chlupáč et al. 2002) and the formulation and solution of specific and current research problems in selected localities. Examples include works on Quaternary geological and geomorphological topics (Záruba et al. 1977; Tyráček et al. 2004; Tyráček 2010; Balatka et al. 2015).

The geomorphology of the middle Labe and lower Jizera valleys has been studied by many authors. Most of the works focused on the description and development of morphological formations (Drahota 1931; Balatka 1966; Novotná 1998; Růžičková and Zeman 1994; Mikisková 2009) and/or on climatically and morphogenetically significant periods in the Quaternary (e.g., Balatka 1960; Balatka and Sládek 1965; Hrubeš 1999; Boháčová et al. 2000). Detailed geomorphological research in the Labe and Jizera confluence area is also motivated by recent studies on the evolution of the valley and river accumulation terrace system in the central part of the Bohemian Massif (Balatka and Kalvoda 2008; Balatka et al. 2015), including the Sázava River basin (Balatka and Kalvoda 2010; Balatka et al. 2010).

The methodological procedure of geomorphological research in the Labe and Jizera confluence area is based on a comprehensive approach to the topic under scrutiny, systematic processing, and interpretation of field work results. The basis of this research was field reconnaissance based on the evaluation of available data from geological, geophysical, and geographical publications and map documents. In the studied area, the following sub-thematic areas were gradually addressed: 1) field documentation of morphostructural and climate-morphogenetic landform assemblages and their development, including recent morphogenetic processes; 2) interpretation of geological data and results of geomorphological analysis focused on the morphostructural relief evolution; 3) identification of significant changes in intensity and integration of neotectonic and climate-morphogenetic processes during the Quaternary. Based on existing and newly discovered data, the present paper describes the characteristic features of structural landforms and identifies the main stages of morphostructural evolution of the Labe and Jizera confluence area during the Cenozoic.

The research of river accumulation terraces in the Labe and Jizera confluence area was based on the evaluation of an extensive set of older research works that focused on the river terrace systems of the middle Labe, lower Jizera and their tributaries. The obtained data on fluvial sediments, together with the 1 : 50,000 scale geological map (Czech Geological Survey 2019), were used mainly in the field survey of the studied area to verify the existence and update the delimitation of the extent of the river accumulation terraces. In addition to the localisation of the individual fluvial terraces, the relative heights of their surface and base and the opinions of the individual authors on the stratigraphic classification of the respective fluvial accumulations were monitored.

In the next stage of the work, the studied river terraces were categorised based on the relative height of their base and/or surface. The surface and base elevations of fluvial accumulations were derived from ZABAGED data (2014), as well as from maps of Quaternary base isolines (Herrmann and Burda Eds. 2016) and from borehole data from the GDO database (2020). The Labe and Jizera river terrace dataset organised in this manner was compared with the river accumulation terraces of the Vltava River, according to the works of Záruba et al. (1977), Tyráček et al. (2004) and Tyráček and Havlíček (2009). The INQUA stratigraphic classification of the Quaternary was used as the current temporal parameter (see, e.g., Gibbard and Cohen 2008; Gibbard et al. 2009).

## 2. Geological evolution and origin of morphostructural landforms in the study area

### 2.1 Palaeogeographic history from the Precambrian to the end of the Mesozoic

The oldest rocks of the Středolabská tabule Table and the surrounding areas were formed in the Upper Proterozoic, when the terrestrial weathered rocks were deposited in the marine basin. Proterozoic sediments were consolidated during the Cadomian orogeny (Havlíček 1963; Havlíček et al. 1987; Volšan et al. 1990; Holásek et al. 2005), during which the Barrandian rock complex was formed. The intensity of metamorphosis of Proterozoic rocks varies, but weakly regionally metamorphosed sediments predominate. These rocks of the Kralupy-Zbraslav Group, represented mainly by wacke, siltstones and phyllitic schists, form together with Ordovician sediments the north-eastern Barrandian zone (Fig. 2).

During the Cadomian orogeny at the end of the Upper Proterozoic and the beginning of the Cambrian, the Neratovice body of basic volcanic rocks, which has a volcano-sedimentary character caused by repeated intrusions along tectonically predisposed zones, was formed (Fediuk et al. 1966; Šmejkal and Melková 1969; Volšan et al. 1990). The rocks of the Kralupy-Zbraslav Group are strongly affected by kaolinic weathering up to a depth of several tens of metres (Havlíček et al. 1987) and were therefore exposed to exogenous agents for a long time. In younger geological periods, silicic sediments with higher resistance to weathering rose above the surrounding palaeo-relief or above sea level in the form of cliffs (Loyda 1950). Conversely, sedimentary rocks with a predominance of siltstones and slates formed the lower parts of the pre-Cenomanian relief due their faster weathering and denudation.

The oldest crystalline rocks of the central part of the Bohemian Massif were developed by a long-term sedimentation of material that was transported from the mantle rock of the Precambrian dry land to an epicontinental sea. These marine sediments were repeatedly and to various extents metamorphosed during the Precambrian and the Early Palaeozoic. The complex of sedimentary rocks in the wider area of the present-day Labe and Jizera confluence area has no rocks from the Cambrian period. According to Holásek et al. (2005), this area was outside the sedimentary zone during the Cambrian, or the Cambrian sediments may have been rapidly eroded. The Ordovician sediments of the Barrandian were then discordantly deposited on the tectonically disturbed Cadomian bedrock, of which five formations have been preserved: the Třenice (Tremadocian; conglomerates, sandstones), the Klabava (Arenig; clay shales), the Šárka (Llanvirn; sandy shales), the Dobrotivá (Dobrotiv; clay shales, rock quartzites) and the Beroun (Havlíček et al. 1987; Vaněk 1999). These Ordovician rock formations were formed in shallow marine basins and plateaus, and the character of each formation shows considerable changes in palaeo-relief and sedimentary conditions.

The sediments of the Třenice and Klabava Formations are composed of local material that was transported from the close vicinity of the sedimentary basin by abrasion, occasional flows, mudflows, or slides. The Třenice Formation was created by sedimentation in a shallow sea that was flanked by mountain ranges. The Klabava Formation was created in an environment of isolated marine basins and bays, in the vicinity of which there were already deeply eroded relics of mountain ridges. The sedimentation of the Šárka Formation material took place mainly in lagoons, with its source area likely being more distant parts of the landmass (Havlíček et al. 1987; Vaněk 1999). The Šárka sandy shale formations are rich in siliceous concretions with bio-stratigraphically significant fossil fauna (Röhlich 1952), which confirms their Llarvinian age. The Dobrotivá Formation was formed by sedimentation of weathered rocks in a shallow basin environment with extensive plateaus and deltas (Kukal 1963). According to Holásek et al. (2005), the sedimentation of the north-eastern Barrandian Formation is likely to have continued until the Middle Devonian.

In the Upper Devonian and Lower Carboniferous, the Proterozoic and Early Palaeozoic sediments of the Barrandian area were strongly influenced by Variscan (Hercynian) orogeny. The tectonic disintegration of the Proterozoic rock mass is evidenced by the numerous occurrences of fissures, fractures, fault zones and crushing of some silicate layers (Kovanda et al. 2001; Chlupáč et al. 2002). The Early Palaeozoic rocks were consolidated, folded, and permeated by faults and reverse faults during the Variscan orogeny. For example, in the quarry to the west of Popovice, the so-called Závist-type fault was exposed, according to which the Upper Proterozoic rocks were pushed onto the younger Třenice Formation. No Závist-type reverse faults developed to the east of Prague, but smaller and younger reverse faults caused by similar tangential pressures were formed there. Havlíček (1963) places the origin of the Závist-type fault in the pre-Westphalian phase of the Variscan folding, and Knížek (2013) specifies the period of its origin to the Tournaisian-Visean boundary in the Lower Carboniferous. Another tectonic reverse fault was discovered by a borehole at the dam of the Hrušovský Pond (Kukal 1963), where the Šárka Formation is covered by younger strata of Dobrotivá shales and Skalec quartzites. The Klabava and Šárka Formations were also disrupted by transverse faults in the NW–SE direction (Havlíček et al. 1987; Holásek et al. 2005).

During the Upper Carboniferous, the north-eastern Barrandian area was probably part of the margin of limnic basins (Holásek et al. 2005). To the NW of the studied Labe and Jizera confluence area, between

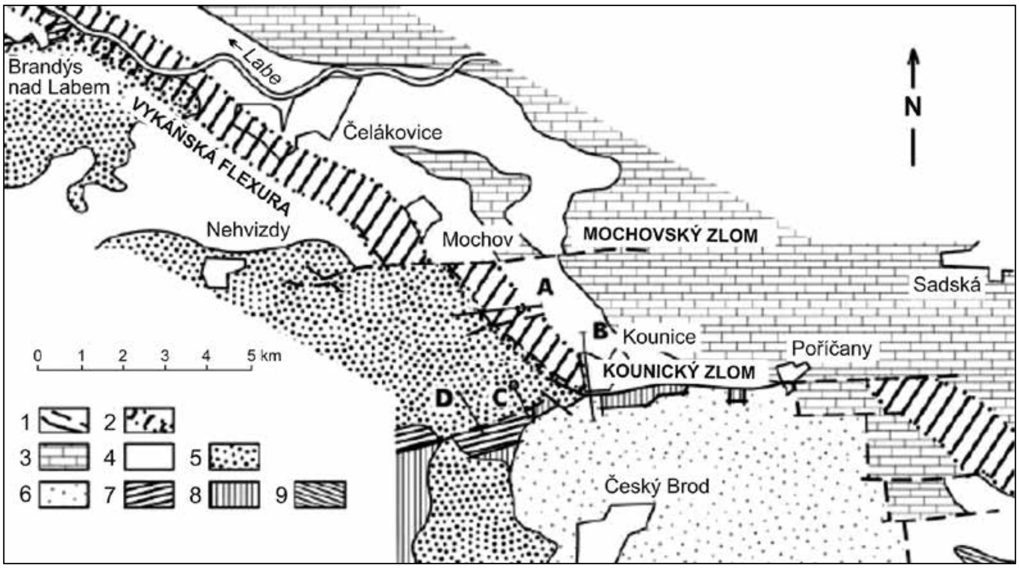

**Fig. 4** Scheme of the geological structure of the Vykáň flexure in the southern part of the Bohemian Cretaceous Basin. Key: 1 – fault: identified, expected, 2 – flexural folding, 3 – Jizera formation (Upper Cretaceous), 4 – Bílá hora formation, 5 – Peruc-Korycany formation, 6 – Černý Kostelec formation (Permian), 7 – the Ordovician rocks of the Prague Basin, 8 – Štěchovice group (Upper Proterozoic), 9 – Kutná Hora crystalline complex, A – geological section of the Vykáň flexure (Fig. 5), B – geological section of the Kounice fault (Fig. 6), C, D – geological sections of the western part of the Kounice fault (Fig. 7). Source: Coubal 2010.

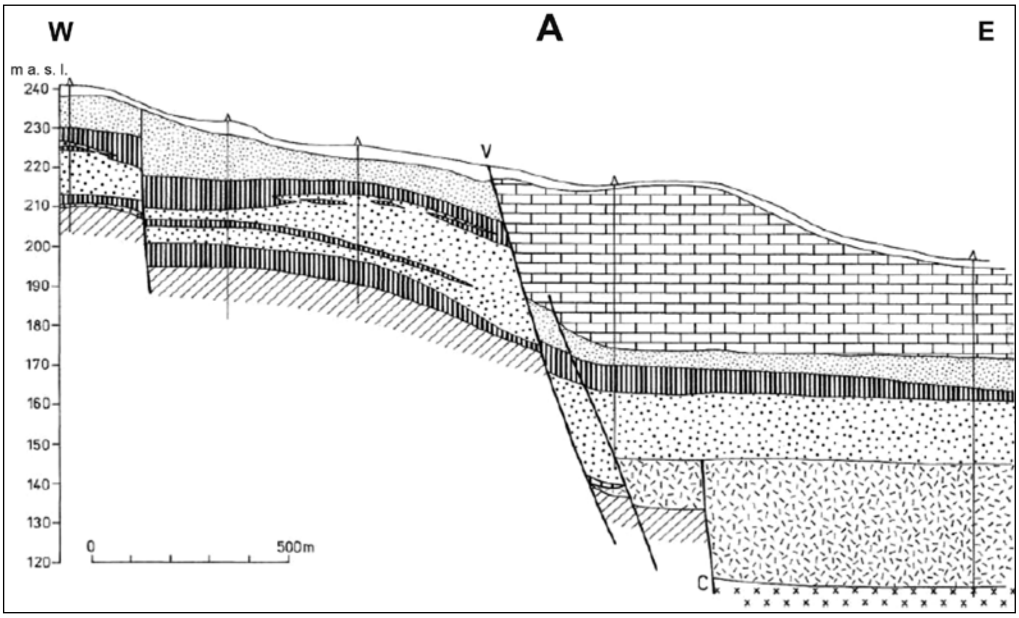

**Fig. 5** Geological section of the Vykáň flexure. The location of section A is presented in Fig. 4 and the key is in Fig. 6. Source: Coubal 2010.

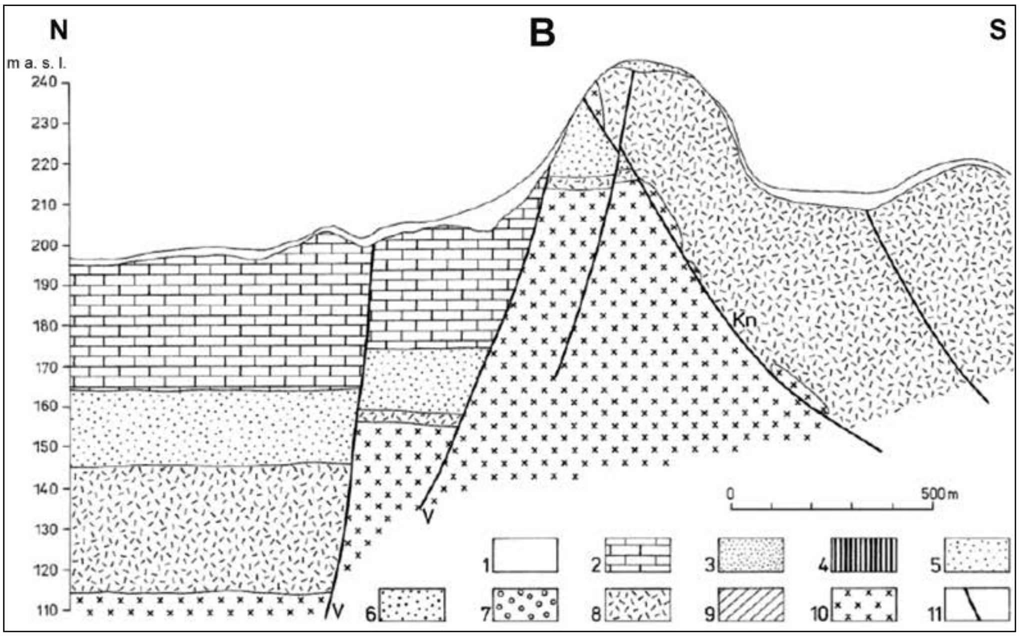

Fig. 6 Geological section of the Kounice fault. The location of section B is presented in Fig. 4. Key: 1 – Quaternary sediments, 2 – Jizera and Bílá hora formation (Upper Cretaceous), 3 – Korycany formation (fine-grained sandstone), 4 – clay parting of the Peruc formation, 5 – fine/medium-grained sandstone of the Peruc formation, 6 – coarse-grained sandstone of the Peruc formation, 7 – conglomerate parting of the Peruc formation, 8 – Černý Kostelec formation (Permian), 9 – the Ordovician rocks of the Prague Basin, 10 – Štěchovice group (Upper Proterozoic), 11 – fault, V – longitudinal fault of the Vykáň flexure, Kn – Kounice fault, C – Černice fault (see Fig. 5). The location of section B is presented in Fig. 4. Source: Coubal 2010.

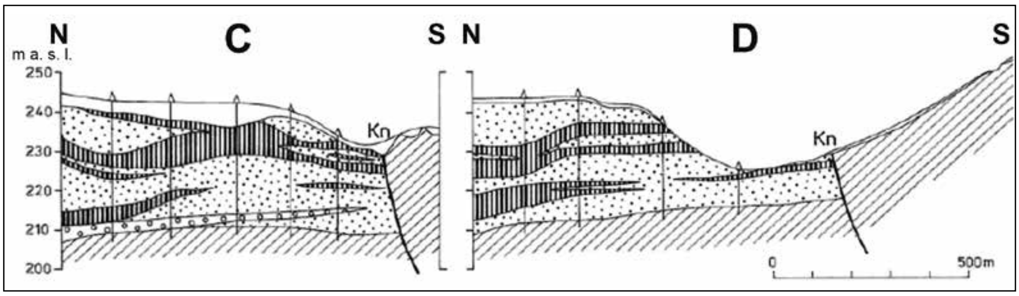

Fig. 7 Geological sections C and D, in the western part of the Kounice fault. The locations of these sections are presented in Fig. 4 and the key is in Fig. 6. Source: Coubal 2010.

Tišice and Dřísy, the southern margin of the Roudnice and Mšeno Carboniferous basins is located. There, in the substratum of Cretaceous sediments, a borehole survey has also revealed the Radnice (silty and coaly claystones, sandstones, conglomerates) and Nýřany layers (arkosic sandstones, siltstones, claystones) of the Kladno Formation (Zelenka et al. 2006). On the other hand, to the southeast of the studied area, in the vicinity of Český Brod, Permo-Carboniferous sediments of the Blanická brázda Furrow have been preserved (Fig. 4). In the Labe and Jizera confluence area, Permo-Carboniferous sediments were found in only one borehole, west of Lysá nad Labem at a depth of 117 m. Their absence in a major part of the studied area is probably caused by erosion during the Lower Cretaceous.

The denudation and erosion of the north-eastern Barrandian zone also continued in the Permian and Lower Cretaceous (Holásek et al. 2005), and this area was part of the Variscan consolidated core of the Bohemian Massif. This is how the pre-Cenomanian planation surface was created in a semiarid and very warm climate, which cuts through both Proterozoic and Palaeozoic rocks (Svoboda 1998). Extensive marine transgressions in the Triassic formed the Hercynian platform into a peninsula and later into an island of the so-called Vindelician Ridge, whose northern part was central Bohemia.

The Jurassic Sea in the Bohemian Massif was a relatively narrow and shallow strait connecting the German and Carpathian Seas. In the Lower Cretaceous, intense rock weathering took place in a humid tropical climate, forming a powerful mantle of tropical weathered rocks. The part of the Bohemian Massif that emerged above the "Cretaceous" sea was still a compact block of Hercynian origin, on the surface of which a peneplain with a thick mantle of regoliths was largely developed (Demek 2004). This morphostructurally relatively uniform surface, flattened by erosion-denudation processes, had a height of up to approximately 200 m above the then sea level.

The north-eastern part of the Bohemian Massif subsided during the Austrian phase of Alpine orogeny. For this reason, marine sedimentation took place there from the Cenomanian to the Santonian, during which mainly the deposits of the Bohemian Cretaceous Basin were formed. The source areas of mainly clastic Cretaceous sediments were the landmasses of the Central Bohemian and Sudeten Islands (see, e.g., Engel and Kalvoda 2002). The marine Cretaceous sediments cover the Permo-Carboniferous sedimentary formation, which is underlain by the crystalline rocks of the Bohemian Massif, including granitoids. The shallow sea advanced from the Turonian to the Middle Coniacian quite far south of the Prague area (Kovanda et al. 2001; Chlupáč et al. 2002). This transgression of the sea into the central part of the Bohemian Massif, during which for the first time since the Precambrian exhumed crystalline rocks were submerged and the post-Hercynian planation surface on top of them caused by denudation, was terminated by secular epiplatform uplift during the Santonian, 85.5–83 million years ago.

The ruggedness of the relief of the pre-Cenomanian planation surface significantly influenced the extent and nature of marine sedimentation in the Upper Cretaceous (Fig. 2). This extensive marine sedimentation was caused by the subsidence of part of the Bohemian Massif along the Labe Fault zone (i.e., in the NW–SE direction) and by the subsequent eustatic rise of the ocean surface (Uličný 1997). The essential morphostructural landforms of the palaeo-relief of the studied area included mainly two morphostructural elevations of the NW–SE direction. This is the Kojetice elevation, which forms the eastern foreland of the extensive Unhošťsko-Turský hřbet Ridge (Matějka 1936), and the parallel elevation between Prague and Brandýs nad Labem (Žítt et al. 1998). This ridge extended into the area of the present-day Labe and Jizera confluence area from the outskirts of Prague through Kuchyňka and Černá skála to the Labe in the Veleň – Přezletice – Záryby – Brandýs nad Labem zone. In the early stages of Cretaceous sedimentation, the flat ridges rose above sea level (Svoboda 1996) and their complete submergence occurred only during the Upper Cenomanian and Lower Turonian sedimentation stages. In places, abrasion facies were also preserved, showing the position of the then marine coastline (Havlíček et al. 1987; Volšan et al. 1990). In contrast, the areas with Ordovician rocks were in lower areas compared to Proterozoic rocks and thus were part of the marine sedimentary area already for the oldest Peruc layers.

The transition from a continental to marine sedimentary environment during the Upper Cenomanian is evidenced in the Středočeská tabule Table by the character of the sediments of the Peruc Formation, which is made up of fluvial, lacustrine, deltaic, and lagoonal type accumulations. The low thickness of the Peruc layers and their heteropic juxtaposition with younger Korycany layers suggest the Upper Cenomanian age of their sedimentation. However, an older age of the Peruc layers, namely the Lower Cenomanian–Albian layers, cannot be ruled out (Havlíček et al. 1987; Holásek et al. 2005; Volšan et al. 1990). The lower Peruc layers were probably deposited in the fluvial environment of freely meandering and/or braided streams. According to Volšan et al. (1990), the valley of this paleoflow was formed on poorly consolidated Carboniferous sediments. Findings of marine microplankton in the upper clay layers of the Peruc Formation demonstrate that their deposition occurred in the environment of coastal lagoons and estuaries occasionally connected to the sea (Kříž et al. 1984). For example, west of Třeboradice, both lagoonal sediments of the upper clay layer and marine sediments were simultaneously deposited next to each other. According to Svoboda (2004), their synchronous deposition is a consequence of the influence of epeirogenetic movements on the formation of sedimentary basins.

The younger Korycany layers (quartzose sandstones, calcareous sandstones) were already being deposited at the bottom of the shallow Upper Cenomanian Sea. Their age is confirmed by local finds of rich fauna in the highest altitudes of this layer (e.g., Černá skála quarry; Enc 1984). The Upper Cenomanian sediments are absent only in the highest altitudes of the Unhošťsko–Turský hřbet Ridge and the elevation zone Veleň – Přezletice – Záryby – Brandýs nad Labem, which were not flooded during this marine transgression. In the sand pit near Přezletice, it was documented (Havlíček et al. 1987; Volšan et al. 1990) that the Korycany layers were deposited between two bands of Ordovician quartzites, which probably formed islands during the sedimentation of coarse clastics.

The relics of abrasion (surf) facies, which were found on the Proterozoic elevations in the belt between Čakovice and Brázdim (Břízová et al. 2005; Havlíček et al. 1987), also come from the Upper Cenomanian period. The best-preserved remnants of abrasion facies are on Kuchyňka Hill (242 m a.s.l.) east of the village of Brázdim (Fig. 3). The well-sorted and rounded bioclasts, spastic matrix and coarse terrigenous clastics indicate that these sediments were deposited in an environment with a relatively high transport rate. These Upper Cenomanian sediments were probably deposited in the upper part of the sublittoral zone (Havlíček et al. 1987; Volšan et al. 1990), and Žítt et al. (1998) identified at least three sedimentation cycles at the Kuchyňka site. Two of these cycles took place in the Upper Cenomanian and one only in the Lower Turonian. Traces of abrasion deposits have also been found in the studied area at other elevations formed by Proterozoic silicates, e.g., at Černá skála and Kojetice quarry (Žítt and Nekvasilová 1991).

After an interrupted sedimentation at the beginning of the Turonian, there was a transgression and deepening of the seabed, during which the highest flat ridges were flooded and then the sediments of the Bílá Hora Formation were deposited under open sea conditions (Holásek et al. 2005). The deposition of the Jizera Formation took place in similar marine conditions. In terms of lithofacies, the Cretaceous sediments in the studied area belong to the Prague region (Havlíček et al. 1987; Volšan et al. 1990). Towards the north, the area of the Bílá Hora and Jizera Formations increases substantially, which indicates a deepening of the sedimentary basin after the marine transgression in the Lower Turonian.

Shallow sedimentary basins were formed on crystalline bedrock also in southern Bohemia, and the nature of their Cretaceous sediments shows that they were transported from the surrounding areas together with the products of tropical weathering. The relics of Cenomanian freshwater sediments in the Bohemian Massif are mainly represented by kaolinic sandstones whose material comes from the denuded surface of rising Cretaceous basins with abundant vegetation and newly emerging regolith. The post-Hercynian peneplain was thus covered by kaolin and lateritic regoliths and currently lies beneath the Upper Cretaceous sediments of the Bohemian Cretaceous Basin. The tectonic uplift of the central part of the Bohemian Massif at the end of the Santonian was then caused by the ongoing Alpine and Carpathian orogeny and manifested itself by the complete subsidence of the Upper Cretaceous epicontinental sea.

## 2.2 The dynamics of Cenozoic evolution of morphostructural landforms

At the end of the Cretaceous period, during the onset of Alpine orogeny, inversion of the Bohemian Cretaceous Basin took place, so the studied area became dry land during the Tertiary. The extent and thickness of the Cretaceous sediments were significantly higher in the beginning of the Tertiary than they are today. These sediments were substantially reduced by the long-term Tertiary erosion and denudation and only the oldest formations have been preserved. The significant denudation of the Cretaceous sediments is also confirmed by the exhumed neovolcanics of Eocene and Lower Miocene age (Holásek et al. 2005). These diatremes, veins and lava plugs of volcanic funnels and principal vents, penetrated the Cretaceous sediments of the Coniacian and Turonian age, but they did not reach the surface of the Tertiary palaeo-relief at the time of their origin. The nearest neovolcanic outcrop to the present-day Labe and Jizera confluence is situated northeast of Neratovice on the Záboří Hill (228 m a.s.l.). It is made of olivine nephelinite, which encloses fragments of Cretaceous sediments. A chart

Tab. 1 A chart of the morphostructural evolution of the Barrandian and Bohemian Cretaceous Table contact area from the Neo-Proterozoic to the Quaternary.

| Geological periods | Principal morphostructural and climate-morphogenetic processes and phenomena |
|---|---|
| **Quaternary:** | Evolution of river systems of accumulation terraces (see Tab. 2). |
| | Differencial tectonic uplift and movements along fault zones. |
| **Neogene:** | |
| Pliocene | Evolution of the oldest relics of fluvial sediments of rivers in Central Bohemia (Klínec stage). |
| | Vault uplifts of the Labe and Sázava watershed regions. |
| Middle Miocene | Rivers from the present-day Polabí region headed eastwards through the Chlum Gate to the East Bohemian Gulf of the Miocene Sea. |
| | Mega-syncline fold of the Labská pánev Basin. |
| | Formation of the Neogene post-volcanic planation surface and exhumation of neovolcanites. |
| | Reduction of sedimentary formations by long-term erosion and denudation. |
| Lower Miocene | |
| Aquitanian – Burdigalian | Tectonic disintegration of the Palaeogene planation surface caused by differential movements of new and revived fault structures (NW-SE, WNW-ESE) during the Saxonian phase of Alpine orogeny. |
| End of Oligocene and Lower Miocene | Planation processes were interrupted by tectonic movements.<br>The intrusion of plutons of the rifting stage of volcanism into Barrandian, Permo-Carboniferous and Cretaceous rocks.<br>Formation of olivine nephelinite elevations. |
| **Palaeogene:** | Palaeo-flows in Central Bohemia form shallow and wide valleys with a low gradient. |
| | Development of the Palaeogene planation surface with a cover of lateritic and kaolinic weathering products of rocks (formation of duricrusts). |
| | Laramide phase of Alpine orogeny:<br>– Uplift and tectonic dissection of the Bohemian Massif<br>– Formation of graben structures and tectono-volcanic zones |
| | Gradual exhumation and reduction of rock complexes of Cretaceous age by long-term erosion and denudation. |

| | |
|---|---|
| **Mesozoic:**<br>Upper Cretaceous<br>Santonian | Marine sedimentation was terminated by secular epiplatform uplift of the Czech part of the Bohemian Massif during the ongoing Alpine and Carpathian orogeny. |
| Coniacean | Advance of the shallow sea to the south of the Prague area and submergence of the post-Hercynian planation surface. |
| Turonian | Sedimentation in the open sea conditions (Bílá Hora Formation).<br>Flooding of the highest elevations of the pre-Cenomanian relief (Jizera Formation).<br>Transgression and deepening of the seabed.<br>Interruption of sedimentation during the sub-Hercynian stage of Alpine orogeny (stratigraphical hiatus). |
| Cenomanian | Sedimentation in the shallow sea (Korycany layers).<br>The highest parts of the pre-Cenomanian relief rise above the sea level in the form of coastal or island cliffs (relics of the abrasion facies).<br>Epeirogenetic movements influenced the development of sedimentary basins with lagoonal and marine sediments.<br>Transition from continental to marine sedimentary environments with gradual deposition of fluvial, lacustrine, deltaic, and lagoonal-type sediments (Peruc layers). |
| Lower Cretaceous | The Austrian phase of the Alpine orogeny:<br>– Subsidence of the north-eastern part of the Bohemian Massif along the Labe Fault zone (NW–SE).<br>– Eustatic uplift of the ocean level.<br>Continued erosion and denudation of the consolidated crust of the Bohemian Massif created a pre-Cenomanian planation surface that cuts the rocks of the Barrandian complex and underlies the Cretaceous sediments of the basin. |
| Jurassic<br>Triassic | Origin of a shallow strait of the Jurassic Sea in the northern and north-eastern part of the Bohemian Massif.<br>Long-term effects of erosion and denudation (stratigraphic hiatus).<br>Central Bohemia is part of the Hercynian platform, a peninsula/island of the so-called Vindelician Ridge. |
| **Palaeozoic:**<br>Permian | Formation of the post-Hercynian planation surface in the Bohemian Massif.<br>Sedimentation of a predominantly limnic filling in the Blanická brázda Furrow.<br>Asturian phase of Hercynian (Variscan) orogeny:<br>– Tectonic subsidence in the Labe Fault zone with a NW-SE direction of morpholineaments |
| Carboniferous | – Formation of the Blanická brázda Furrow and morpholineaments with a NNE-SSW direction.<br>Extensive denudation of the Hercynian (Variscan) mountains of the Bohemian Massif.<br>Formation of sediments in the Roudnická and Mšenská pánve Basins, the Kladno Formation, mainly in the limnic environment.<br>Hercynian (Variscan) orogeny in the Bohemian Massif:<br>– Formation of a chain of mountains with a height of several thousand meters and deep intrusion of granitoids of the Central Bohemian Suture<br>– Tectonic disruption of the Barrandian complex associated with the formation of faults and reverse faults.<br>Marine sedimentation and basic submarine volcanism.<br>Evolution of the Barrandian Formation in the Prague area.<br>Sedimentation of weathered rocks in a shallow marine basin environment with extensive plateaus and deltas (Dobrotivá Formation).<br>Sedimentation of material from more distant parts of the land in the environment of lagoons (Šárka Formation). |
| Devonian | |
| Silurian | |
| Upper Ordovician<br>Keradoc | |
| Middle Ordovician<br>Llarvinian | |
| Lower and Middle Ordovician<br>Arenig | Sedimentation of local material into the environment of isolated marine basins and bays fringed by eroded mountain ridge relics (Klabava Formation). |
| Lower Ordovician<br>Tremadoc | Sedimentation of local material transported by abrasion, occasional flows, mudflows or slides into a shallow sea fringed by mountain ranges (Třenice Formation). |
| Cambrian | The studied area is outside the sedimentation zone. Extensive erosion and transport of deposited material (stratigraphic hiatus).<br>Cadomian orogeny in the Bohemian Massif:<br>– Consolidation of the Barrandian complex<br>– Repeated lava intrusions along predisposed zones (formation of the Neratovice body).<br>Sedimentation of the weathering material mantle into the epicontinental sea (Kralupy-Zbraslav group of sediments). |
| **Neo-Proterozoic:**<br>Ediacaran | |

of the morphostructural evolution of the Barrandian and Bohemian Cretaceous Table contact area from the Neo-Proterozoic to the end of the Neogene is presented in Tab. 1.

In the studied area of the Labe catchment, during the Saxonian phase of Alpine orogeny, the development of new faults took place along with reactivation of fault systems with a predominant NW–SE to WNW–ESE direction (Volšan et al. 1990). Along most of the faults, there was subsidence of blocks located closer to the axis of the Cretaceous basin. The main fault zone, with a NW–SE direction, runs along the current watercourse of the Labe. It continues in a south-eastward direction as a remarkable fault system of the Vykáň flexure, whose down-faulted blocks subsided by up to 30 m with an east-northeast flank fold of 3–5° (Figs. 4 and 5). The height of the vertical displacement on this fault zone decreases towards the WNW (Vohanka 1966), so neotectonic movements of only a few meters have been detected NW of Neratovice. Along this main fault zone, the Cretaceous formations of the northeastern subsided block are in direct contact with the Proterozoic and Palaeozoic rocks. Several morpholineaments of the NE–SW direction cut through the rocks of the Barrandian complex and Cretaceous sedimentary formations in the form of straight valley sections. Considering their present location, we conclude that in addition to the vertical component of neotectonic movements, there was also an overall horizontal shift of up to *ca* 400 m along the Labe fault. The fault zone of the Vykáň flexure gave rise to morphologically conspicuous cross faults, such as the Mochov and Kounice faults (Figs. 4, 6 and 7), while a pure left-slip by up to 1400 m was identified at the Mochov fault (Coubal 2010). The convergence of two originally parallel faults, namely the Kounice Fault and the Vykáň Flexure fault, led to the tectonic separation of the Polabí morphostructures from the area of the Permian rocks of the Český Brod and the Blanická brázda Furrow.

According to Volšan et al. (1990), tectonic movements during the Quaternary are linked to NE–SW faults, which affected the considerable thickness of the fluvial sediments of the Mělnický úval Basin. Havlíček et al. (1987) agree with this opinion; young tectonic movements in the younger Quaternary explain the higher fluvial sediment strengths on the right bank of the Labe River. In the Labe and Jizera confluence area, it is more difficult to identify the evolution of fault structures precisely because of the extensive cover of Quaternary sediments, especially the fluvial accumulation terraces of the Labe River.

## 3. Identification of Quaternary morphostructural landforms in the Labe and Jizera confluence area

The geological structure and lithology of the rocks in the Labe and Jizera confluence area played a significant role in the development of the current morphostructural landforms (Fig. 8). Particularly striking is the asymmetry of the slopes of the Labe valley (Fig. 9),

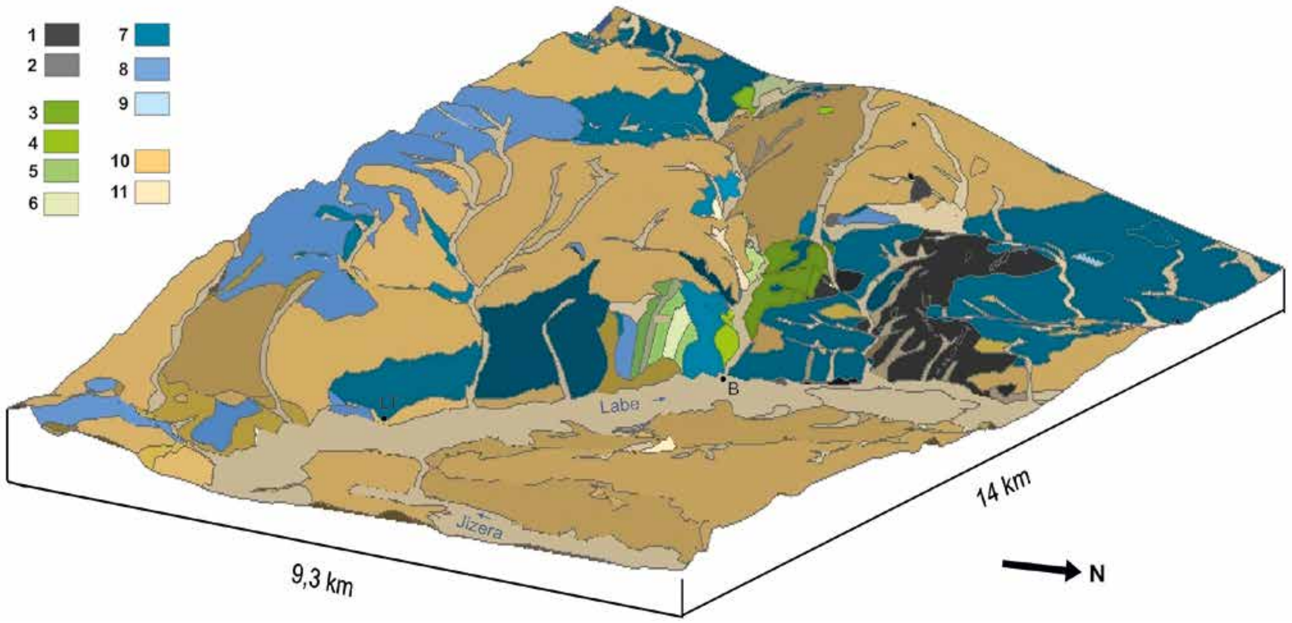

Fig. 8 Digital model of the terrain featuring the geological structure of the Labe and Jizera confluence area, viewed from NE to SW. Key: 1 – Kralupy-Zbraslav group (Proterozoic), 2 – Štechovice group (Proterozoic), 3 – Klabava formation (Ordovician), 4 – Šárka formation (Ordovician), 5 – Dobrotiv and Libeň formations (Ordovician), 6 – Dobrotiv formation (Ordovician), 7 – Peruc-Korycany formation (Cretaceous), 8 – Bílá hora formation (Cretaceous), 9 – Jizera-Bílá hora formation (Cretaceous), 10 – Pleistocene sediments, 11 – Holocene sediments, B – Brandýs nad Labem, LT – Lázně Toušeň. A detailed description of the rock assemblages from the marked geological periods is presented in the 2nd chapter. Source: Tereza Steklá, ZABAGED 2014.

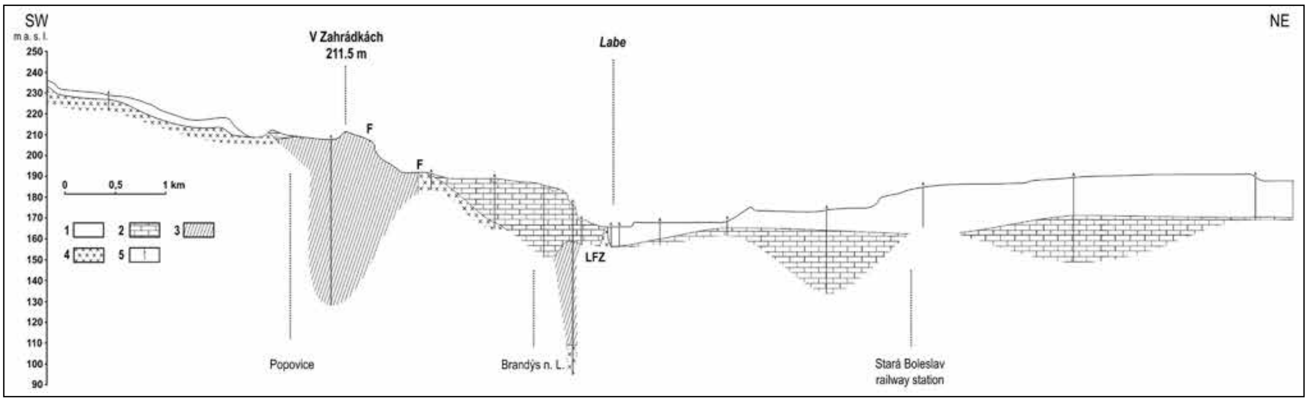

**Fig. 9** Topographical cross-profile through the asymmetrical Labe valley with relief of the morphostructural plateaus on the left bank and the moderate stepped slopes formed of the Quaternary river accumulation terraces on the right bank. The steep structural slope of the left bank of the Labe River developed along the tectonic fault of the Labe Fault zone. Key: 1 – Quaternary (fluvial and aeolian sediments), 2 – Cretaceous (sandstones, marlites, limestones, claystones), 3 – Ordovician (black shales, quartzites), 4 – Proterozoic (wacke, siltstones and phyllitic schists), 5 – borehole, F – fault, LFZ – Labe Fault zone. Source: Tereza Steklá; Uličný et al. 2009; Czech Geological Survey: Map applications, version 1B.2, 2019; GDO 2020.

which was formed by fluvial erosion along the fault system of the Labe Fault zone (Fig. 2). The Labe valley thus represents a morphological boundary between different types of relief on its right (NE) and left (SW) banks.

A relatively steep tectonically controlled left bank of the Labe valley gradually transitions into a structurally denudation relief with relics of planation surfaces in the south-western part of the studied area (Fig. 9). The Proterozoic and Palaeozoic rocks of the Barrandian are close to the surface and already exhumed in denudation windows. The most pronounced are bodies of Neo-Proterozoic silicates, which are more resistant to weathering and form knobs and elongated elevations mainly in the SW–NE direction (Volšan et al. 1990; Holásek et al. 2005). Most of these structural ridges occur in the Veleň – Brandýs nad Labem zone. The most important localities of Neo-Proterozoic lydites are the Kuchyňka (242 m a.s.l.) and Černá skála (157 m a.s.l.) knobs. The original size of most knobs and silicate elevations was often substantially reduced by quarrying.

The Barrandian rocks with a predominance of siltstones and slates have not yet been exhumed by denudation of the overlying layers. Ordovician rocks crop out in Brandýs nad Labem and its western surroundings, close to the erosional edge of the Labe valley, the Vinořský potok Brook, the Záhořská svodnice Brook and their tributaries. Elevations of Ordovician rocks occur only at the south-western edge of the studied area, where Upper Cretaceous sediments were less thick (Havlíček et al. 1987). Distinctive is a structural monadnok called Zabitý kopec Hill (264 m a.s.l.) near Miškovice, where the Třenice Formation has been preserved together with the prevailing Proterozoic silicates.

Cretaceous sediments in this part of the Polabí region have less thickness and area, due to both the ruggedness of the pre-Cenomanian relief and tectonic movements during the late Cenozoic (Havlíček et al. 1987; Volšan et al. 1990). The erosional activity of the Vinořský potok and Mratínský potok Brooks has exhumed the Korycany layers, while the older Peruc Formation does not crop out at all. Extensive areas of the Bílá Hora Formation (Turonian, calcareous claystones and marlstones) are denuded in the vicinity of Zeleneč and Svémyslice, as part of the Neogene planation surface, which is markedly dissected by the valleys of the Zelenečský potok Brook and Svémyslická svodnice Brook. The Bílá Hora Formation is preserved in varying thickness on the left bank of the Labe and is largely overlain by Quaternary aeolian and fluvial sediments (Holásek et al. 2005). Relatively deeply incised valleys of the Labe tributaries suggest their increased erosional activity during the late Quaternary (Fig. 8), which resulted from both the gradual deepening of the Labe valley and neotectonic movements in the area of the Labe Fault zone and Vykáň Flexure.

On the right bank of the Labe, the accumulation landforms are more pronounced. The rocks of the Barrandian complex do not crop out in any place there and have been detected only by a few boreholes (Coubal 2010; Zelenka et al. 2006). Also, the base of the Cretaceous sediments decreases towards the NE, while the Bílá Hora Formation has been detected here beneath Quaternary sediments in the tectonically subsiding block (Havlíček et al. 1987; Volšan et al. 1990). Therefore, structurally conditioned landforms are not as frequent in this part of the studied area as in the southwestern region. Their occurrence increases towards the NE, i.e., deep down into the Bohemian Cretaceous Basin. An example is the Na Viničkách locality northeast of Lysá nad Labem (Fig. 10), where the Jizera Formation crops out and, together with fluvial sediments of Pleistocene age, forms a morphologically distinct level of the Hlavenec Terrace

**Fig. 10** The erosion-denudational slopes of the southern edge of the morphostructural plateau Na Viničkách, which is situated NW of Lysá nad Labem, are built by the Cretaceous rocks of the Jizera formation. The surface of the platform is covered by the relics of the river terrace IV (Hlavenec, 222–225 m a.s.l.) belonging to the terrace system of the Labe and Jizera. Source: Tereza Steklá.

(Holásek et al. 2005, Tab. 2). A similar morphostructural character of coarse-grained siltstones to fine-grained sandstones is also present in the transverse sill in the Jizera River basin approximately 2 km south of Otradovice. However, the stratigraphic assignment of these sediments has not yet been paleontologically documented (Břízová et al. 2005). The evolution of the present-day accumulation relief was conditioned by neotectonic subsidences of this part of the Polabí region along the main fault of the Labe Fault zone and Vykáň Flexure (Figs. 2, 4 and 5). In the overlying Upper Cretaceous sediments, a system of river accumulation terraces (sometimes strikingly asymmetrical) was formed during the Quaternary, which is interconnected with slope and aeolian sediments.

Part of the identification of the morphostructural features of the Labe and Jizera confluence area were the measurements of morphologically distinct lineaments of tectonic and lithological origin. The Barrandian rocks and Cretaceous sediments are divided there by valleys that follow lineaments in four main directions, namely ENE–WSW (Rudohorský direction), WNW–ESE (Sudeten direction), NNE–SSW (Vltava or Jizera direction) and NW–SE. The location of the main morpholineaments on both banks of the Labe River is shown in Fig. 11 and the frequency of their occurrence in these directions in Fig. 12.

Morpholineaments of the Sudeten WNW–ESE direction are found on both banks of the Labe River, i.e., in all local types of geological structure. On the right bank of the Labe, the WNW–ESE morpholineaments run in a relatively dense network. Most of the morphologically distinct lineaments on the left bank of the Labe occur close to the erosional edge of the Labe valley, which indicates their relation to the morphostructures of the Labe Fault zone and Vykáň Flexure. NW–SE morpholineaments (Fig. 12), which are mainly pronounced in the Labe valley, are likely to be linked to these fault zones as well. This is also suggested by the frequent overlapping of lineaments with proven faults and their length, which reaches even more than 10 km.

The morpholineaments in the NNE–SSW direction are not frequent in the studied area – only the lineament in the Jizera River valley and southwest of the Labe River is more pronounced in this direction (Fig. 11). The lineaments in the ENE–WSW direction are more pronounced in the relief on the left bank of the Labe River, where they are mostly bound to the Proterozoic bedrock. Their position suggests that they indicate fault lines or lithological boundaries. The NE–SW morpholineaments are of similar origin, occurring more frequently to the northeast of the Labe and follow parts of the Jizera valley. In the north-western part of the area, NE–SW morpholineaments are bound to the Proterozoic rocks of the Kojetický hřbet Ridge and in its south-eastern part they occur on a structurally and lithologically similar ridge near Úvaly.

The current morphostructural landforms in the Labe and Jizera confluence area are conditioned by the extent of exhumation of the pre-Cenomanian relief. This exhumation of the rocks and palaeo-relief was influenced by the depth of denudation and erosion of the Cretaceous formations, the arrangement of the fault systems and neotectonic movements in the late Cenozoic. The influence of the pre-Cenomanian relief

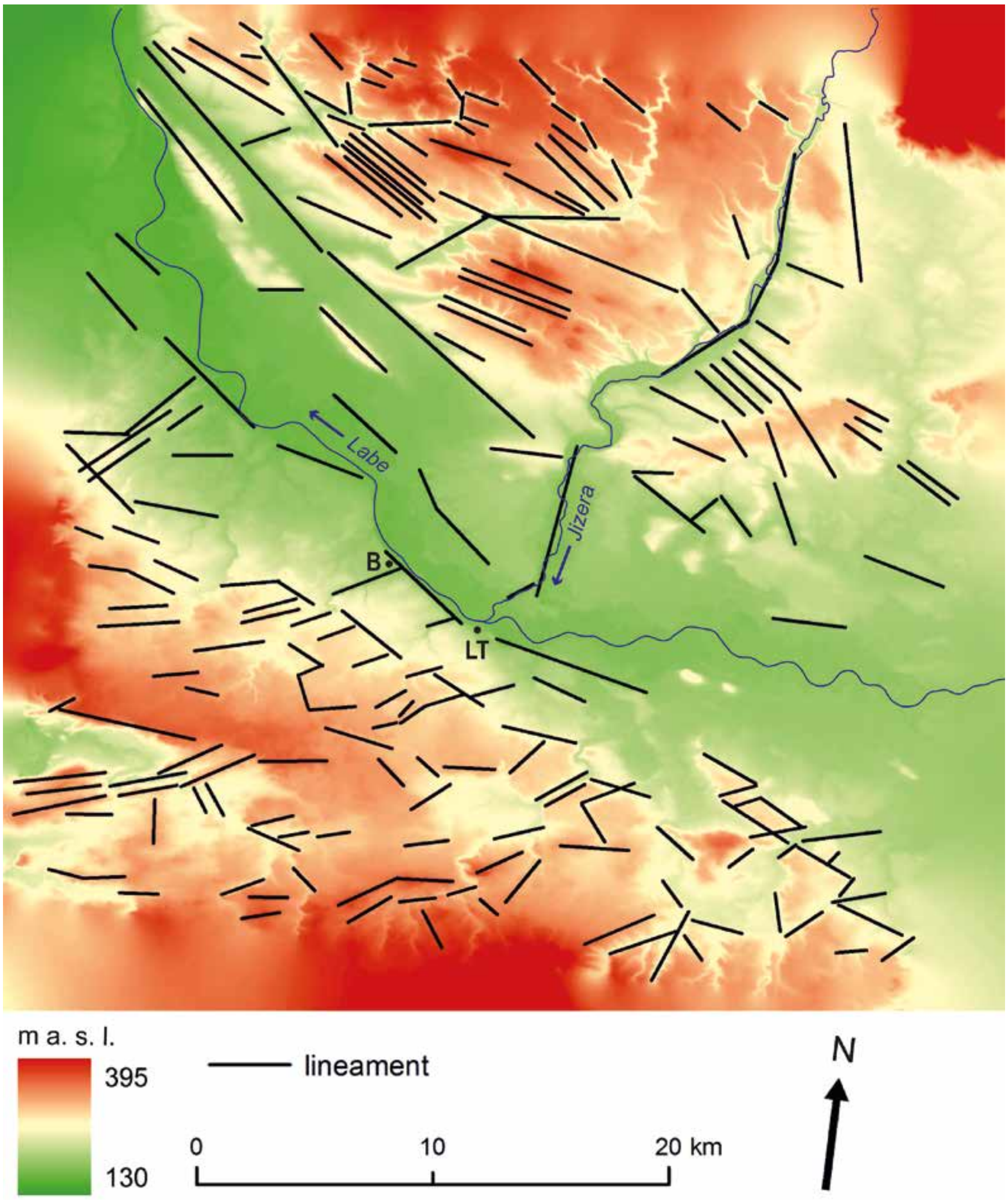

**Fig. 11** Topographical situation and morpholineaments in the Labe and Jizera confluence area.
B – Brandýs nad Labem, LT – Lázně Toušeň. Source: Tereza Steklá.

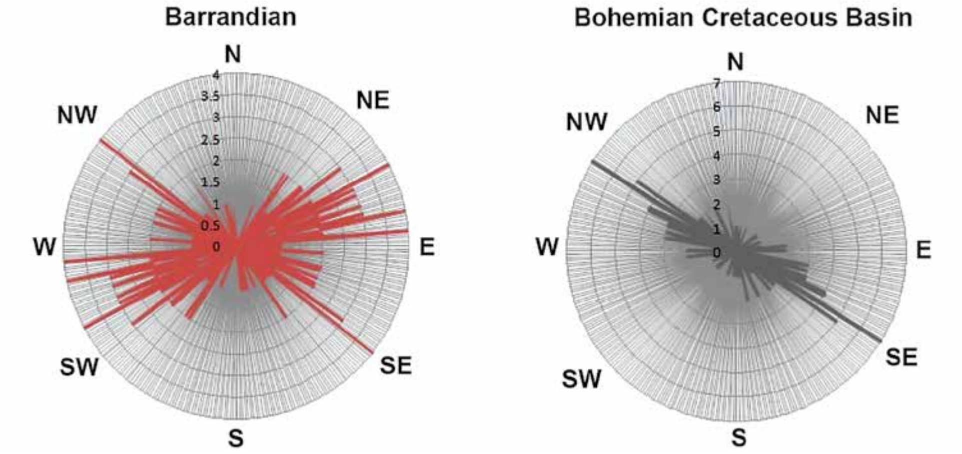

**Fig. 12** Circular diagrams of identified morpholineaments in the Labe and Jizera confluence area. Source: Tereza Steklá.

on the development of the present-day landforms is more pronounced to the SW of the Labe valley. This is mainly due to the late Quaternary tectonic subsidence of the north-eastern part of the studied area.

The denudation of Cretaceous rocks on the right bank of the Labe has not yet reached the level of the pre-Cenomanian relief. Significant morphostructural landforms here mainly take the form of structural plateaus and witness hills. They were formed by the joint action of neotectonic movements and erosion processes on the base of the Cretaceous formations during the Quaternary. These are, for example, the striking elevations called Turbovický hřbet Ridge (229 m a.s.l.), Cecemín (239 m a.s.l., Na Viničkách (227 m a.s.l.) and Šibák (227.8 m a.s.l.). Towards the north, the rocks of the Jizera Formation form a large table broken up by erosional activity of the right-side tributaries of the Labe and the left-side tributaries of the Jizera.

To the SW of the Labe valley, the long-term denudation of the Cretaceous sediments has created a relief of low structural tables with relics of planation surfaces of Tertiary age, with knobs made of resistant Proterozoic lyddites cropping out in places. These low erosion-denudation platforms are dissected by the activity of the left-side tributaries of the Labe, with deep and backward erosion having already reached the bedrock formed by the Barrandian rocks in several locations. The most pronounced exhumation of the Barrandian complex has occurred near the erosional edge of the Labe valley, which in this area is a significant divide between the relief of low structural tables

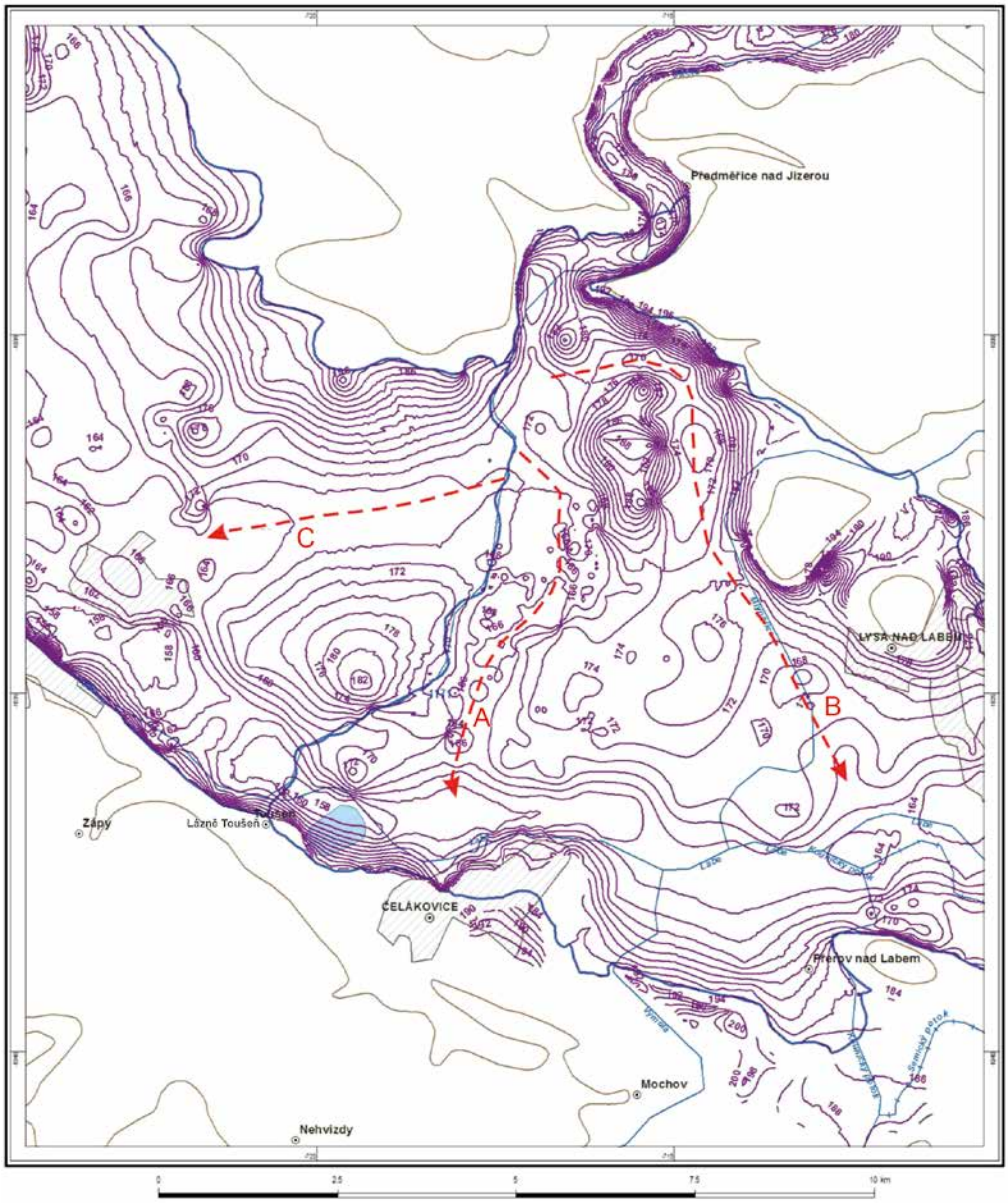

**Fig. 13** Isolines (in m a. s. l.) of the base of the Quaternary sediments in the confluence area of the Labe and Jizera.
The red arrows indicate the direction of the Jizera paleobeds during the different development phases of the VII. terrace (see Tab. 2).
A – initial incision phase, B – maximum deepening, C – main accumulation phase. Source: Herrmann and Burda Eds., 2016.

on the left bank of the Labe and the Quaternary system of fluvial accumulation terraces of the Labe and Jizera rivers.

## 4. Morphological manifestations of tectonic activity in the Labe and Jizera confluence area during the Quaternary

The main geomorphological testimony of exogenic processes in the Labe and Jizera confluence area during the Quaternary are river accumulation terraces. The terrace system of the studied part of the Labe and Jizera rivers is characterised by advanced erosion of the terrace accumulations and by the sporadically preserved group of older (higher) terraces. The highest fluvial sediments developed as accumulations of the Labe tributaries and their morphological position gives evidence of a gradual deepening of the river network during the Pleistocene (Tyráček et al. 2004; Tyráček 2010). The activity of fault systems in the NE–SW to WNW–ESE directions is evidenced by tectonic disruption of Quaternary sediments noted by Coubal (2010) on a geological section of the Vykáň Flexure near Vykáň (Fig. 5). Quaternary tectonic movements along these faults were already envisaged by Havlíček et al. (1987) and Volšan et al. (1990).

To determine the extent and progression of neotectonic subsidence, an analysis of the position of the base of the Quaternary sediments was first used (Fig. 13). The neotectonic subsidence near Brandýs n. L. was determined by comparing the present level of the higher rock base of VII$_2$ Terrace (166 m a.s.l.), which was formed by lateral erosion before the subsidence of the valley floor, and the surface of the Cretaceous formations near the erosional edge of the Labe valley (*ca* 180 m a.s.l.). At Stará Lysá, it was possible to determine the extent of tectonic subsidence by finding the difference in height between the paleochannel of Mlynařice (188 m a.s.l.) and the paleochannel of Jizera B (172 m a.s.l.), which were probably at the same elevation during the maximum deepening of the Labe (Fig. 14). At present, the difference in height at both sites is *ca* 14 m.

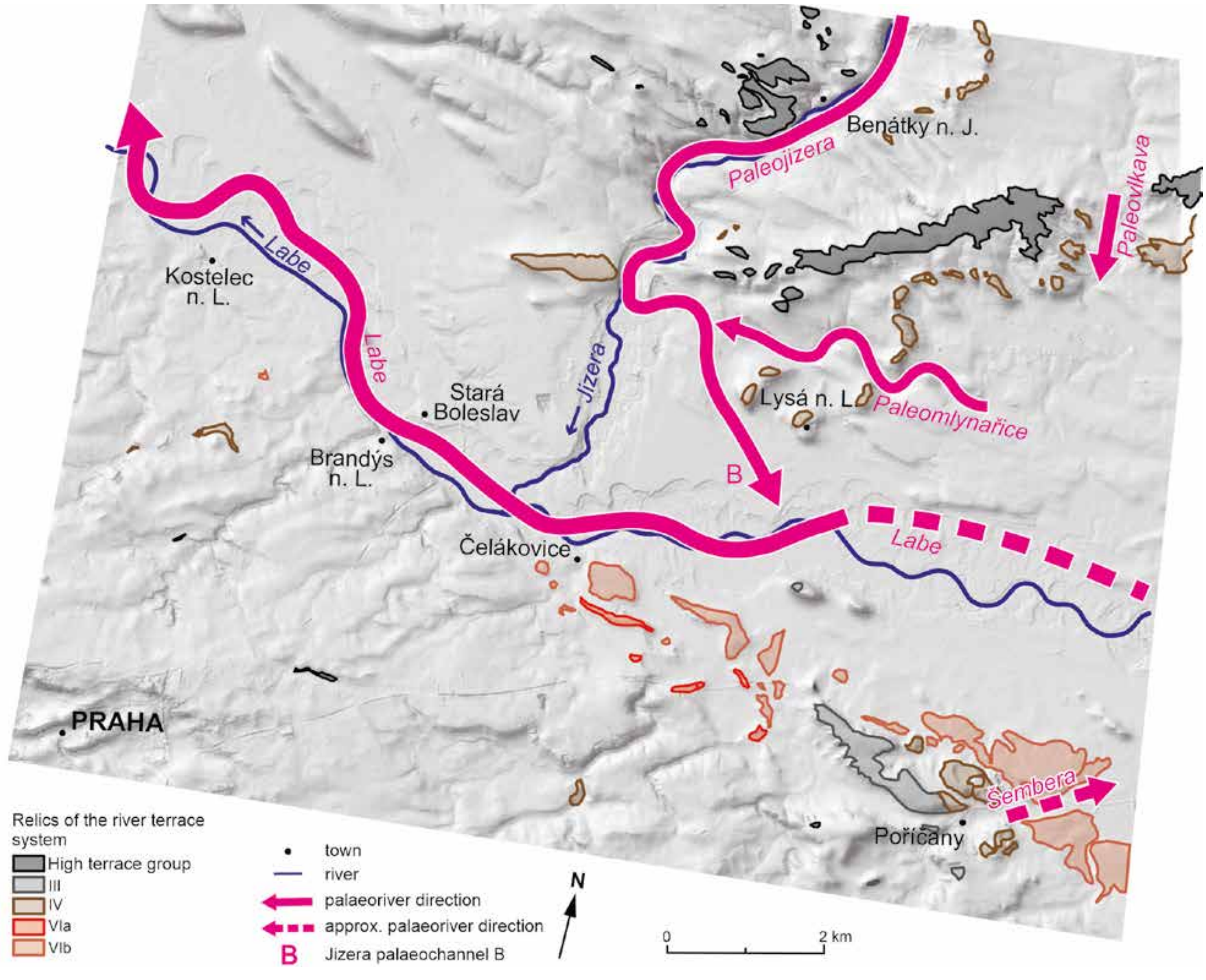

**Fig. 14** The directions of paleoflows in the area of today's Labe and Jizera confluence in the period of maximum deepening during the development of the VII. Terrace. Source: Tereza Steklá; DEM by Czech Office for Surveying, Mapping and Cadastre 2019.

Indications of differential neotectonic movements were also found by analysis of isolines of the base of Quaternary sediments and longitudinal profiles of the Labe and Jizera paleochannels. These isolines have a very uneven course with frequent steps. As regards the Jizera paleochannel, these changes in elevation may have been caused by neotectonic movements linked to the NE–SW Jizera fault. In the Labe paleochannel, we compared the elevated steps of Quaternary sediments base with morpholineaments of the same direction, i.e., NE–SW (Figs. 11 and 12).

The morphostratigraphic classification of the river terraces according to the current Quaternary classification system is proposed in Tab. 2 and Fig. 15. The geomorphological analysis of the river accumulation terraces, and their morphostratigraphic classification are made more difficult in this area by neotectonic and erosional interventions, relatively extensive covers of aeolian sediments in the form of loess and drift sands and, moreover, the effects of anthropogenic activity.

The current state of the relics of fluvial sediments and the structure of river terraces in the Jizera and Labe confluence area demonstrate morphologically significant tectonic activity in the younger Quaternary. Five main river accumulation terraces are preserved in this area, two of which are further subdivided by secondary levels of erosional or erosional-accumulation origin (Tab. 2). These river terraces were formed in a climatically determined alternation of erosional and accumulation phases of the valley development (Balatka and Kalvoda 2008; Hradecký and Brázdil 2016), which were supported by differential tectonic uplifts of the central part of the Bohemian Massif. The fluvial accumulations were substantially dissected by post-sedimentary erosion processes resulting in sporadic preservation of older (higher) terraces. The neotectonic subsidence of a part of the Labe valley in the Upper Pleistocene then caused a marked asymmetry in the extent and position of river accumulation terraces, with the predominance of accumulation of fluvial sediments of Terrace VII on the right bank of the Labe (Fig. 15).

The highest, and therefore the oldest preserved fluvial sediments in the Labe and Jizera confluence area were deposited by paleotributaries of the Labe.

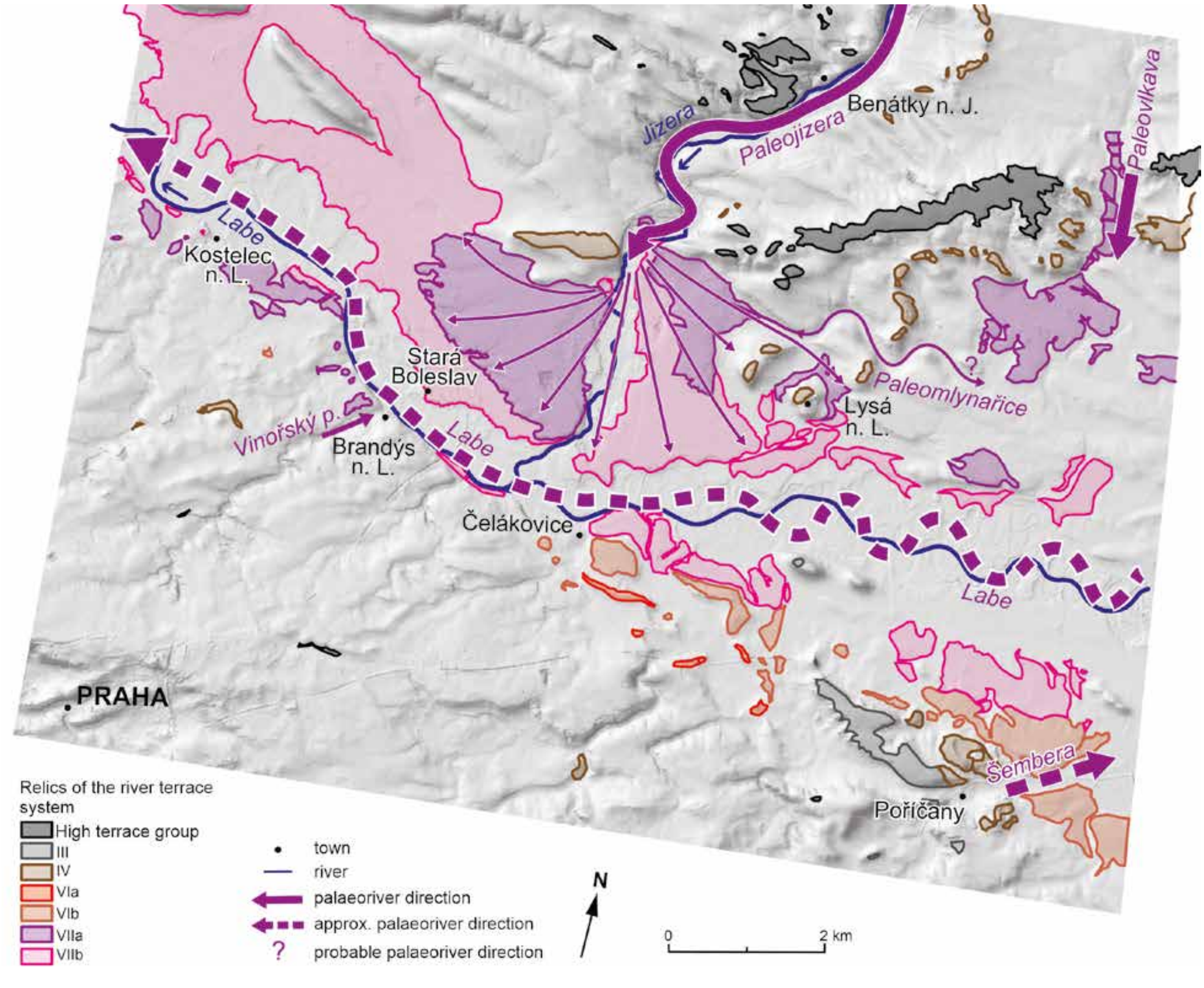

Fig. 15 The directions of paleoflows around today's Labe and Jizera confluence during the main accumulation phase of the VII. terrace after the tectonic subsidence of the Labe valley. Source: Tereza Steklá; DEM by Czech Office for Surveying, Mapping and Cadastre 2019.

**Tab. 2** The arrangement of river accumulation terraces in the Labe and Jizera confluence area and their morphostratigraphic correlation with the Vltava river terrace system. The surface (s.) and base (b.) heights are given in metres above sea level, the relative height in metres is given in brackets. Source: Tereza Steklá.

| Stratigraphical division (stage/substage) of the Quaternary (Gibbard and Cohen 2008; Gibbard et al. 2009) | Labe river km 854–891 | Jizera river km 0–20 | Labe and Vltava Confluence river km 803–840, 0–22 Záruba et al. (1977) Tyráček et al. (2004) Tyráček, Havlíček (2009) | Vltava in Prague river km 204 Záruba et al. (1977) Tyráček et al. (2004) Tyráček, Havlíček (2009) |
|---|---|---|---|---|
| Holocene<br>-------- 0.0117 mil. years | Lower alluvial level<br>s. 165–179<br>b. 156–164 (−10 to −6) | Alluvial level<br>s. 171–180<br>b. 158–178 (−20 to −2) | Alluvial level<br>s. (5)<br>b. (−10) | Alluvial level<br>s. 180<br>b. 168 (−8) |
| | Higher alluvial level<br>s. 166–181<br>b. 156–164 (−10 to −6) | | | |
| Upper Pleistocene<br>Weichsel<br>-------- 0.12 mil. years | VIIb<br>s. 170–185 (8–13)<br>b. 156–184 (−10 – 12) | Jizera Fan<br>s. 180–196 (9–22)<br>b. 164–196 (−7 – 22) | VII Hostín Terrace<br>s. (12)<br>b. (−10) | VII Maniny Terrace<br>s. 187 (11)<br>b. 168 (−8) |
| | VIIa<br>s. 180–196 (14–24)<br>b. 166–196 (1–24) | | | |
| Middle Pleistocene<br>saale, warthe<br>-------- 0.19 mil years | VIb<br>s. 188–201 (16–29)<br>b. 186–200 (14–28) | The relics of Terrace VI can be buried here by the Jizera Fan[2] | VI Veltrusy Terrace<br>s. (25)<br>b. (0) | VI Veltrusy Terrace<br>s. 193 (17)<br>b. 174 (−2) |
| | VIa (Čelákovice)<br>s. 199–208 (27–36)<br>b. 198–205 (26–33) | | | |
| Middle Pleistocene<br>saale, drenthe<br>-------- 0.20 mil years | Terrace V was eroded here during the erosion phase of Terrace VI [1] | Terrace V was not deposited on the erosional and tectonic right bank of the Jizera valley. On the left bank it was eroded during the erosion phase of Terrace VI[3] | V Cítov Terrace<br>s. (40)<br>b. (16) | V Dejvice Terrace<br>s. 214 (38)<br>b. 194 (18) |
| Middle Pleistocene<br>saale, fuhne<br>-------- 0.38 mil. years | IV Hlavenec Terrace<br>s. 218–225 (53–56)<br>b. 217–220 (49–52) | IV Hlavenec Terrace<br>s. 218–225 (41–44)<br>b. 217–220 (37–40) | IV Hněvice Terrace<br>s. (60)<br>b. (43) | IV Letná Terrace<br>s. 226 (50)<br>b. 215 (39) |
| Middle Pleistocene<br>elster<br>-------- 0.48 mil. years | III Přerov Terrace<br>s. 232–236 (59–63)<br>b. 230–234 (57–61) | III Jiřice Terrace<br>s. 242–256 (62–68)<br>b. 234–248 (54–60) | III Straškov Terrace<br>s. (75)<br>b. (55) | IIIb Vinohrady Terrace<br>s. 240 (64)<br>b. 225 (49) |
| Middle Pleistocene<br>Cromer Complex, Glacial C | | | | IIIa Kralupy Terrace<br>s. 249 (73)<br>b. 240 (64) |
| Middle Pleistocene<br>Cromer Complex, Glacial C | Terrace II was eroded during younger development phase [1] | II Sedlec Terrace<br>s. 266 (84)<br>b. 253 (71) | II Ledčice Terrace<br>s. (90)<br>b. (75) | II Pankrác Terrace<br>s. 262 (86)<br>b. 249 (73) |
| Middle Pleistocene<br>Cromer Complex, Glacial B | Terrace I was eroded during younger development phase[1] | The palaeo-flow of the Jizera River was located further to the E from its present course[4] | | Ib Suchdol Terrace<br>s. 272 (96)<br>b. 260 (84) |
| Middle Pleistocene<br>Cromer Complex, Glacial A<br>-------- 0.78 mil. years | | | I Krabčice Terrace<br>s. (115)<br>b. (105) | Ia Lysolaje Terrace<br>s. 288 (112)<br>b. 268 (92) |

[1] The nearest preserved fluvial sediments of Labe Terraces I (Krabčice Terrace), II (Ledčice Terrace) and V (Cítov Terrace) are located in the Labe and Vltava confluence area. [2] The nearest fluvial sediments of Terrace VI of the Jizera River were found near Nová Ves u Bakova. [3] The nearest relics of deposits of Terrace V of the Jizera are near Mladá Boleslav. [4] Terrace I accumulations have not been found in the Jizera basin.

On the right bank of the Labe, the highest fluvial accumulations are located near the village of Mečeříž and in the locality of Na Zlatě (surface: 278–290 m a.s.l., r. h. 106–118 m; base: 275 m a.s.l., r. h. 103 m), which Balatka and Sládek (1962) identified as the accumulations of the Mohelka paleostream. Near the village of Sedlec, there are relics of lower-level fluvial accumulations preserved (Sedlec Terrace, surface: 266 m a.s.l., r. h. 94 m; base: 253 m a.s.l., r. h. 81 m), which Zelenka et al. (2006) described as sediments of the Jizera paleostream. Tyráček (2010) classified all fluvial accumulations of the high terrace group at Mečeříž, Sedlec and Kochánky as Lower Pleistocene to upper part of Middle Pleistocene.

**Fig. 16** View to the asymmetric valley of the Jizera in Skorkov towards the NE, i.e. upstream of the river. The erosion-denudation slope of the structural plateau formed by Cretaceous rocks (in the foreground) drops steeply to the valley floor with alluvial sediments. On the left bank of the Jizera, now forested fluvial sediments of the VII. terrace occur (in the right part of the picture). Behind this accumulation, three elevations built by the Jizera formation (Čihadla 240.2 m, Na vršcích 245.8 m and Raštice 241.4 m a.s.l.) are striking on which relics of III. (Jiřice) terrace of the Jizera remain. Source: Tereza Steklá

The oldest relics of the fluvial accumulations of Terrace IV (Hlavenec, 222–225 m a.s.l.) contain admixture of crystalline rock from the upper Jizera catchment. These fluvial sediments were probably developed in the locality of earlier Labe and Jizera confluence (Holásek et al. 2005; Tyráček 2010). Main occurrences of these deposits were identified on the plateau between Hlavenec and Skorkov and Na Viničkách (Fig. 10), *ca* 8 km away from the current confluence of the Labe and Jizera. The deposits of Terrace V have not been preserved in the studied area due to following intensive deep erosion and widening of the Labe valley (Balatka and Sládek 1965; Tyráček 2010). On the left bank of the Labe river, two levels of Terrace VI have been preserved, their distinction being mainly reflected at the level of their bases (Záruba et al. 1977; Holásek et al. 2005; Tyráček 2010).

River accumulation terrace VII in the Labe and Jizera confluence area is characterised by a complex internal structure and surface morphology (Fig. 16). In the main erosion phase during the younger Pleistocene, the Labe formed a deepened riverbed about 10 m below its present level (Figs. 13 and 14). To the N of Sojovice, Paleojizera diverted its flow from the original N–S direction to the E, namely to the former valley of the lower Paleomlynařice. The paleobed of the Jizera (B) formed a wide arch here, namely south from the buried elevation of Cretaceous rocks between Sojovice and Stará Lysá. This paleobed B continues in the southern direction towards Dvorce and then in a straight section to the SE. Due to antecedent deepening in the resistant rocks of the Cretaceous formations, the valleys of Paleomlynařice and Paleovlkava near Jiřice have been preserved in the same position as during former periods. After the riverbed was filled with younger fluvial sediments, the river valley was widened by lateral erosion and a higher bed was formed, on which aggradation sediments were deposited by the raging flow. Based on the reconstruction of the local Labe and Jizera terrace system (Tab. 2) and its relationships to morphostructural landforms, it is concluded that a neotectonic subsidence took place during the main aggradation phase of Terrace VII in the Upper Pleistocene (Weichselian).

In the late Pleistocene, an extensive accumulation of fluvial sediments in the form of an alluvial fan was formed in the last 10 km of the Jizera valley (Fig. 15). These sediments were deposited by the Jizera River at its entering to the broad and flat Labe valley and covered the older erosional relief (Balatka 1966; Hrubeš 1999; Tyráček 2010). This extensive fluvial accumulation overwhelmed the earlier relief, including the paleobed of the Jizera C (Fig. 13) and elevations of the Cretaceous bedrock up to 188 m a.s.l. Higher elevations in the vicinity of Lysá nad Labem, on which the relics of the IV. river terrace remain, rose above the surface of the Jizera fan at this time. They diverted the transported material of the Paleojizera to the Paleomlynařice valley. The morphology of the massive alluvial fan of the Jizera indicates that it was formed mainly in the environment of shallowly raging flow and flat streams. They caused the Labe flow to be gradually shifted to the south. At the present-day confluence of the Labe and the Jizera, the Labe floodplain was significantly narrowed, which slowed down its flow between Lysá and Labem and Přerov and Labem and wide meanders were formed (Fig. 15). Less marked erosion levels preserved in the fluvial sediments of the alluvial fan were formed only during the Late Glacial and Holocene.

## 5. Discussion of geomorphic patterns in the Labe and Jizera confluence area related to the morphostructural evolution of the Bohemian Massif

Objective of presented research was to find out the key phases of the morphostructural evolution of the Labe and Jizera confluence area. Current landforms in the region provide a reliable record of palaeogeographical changes in the natural environment. For this reason, it was possible to carry out a detailed historical-genetic analysis of the landforms. Special attention was paid to the influence of neotectonic activity and climate-morphogenetic processes on the changes in the drainage pattern. The morphostratigrafical system of the river terraces was updated and applied as a primary timeline.

Tectonic uplift of the Bohemian Massif, which has started at the end of the Santonian, led to a complete retreat of the Upper Cretaceous epicontinental sea. The extent of denudation of the Bohemian Cretaceous Basin sediments during the Neogene is estimated at 500–600 m by the morphological position of the sediments and volcanics (Kovanda et al. 2001; Balatka and Kalvoda 2006). In the region of the Labe and Jizera confluence, the thickness of the Cretaceous sediments is influenced by a vertical differentiation of the pre-Cenomanian relief.

The palaeogeographical record of the morphostructural evolution of the contact area between the north-eastern Barrandian zone and the south-eastern margin of the Bohemian Cretaceous Basin shows that the main lithological and tectonic features of the present relief have been gradually formed since the Palaeozoic (Tab. 1). Geological structures and landforms of Central European region testifies to a very dynamic evolution of the relief in the palaeogeographical history of the Bohemian Massif (e.g., Chlupáč et al. 2002; Balatka and Kalvoda 2006; Pánek and Hradecký Eds., 2016). The Hercynian orogenic processes united the Bohemian Massif into a structurally complex unit, the central part of which consists of the collisionally deformed and metamorphosed crystalline rocks of the Moldanubic age.

During the main phase of the Hercynian orogeny, extensive deep-seated intrusions of granitoid rocks took place, and in its final phase 290–260 million years ago, shear movements with the formation of fault systems also took place. This is how tectonic subsidence in the Lower Permian occurred in the NW–SE direction in the Labe Fault zone and in the Blanická, Jihlavská and Boskovická brázda Furrows in the NW–SE direction. During the Hercynian orogenetic processes, the Moldanubicum was not only the central part of the gradually consolidated Bohemian Massif, but also an area where mountain ranges with heights of several thousand metres were formed (Chlupáč et al. 2002). However, the extensive denudation of these mountain ranges caused the exposure of deep metamorphic rock masses as early as at the end of the Permian. In the Upper Permian, the palaeo-relief of the Bohemian Massif took the form of a post-Hercynian planation surface, the denudation of which took place in a semiarid and very warm climate (Demek 2004).

The Triassic sedimentation and its termination can be interpreted as the beginning of the next platform development of the Bohemian Massif (Grygar 2016), because erosion and planation of its surface took place until the end of the Jurassic period. This period of extensive denudation of the Bohemian Massif was ended first by continental and then by marine sedimentation (especially in its northern part) as late as during the eustatic uplift of the world ocean level during the Cretaceous period.

In terms of palaeo-climate, the changes in the position of the Bohemian Massif as part of the Pangea palaeocontinent in the Mesozoic and Palaeogene were significant, when it was moved from the tropical zone to the north of the equator to about 45° N, i.e., west of the current zero meridian (Chlupáč et al. 2002). It was only the dynamic development of the rift in the northern part of the Atlantic Ocean, and the associated opening of oceanic plates, that moved the

Hercynian and older crystalline basement of the continental plate of Europe at the end of the Palaeogene to approximately its present geographic position.

The tectonic uplift of the Bohemian Massif from the end of the Cretaceous period were a response to the continuing Alpine and Carpathian orogeny, which consisted mainly in the retreat of the continental sea. It was shown by radiometric dating and modelling using a combination of zircon (U-Th)/He and apatite (AFT and U-Th-[Sm])/He thermochronology methods on rock samples from planation surfaces in the Krkonoše and other Sudetic Mountains ridges (Danišík et al. 2010, 2012) that these peneplains were probably formed by extensive exhumation of a Late Permian planation surface originally located under a several kilometre-thick layers of Cretaceous sediments.

The current orography and landform assemblage of the Bohemian Massif developed as late as during the Neogene and Quaternary periods, i.e., in the last 20–25 million years of its palaeogeographical history. The Palaeogene planation of the relief of the Bohemian Massif was interrupted at the end of the Oligocene by tectonic movements, which were accompanied in its western and north-western parts by the formation of the Oherský Rift and intense volcanic activity 35–17 million years ago (e.g., Grygar 2016). The evolution of the Bohemian Massif relief was also substantially influenced by two other phases of volcanic activity, namely in the Upper Miocene between 9.0 and 6.4 million years ago, and from the Upper Pliocene to the Pleistocene between 2.7–0.17 million years ago (Wagner et al. 1998). The extent of denudation of the sediments of the Bohemian Cretaceous Basin from the beginning of the Miocene to the present is documented by the morphostructural position of the volcanic massifs. The extent of erosion and denudation in the Central Bohemian Uplands during the Neogene is estimated at 500–600 m assessed from the layers of sedimentary rock relics and volcanic bodies (Malkovský 1975; Chlupáč et al. 2002).

The primary arrangement of the river network of the Bohemian Massif originated as late as in the Neogene (e.g., Balatka and Kalvoda 2006; Tyráček and Havlíček 2009). The main differences between the Early Miocene river network and the present-day relief comprise: 1) the upper part of the Labe basin drained into the Carpathian foredeep, 2) the upper part of the Vltava basin drained to the south into the Alpine foredeep, and 3) the West Bohemian rivers, including the Berounka, flowed into freshwater lakes, which were formed in the basins of the Oherský Rift (Tyráček and Havlíček 2009). Along the south-eastern edge of the Bohemian Massif, deep river valleys were formed in the Neogene (Czudek 1997; Pánek and Kapustová 2016). Today, they are filled with and partly covered by Miocene sediments.

The combined effect of changes in climate-morphogenetic processes and long-term neotectonic uplift created systems of river accumulation terraces during the Pliocene and Quaternary in the valleys of most of the main streams of the Bohemian Massif. These fluvial deposits are, together with the overall arrangement of the river network and other manifestations of epigenetic and antecedent evolution of watercourse valleys, an important source of data on the relief history of the Bohemian Massif (Balatka and Kalvoda 2006; Kalvoda and Balatka 2016). The evolution of the Labe and Jizera terrace system has been studied by numerous authors and their findings are evaluated in several older papers (e.g., Balatka and Sládek 1962; Růžičková and Havlíček 1981).

The geomorphological analysis of the longitudinal profile of the river terrace system and the development of the river valley assumes that the individual parts of the river terraces maintained a constant slope corresponding to their longitudinal profile. The flow and transport capacity of the stream are in dynamic equilibrium with the material input. Therefore, the river does not erode or accumulate in this section of the stream and all its energy is concentrated on material transport (Mackin 1948). This condition is substantially influenced by tectonic movements (uplift and subsidence) and/or climatic changes that determine the sedimentary regime. Individual sites of fluvial sediments must therefore be assessed with respect to their lithological characteristics, including petrographic composition, and to the landforms in their wider vicinity.

The distinct morphostructural segmentation of the area around the Labe and Jizera confluence, which is manifested on both banks of the Labe by block subsidence and uplift both in the relief and at the height of the base of Quaternary sediments, supports the view of the formation of an interaction zone between two significant fault systems. The interaction zone development principles are described by, e.g., Peacock (2001), Peacock et al. (2017) and van Gent and Urai (2020). In the studied area it is the interaction between the faults of the Labe Fault zone (WNW–ESE) and the Jizera Fault (N–S). The described morphostructural features of the near-surface geological structure testify to the action of high stress and friction in the rocks of the contact zone between both fault systems. The main Labe Fault and the compact rocks of the Barrandian complex limited the extension of the Jizera Fault further to the south, but older morphostructural zones were activated and secondary block-type deformations occurred.

The specific morphostructural conditions in the Labe and Jizera confluence area conditioned the formation of asymmetrical system of river terraces, in which fluvial sediments deposited on the right bank of the Labe predominate. Due to the action of post-accumulation erosion processes, the relics of the river terraces of the Labe and its tributaries have been preserved only in a limited morphostratigraphic sequence (Table 2). The disruption of the relics of fluvial sediments by erosion indicates that the Labe and Jizera confluence area has undergone significant changes in the natural environment from the Upper Pleistocene to the present day, influencing the development of the river network.

In the upper glacial phases, aeolian material was drifted away from slopes and from fluvial sediments and deposited on fluvial sediments of Middle to Upper Pleistocene age. In this respect, discontinuous covers of drift sands, often in the form of dunes and dune banks, are striking (Hrubeš 1999; Břízová et al. 2005). Most of the drift sands was stabilised by vegetation during the Holocene. To the east of the Labe and Jizera confluence area, near the village of Písty, an unconsolidated sandbank up to 8 m high has been preserved (Čech et al. 2009).

The deposition of fluvial sediments continued during the Holocene in the form of flood clays, loams, and fluvial sands (Růžičková and Zeman 1994). Palynological analysis of the organic sediments of oxbows confirms the long-term human influence on the natural environment of this area, e.g., by changes in the natural composition of vegetation since the Middle Holocene (Hrubeš 1999; Břízová et al. 2005). In recent centuries, there have been extensive anthropogenic influences on the natural environment. These include intensive farming, large-scale housing developments, alterations to watercourse routes and banks, construction of transport networks, gravel extraction and creation of detritus heaps.

## 6. Conclusions

The presented research in the Labe and Jizera confluence area contributes to the determination of remarkable changes in the landform patterns of the Bohemian Massif during the Quaternary. Morphostructures of the contact area between the Barrandian and the Bohemian Cretaceous Basin has been gradually evolving from the Early Palaeozoic to the Quaternary.

Tectonic subsidence of the northeastern part of the Bohemian Massif and the Cretaceous transgression of the sea caused extensive marine sedimentation, which covered pre-Cenomanian relief. The uplift of the Bohemian Massif during the Santonian initiated widespread erosion and denudation in the Tertiary. Neotectonic activity and climate-morphogenetic processes determined the evolution of present landforms during the Upper Cenozoic (Tab. 1).

Historical-genetical relations between morphostructural landforms of the studied area and Quaternary deposits indicate significant influence of different rock resistance to weathering, the arrangement of fault structures and neotectonic movements on the intensity of varied climate-morphogenetic processes. The location and the depositional character of the river terraces in the Labe and Jizera confluence area were used to determine the changes in direction of the paleoriver flows in the Quaternary. The morphostructural platform surfaces on the left bank of the Labe River are dissected by erosion of its tributaries, which has reached the Barrandian bedrock at several sites.

Regional geomorphic research revealed that most of the relics of fluvial deposits in the Labe and Jizera confluence area are younger than reported in the previous studies (Tab. 2). Originally extensive and currently already considerably eroded III. river terrace of Labe River was formed in the Elster glacial period. The conspicuous Jizera River alluvial fan developed during the aggradation phase of the VII. river terrace in the Upper Pleistocene.

The degree of river incision between several accumulation phases of the river terraces development and the extent of backward erosion through the valleys of the Labe and Jizera tributaries reflect the changes of the erosional basis caused by neotectonic and climate-morphogenetic processes. Down-slip tectonic movements along the Labe fault zone, which caused the current asymmetry of the Labe valley, reached up to 14 m even before the beginning of the Holocene.

## Acknowledgements

The presented paper was prepared in the framework of the Charles University Project Cooperatio “Geography”.

## References

Balatka, B. (1960): Terasy Jizery. Kandidátská disertační práce. PřF UK v Praze, Praha. (in Czech).

Balatka, B. (1966): Ke středopleistocénnímu a mladopleistocénnímu vývoji údolní nejdolejší Jizery. Sborník České Společnosti zeměpisné 71(3), 217–230, https://doi.org/10.37040/geografie1966071030217.

Balatka, B., Gibbard, P., Kalvoda, J. (2010): Morphostratigraphy of the Sázava river terraces in the Bohemian Massif. AUC Geographica 45(1–2), 3–34, https://doi.org/10.14712/23361980.2015.54.

Balatka, B., Kalvoda, J. (2006): Geomorfologické členění reliéfu Čech. Kartografie Praha. (in Czech).

Balatka, B., Kalvoda, J. (2008): Evolution of Quaternary river terraces related to the uplift of the central part of the Bohemian Massif. Geografie 113(3), 205–222, https://doi.org/10.37040/geografie2008113030205.

Balatka, B., Kalvoda, J. (2010): Vývoj údolí Sázavy v mladším kenozoiku. Česká geografická společnost, Praha.

Balatka, B., Kalvoda, J., Gibbard, P. (2015): Morphostratigraphical correlation of river terraces in the central part of the Bohemian Massif with the European stratigraphical classification of the Quaternary. AUC Geographica 50(1), 63–73, https://doi.org/10.14712/23361980.2015.87.

Balatka, B., Sládek, J. (1962): Říční terasy v českých zemích. Československá akademie věd. Praha. (in Czech).

Balatka, B., Sládek, J. (1965): Pleistocénní vývoj údolí Jizery a Orlice. Rozpravy Československé akademie věd, Řada matematických a přírodních věd 11, 3–26. (in Czech).

Boháčová, I., Břízová, E., Nývlt, D., Růžičková, E. (2000): Holocene flood plain of the Labe river (past climatic changes and their impact on natural and human development). Excursion Guide, the International Conference on Past Global Changes, September 6–9, 2000, Prague.

Břízová, E., Dušek, K., Havlíček, P., Holásek, O., Manda, Š., Vodrážka, R. (2005): Geologie středního Polabí: Předběžné výsledky geologického mapování na listu 13–131 Brandýs nad Labem – Stará Boleslav. Zprávy o geologických výzkumech v roce 2004, 19–22. (in Czech).

Coubal, M. (2010): Tektonické založení jižního okraje české křídové pánve v okolí Kounic. Zprávy o geologických výzkumech v roce 2009, Česká geologická služba, 27–30. Available online https://app.geology.cz/img/zpravyvyzkum/fulltext/2009-8.pdf (accessed on 12. 11. 2019).

Czech Office for Surveying, Mapping and Cadastre (2019): Analýza výškopisu. Prohlížecí služba WMS – DMR 5G. Available online https://ags.cuzk.cz/av/ (accessed on 3. 12. 2022).

Czudek, T. (1997): Reliéf Moravy a Slezska v kvartéru. Sursum, Tišnov. (in Czech)

Czech Geological Survey: Map applications, version 1B.2. Available online http://www.geology.cz/app/ciselniky/lokalizace/show_map.php?mapa=g50&y=724200&x=1034400&r=7000&s=1&legselect=0 (accessed on 12. 11. 2019).

Čech, S., Holásek, O., Havlíček, P., Skácelová, Z. (2009): Kvartérní a křídové sedimenty na území listu Nymburk. Zprávy geologického výzkumu v roce 2008, 59–61. Available online https://app.geology.cz/img/zpravyvyzkum/fulltext/2008-15.pdf (accessed on 20. 12. 2022).

Danišík, M., Migoń, P., Kuhlemann, J., Evans, N. J., Dunkl, I., Frisch, W. (2010): Thermochronological constraints on the long-term erosional history of the Karkonosze Mts., Central Europe. Geomorphology 117(1–2), 78–89, https://doi.org/10.1016/j.geomorph.2009.11.010.

Danišík, M., Štěpančíková, P., Evans, N. J. (2012): Constraining long-term denudation and faulting history in intraplate regions by multisystem thermochronology: An example of the Sudetic Marginal Fault (Bohemian Massif, central Europe). Tectonics 31(2), TC2003, https://doi.org/10.1029/2011TC003012.

Demek, J. (2004): Etchplain, rock pediments and morphostructural analysis of the Bohemian Massif (Czech Republic). In: Drbohlav, D., Kalvoda, J., Voženílek, V.: Czech Geography at the Dawn of the Millenium. Czech Geographical Society, Palacky University in Olomouc, Olomouc, 69–81.

Demek, J., Kirchner, K., Mackovčin, P., Slavík, P. (2009): Morphostructures on the territory of the Czech Republic (Europe). Zeitschrift fur Geomorphologie 53, Supplementary Issue 2, 1–10, https://doi.org/10.1127/0372-8854/2009/0053S3-0001.

Drahota, F. (1931): Spádová křivka Jizery se zřetelem k morfologickému vývoji její oblasti. Disertační práce. Geografický ústav UK v Praze, Praha (in Czech).

Enc, P. (1984): Flora a fauna nejstarších geologických útvarů na Brandýsku. Studie a zprávy 1981–1982, 5–19. (in Czech).

Engel, Z., Kalvoda, J. (2002): Morphostructural development of the sandstone relief in the Bohemian Cretaceous Basin. In: Přikryl, R., Viles, H. (Eds.): Understanding and managing stone decay. SWAPNET, Karolinum, Praha, 225–231.

Fediuk, F., Ichinkhorloo, B., Ciniburk, M. (1966): Neratovice Komplex – product of metasomatic transformation of volcanites into rocks of plutonic appearance. Paleovolcanites of the Bohemian Massif, 51–60.

Gent, H. van, Urai, J. L. (2020): Abutting faults: a case study of the evolution of strain at Courthouse branch point, Moab Fault, Utah. Solid Earth 11(2), 513–526, https://doi.org/10.5194/se-11-513-2020.

GDO (2020): Database of the geologically documented objects in the Czech Republic. Czech Geological Survey. Available online http:// www.geology.cz/app/gdo/d.php?item=3 (accessed on 17. 12. 2020).

Gibbard, P. L., Cohen, K. M. (2008): Global chronostratigraphical correlation table form the last 2.7 million years. Episodes 31(2), 243–247, https://doi.org/10.18814/epiiugs/2008/v31i2/011.

Gibbard, P. L., Head, M. J., Walker, M. J. L. and the Subcomission on Quaternary Stratigraphy (2009): Formal ratification of the Quaternary System/Period and the Pleistocene Series/Epoch with a base at 2.58 Ma. Journal of Quaternary Science 25(2), 96–102, https://doi.org/10.1002/jqs.1338.

Grygar, R. (2016): Geology and Tectonic Development of the Czech Republic. In: T. Pánek, J. Hradecký (Eds.): Landscapes and Landforms of the Czech Republic. World Geomorphological Landscapes. Springer Verlag, 7–18, https://doi.org/10.1007/978-3-319-27537-6_2.

Havlíček, V. (1963): Tektogenetické porušení barrandienského paleozoika. Sborník geologických věd – Geologie 1, 77–102. (in Czech).

Havlíček, P., Brunnerová, Z., Hrkal, Z., Kříž, J., Růžičková, E., Šalanský, K., Valečka, J., Volšan, V., Zeman, M., Zoubek, J. (1987): Vysvětlivky k základní geologické mapě ČSSR, list 12-242 Čakovice. Ústřední ústav geologický, Praha. (in Czech).

Herrmann, Z., Burda, J. (Eds., 2016): Závěrečná zpráva o řešení geologického úkolu s výpočtem zásob podzemních vod v hydrogeologických regionech 1151 – Kvartér Labe po Kolín, 1152 – Kvartér Labe po Nymburk, 1171 – Kvartér Labe po Jizeru, 1172 – Kvartér Labe po Vltavu. MS archiv Česká geologická Služba. (in Czech).

Holásek, O., Adamová, M., Břízová, E., Čáp, P., Dušek, K., Havlíček, P., Hradecká, L., Kadlecová, R., Kolejka, V., Krupička, J., Majer, V., Manda, Š., Nývlt, D., Rajchl, M., Rudolský, J., Stehlík, F., Svobodová, I., Šebesta, J., Táborský, Z., Tyráček, J., Vodrážka, R. (2005): Vysvětlivky k základní geologické mapě České republiky, list 13–131 Brandýs nad Labem – Stará Boleslav. Česká geologická služba, Praha. (in Czech).

Hrubeš, M. (1999): Výzkum kvartéru mezi Lysou nad Labem a Čelákovicemi – předběžné výsledky studia archivních materiálů. Zprávy o geologických výzkumech v roce 1998, 111–114. (in Czech).

Hradecký, J., Brázdil, R. (2016): Climate in the Past and Present in the Czech Lands in the Central European Context. In: T. Pánek, J. Hradecký (Eds.): Landscapes and Landforms of the Czech Republic. World Geomorphological Landscapes. Springer Verlag, 19–28, https://doi.org/10.1007/978-3-319-27537-6_3.

Chlupáč, L. et al. (2002) Geologická minulost České republiky. Academia, Praha. (in Czech).

Kalvoda, J., Balatka, B. (2016): The Geomorphological Evolution and Environmental Hazards of the Prague Area. In: T. Pánek, J. Hradecký (Eds.): Landscapes and Landforms of the Czech Republic. World Geomorphological Landscapes. Springer Verlag, 43–57, https://doi.org/10.1007/978-3-319-27537-6_5.

Knížek, M. (2013): Radiální tektonika barrandienu. Disertační práce. PřF MU v Brně, Brno. (in Czech).

Kovanda, J. et al. (2001): Neživá příroda Prahy a jejího okolí. Academia, Český geologický ústav, Praha. (in Czech).

Kříž, J. et al. (1984): Vysvětlující text k základní geologické mapě 1:25 000 13-133 Úvaly. Ústřední ústav geologický, Praha. (in Czech).

Kukal, Z. (1963): Výsledky sedimentologického výzkumu barrandienského ordoviku. Sborník Geologických Věd – Geologie 1, 103–132. (in Czech)

Loyda, L. (1950): Buližníkové kamýky v Barrandienu. Diplomová práce. PřF UK v Praze, Brandýs nad Labem. (in Czech).

Mackin, J. H. (1948): Concept of the graded river. Geological Society of America Bulletin 59(5), 463–512, https://doi.org/10.1130/0016-7606(1948)59[463:COTGR]2.0.CO;2.

Malkovský, M. (1975): Paleogeography of the Miocene of the Bohemian Massif. Věstník ústředního ústavu geologického 50(1), 27–31.

Matějka, A. (1936): Svrchní křída. In: Čepek, L. et al.: Vysvětlivky ke geologické mapě Československé republiky, list Kladno 3952. Knihovna Státního geologického úřadu Československé republiky 17, 63–70. (in Czech).

Mikisková, I. (2009): Paleokoryto řeky Jizery. Magisterská práce. PřF UK v Praze, Praha. (in Czech).

Novotná, R. (1998): Geomorfologická analýza a vývoj reliéfu opuštěného pleistocenního údolí Jizery v úseku Domousnice – Všejany. Magisterská práce. PřF UK v Praze, Praha. (in Czech).

Pánek, T., Hradecký, J. (Eds., 2016): Landscapes and Landforms of the Czech Republic. World Geomorphological Landscapes, Springer Verlag, https://doi.org/10.1007/978-3-319-27537-6.

Pánek, T., Kapustová, V. (2016): Long-Term Geomorphological History of the Czech Republic. In: T. Pánek, J. Hradecký (Eds.): Landscapes and Landforms of the Czech Republic. World Geomorphological Landscapes. Springer Verlag 29–42, https://doi.org/10.1007/978-3-319-27537-6_4.

Peacock, D. C. P. (2001): The temporal relationship between joints and faults. Journal of Structural Geology 23(1–2), 329–341, https://doi.org/10.1016/S0191-8141(00)00099-7.

Peacock, D. C. P., Nixon, C. W., Rotevatn, A., Sanderson, D. J., Zuluaga, L. F. (2017): Interacting faults. Journal of Structural Geology 97, 1–22, https://doi.org/10.1016/j.jsg.2017.02.008.

Röhlich, P. (1952): Zpráva o biostratigrafickém výzkumu ordoviku mezi Prahou a Brandýsem nad Labem. Zprávy geologického výzkumu v roce 1952, 99–102. (in Czech).

Růžičková, E., Havlíček, P. (1981): Fluviální sedimenty soutokové oblasti Labe a Jizery. Výzkumné práce ústředního ústavu geologického, Praha. (in Czech).

Růžičková, E., Zeman, A. (1994): Paleogeographical developmemnt of the Labe flood plain during the Holocene. In: E. Růžičková, A. Zeman (Eds.): Holocene flood plain of the Labe River. Geological Institute of the Czech Academy of Science, Prague, 104–112.

Svoboda, P. (1996): Facie s Exogyra sigmoidea Reuss a Cidaris sorigneti Desor ve svrchním cenomanu a spodním až středním turonu české křídové pánve. Studie a zprávy Okresního muzea Praha – východ 12, 81–90. (in Czech).

Svoboda, P. (1998): Transgrese svrchní křídy mezi Kralupy nad Vltavou a Korycany. Studie a zprávy Okresního muzea Praha – východ 13, 129–154. (in Czech).

Svoboda, P. (2004): Vznik, vývoj a fauna předbřežních svrchnocenomanských a spodnoturonských sedimentů české křídové pánve a sousedních oblastí. Vliv klimatu, paleogeografie a tektoniky střední Evropy a severní Tethydy. Studie a zprávy Okresního muzea Praha – východ 15, 115–170. (in Czech).

Šmejkal, V., Melková, J. (1969): Notes on some potassium argon dates of magmatic and metamorphic rocks from the Bohemian Massif. Časopis pro Mineralogii a Geologii 14(3–4), 331–338.

Tyráček, J. (2010): Geologie kvartérních fluviálních sedimentů na soutoku Labe s Jizerou. Zprávy o geologických výzkumech 43, 133–138 (in Czech).

Tyráček, J., Havlíček, P. (2009): The fluvial record in the Czech Republic: A review in the context of IGCP 518. Global and Planetary Change 68(4), 311–325, https://doi.org/10.1016/j.gloplacha.2009.03.007.

Tyráček, J., Westaway, R., Bridgland, D. (2004): River terraces of the Vltava and Labe (Elbe), and their implications for the uplift history of the Bohemian Massif. Proceedings of the Geological Association 115(2), 101–124, https://doi.org/10.1016/S0016-7878(04)80022-1.

Uličný, D. (1997): Sedimentation in a reactivated, intra-continental strike slipe fault zone: the Bohemian Cretaceous Basin, Central Europe. Gaea Heidelbergensis 3, 347.

Uličný, D., Špičáková, L., Grygar, R., Svobodová, M., Čech, S., Laurin, J. (2009): Palaeodrainage systems at the basal unconformity of the Bohemian Cretaceous Basin: Roles of inherited fault systems and basement lithology during the onset of basin filling. Bulletin of Geosciences 84(4), 576–610, https://doi.org/10.3140/bull.geosci.1128.

Vaněk, J. (1999): Ordovician in the easternmost part of the Prague Basin (Úvaly and Brandýs areas) and its comparison with Rokycany area (westernmost part of the basin). Palaeontographica Bohemiae 5(2), 5–20.

Vohanka, L. (1966): Vyšehořovicko 1966. Závěrečná zpráva a výpočet zásob žáruvzdorných jílů. MS Česká geologická služba, Geofond. Praha. (in Czech).

Volšan, V., Havlíček, P., Hrkal, Z., Kovanda, J., Lochmann, Z., Pašava, J., Pražák, J., Růžičková, E., Shrbený, O., Straka, J., Šalanský, K., Valečka, J., Vejlupek, M., Vítek, J., Zeman, A., Zoubek, J. (1990): Vysvětlivky k základní geologické mapě ČSSR, list 12-224 Neratovice. Ústřední ústav geologický, Praha. (in Czech).

Wagner, G. A., Gögen, K., Jonckheere, R., Kämpf, H., Wagner, I., Woda, C. (1998): The age of Quaternary volcanoes Železná hůrka and Komorní hůrka (western Eger Rift), Czech Republic: alpha-recoil track, TL, ESR and fission track chronometry. Excursion guide and Abstracts of Workshop, Intern. Geol. Correl. Progr. No 369 “Magmatism and Rift Basin Evolution”, 7.9.–11.9. 1998, Liblice, Czech Geological Survey, 95–96.

ZABAGED® (2014) – výškopis. Praha: ČÚZK, 2014.

Záruba, Q., Bucha, V., Ložek, V. (1977): Significance of the Vltava terrace system for the Quaternary chronostratigraphy. Rozpravy Československé Akademie Věd, Řada matematických a přírodních věd 87(4), 1–89.

Zelenka, P., Adamová, M., Břízová, E., Čáp, P., Čech, S., Dušek, K., Havlíček, P., Holásek, O., Hroch, T., Hradecká, L., Kadlecová, R., Koleka, V., Krupička, J., Mlčoch, B., Prouza, V., Rajchl, M., Rudolský, J., Smolíková, L., Stehlík, F., Táborský, Z., Tyráček, J., Valečka, J. (2006): Vysvětlivky k základní geologické mapě České republiky, list 13-113 Sojovice. Česká geologická služba, Praha. (in Czech).

Žítt, J., Nekovařík, Č. (2001): Nové poznatky o lokalitě Kuchyňka u Brázdimi (česká křídová pánev). Studie a zprávy okresního muzea Praha – východ v Brandýse nad Labem a Staré Boleslavi 14, 250–255. (in Czech).

Žítt, J., Nekvasilová, O. (1991): Kojetice – nová lokalita svrchnokřídových epibiontů přisedlých na buližníkových klastech. Bohemia centralis, 20, 7–27. (in Czech).

Žítt, J., Nekovařík, Č., Hradecká, L., Záruba, B. (1998): Svrchnokřídová sedimentace a tafocenózy na proterozoických elevacích okolí Brandýsa nad Labem, s hlavním důrazem na lokality Kuchyňka u Brázdimi (česká křídová pánev). Studie a zprávy Okresního muzea Praha – východ 13, 189–206. (in Czech).