DISSERTATION

Titel der Dissertation

„River terraces of the Vltava and Malše: implications for late Pleistocene landscape development and the neotectonic history of the Budějovice basin“

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Mag. Dana Tschegg

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	Dr. Kurt Decker

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1. Introduction

1.1. Problem statement

The Budějovice Basin, which overlies Variscan crystalline basement in the Bohemian Massif (Czech Republic), is a fault-bounded sedimentary basin with a multiphase subsidence history. Permian, Cretaceous and Miocene sediments record repeated reactivation of faults at or close to the basin margin and this may have continued into the Quaternary. The latter is indicated by geomorphological features such as linear topographic scarps characterizing segments of the faults within and at the border of the Budějovice Basin.

The NW-SE-striking Hluboká Fault forms the northeastern margin of the Budějovice Basin and delimits the extent of the sedimentary basin-fill above the Variscan crystalline basement. The Vltava River crosses the Budějovice Basin and subsequently the Hluboká Fault as it flows from south to the north and has formed extensive terrace bodies both within the basin and to the north of the fault. Although there is both morphological and geodetic evidence for normal displacement along the Hluboká Fault during the Quaternary (Vyskočil, 1973, 1979), whether the sediments deposited by Vltava River were displaced by the fault has not yet been resolved. This question can be answered by mapping the Quaternary fluvial terraces of the Vltava River on both sides of the Hluboká Fault and correlating the terrace levels using absolute dating.

The scheme used to date river terraces in most European regions that were influenced by the Pleistocene glacial cycles assigns the Vltava River terraces to the 4 or 5 main Alpine glacial periods. This was first documented by Záruba (1942). Such correlations, however, are not straightforward, since the terraces are not connected to moraine bodies as they are in the Alps, allowing them there to be correlated with the glacial cycles (e.g. van Husen, 2000).

The first investigations of the river terraces in the area of the present-day Czech Republic were carried out at the beginning of the 20th century, although the first terrace chronologies for this region were published in the 1960s and 1970s (e.g. Balatka and Sládek, 1962; Šibrava, 1972; Záruba et al., 1977). These mainly used geomorphological characteristics such as the relative elevation of terraces above the water level and longitudinal profiles of rivers.

Most of these studies deal with terrace bodies along the lower course of the Vltava River, where they are much better developed than those on its upper course. The studies from the 1990s (e.g. Balatka, 1992; Přibyl, 1999) also deal almost exclusively with the morphological characteristics of river valleys and only marginally with the lithologies forming the terrace bodies.

The most recent attempts to place the terraces of the Vltava River into a stratigraphic framework were published by Tyráček (2001), Tyráček et al. (2004), Balatka and Kalvoda (2008) and Tyráček and Havlíček (2009). These authors try to correlate terrace formation with the regional uplift of the Bohemian Massif and the global climatic cycle. They also try to match the terrace bodies of the downstream part of the Vltava River with global oxygen isotope stages (OIS) using not only their relative altitude but also mammalian and molluscan biostratigraphy, analyses of overlying loess/palaeosol sequences and correlations with other river terrace systems across Europe. However, no absolute age data are included in these studies.

1.2. Aims of this study

The main foci of this thesis are mapping and absolute dating of the fluvial terrace bodies of the rivers Vltava and Malše in the Budějovice Basin and adjacent areas. For this, a combination of methods is used, including systematic field work, spatial data analysis, quantitative geomorphological indices, borehole data and petrographic analysis of sediments.

Luminescence dating was used to develop a late Pleistocene stratigraphy of the fluvial deposits in the study area. This allows the terraced staircase of the upper course of the Vltava River to be correlated with other Czech and European catchment areas of comparable dimensions.

Sediment analysis, including X-ray diffraction of bulk samples and heavy mineral analysis, were used to distinguish Quaternary from pre-Quaternary sediments as well as sediments of the Vltava River from other Quaternary deposits in the study area.

Further, both the landscape development as well as neotectonic activity in the research area during the late Pleistocene are evaluated and discussed. As the Budějovice Basin is bounded by several important regional faults, such as the Hluboká Fault in the northeast and the Rudolfov Fault in the southeast, with several other faults cross-cutting the area, an important task was to determine whether these faults were active during the Quaternary or not; for this, quantitative geomorphological indices were used as indicators for potential vertical displacements along these faults.

2. Fluvial sequences in general

Fluvial sequences act as valuable archives of Earth´s history, distributed on all continents and across all climatic zones except of polar regions and driest deserts (Westaway et al., 2009). The morphological build up and sedimentological content of river valleys give us valuable information on processes that have lead to their present form. In combination with different dating techniques, we can reconstruct the landscape formation in a particular area over long periods of time.

2.1. Factors forming fluvial sequences: Climate

It is generally accepted that cyclic climatic fluctuations during the Quaternary have had a major impact on the formation of fluvial terraces, but the steering mechanisms of climate of fluvial systems is still under discussion (Vandenberghe, 2003).

In studies from the beginning of the 20th century (e.g. Penck and Brückner, 1909 and Sörgel, 1921), cold periods were connected with phases of fluvial accumulation in braided-river environments whereas during warm phases, meandering rivers incising into sediments accumulated during the cold phase were though to have prevailed.

Several findings such as the discovery of interglacial deposits within cold terrace sediments, the relatively small thickness of river terraces compared to the duration of cold phases, or the fact, that many Holocene rivers show equilibrium between deposition and erosion, reflecting a steady-state instead of only incision, have forced the scientists to re-think older theories. Another fact is, that different river patterns such as meandering, anastomosing or braided co-exist at the same time under the same climatic conditions, and that rivers can change their pattern without an apparent climatic change (Vandenberghe, 2003).

Another important fact is that there is almost never a match between the number of preserved terraces and the number of glacials/interglacials in one fluvial sequence, with the number of terrace levels being usually higher (Bridland and Westaway, 2008a).

A simple assignment of distinct fluvial terraces to the main glacial periods according to their relative elevation above the recent river floodplain as first done by Penck and Brückner (1909) is therefore no longer valid. More realistic appears the theory, that the major downcutting took place during the transition phases from warm to cold and vice versa and that accumulation took place during phases of relative climatic stability, mainly during cold phases (Starkel, 2003).

An important factor affecting the development of a river valley is also the extent of glaciation in the river´s source area. In non-glaciated regions such as the area of present-day Czech Republic (Tyráček and Havlíček, 2009), the sediment supply as well as the transport energy of streams was generally lower than in regions, where the headwaters were extensively glaciated. Extensive terrace systems with large horizontal and vertical extent occur along rivers affected by valley glaciers in mountain areas such as the Danube or Rhine or by the large continental ice sheet in northern Europe such as the river Elbe.

2.2. Factors forming fluvial sequences: Tectonics

In Europe, the Quaternary is regarded as a period of increased tectonic activity in Alpine orogenic systems as well as in reactivated blocks of older orogenic systems. In both areas, the incised river valleys are characterized by the presence of better or worse preserved fluvial terraces of various thickness, some of them being only erosional (Starkel, 2003).

Beside the large-scale Late Cenozoic *regional uplift*, inevitable for the forming of terrace staircases, small-scale *surface deformation* such as faulting, folding and tilting plays an important role by the formation of river valleys as well (Schumm et al., 2002).

2.2.1. Regional uplift

There are many different mechanisms for regional uplift leading to different uplift rates and subsequently to different rates of fluvial incision (Sandiford and Powell, 1990). In Westaway et al. (2009) four main candidate mechanisms are proposed to account for the regional uplift: plate motions, delamination of mantle lithosphere, mantle plumes and the effects of surface processes (isostatic rebound). The role of lower-crustal flow, pointwise versus flexural isostasy and the evidence of uplift in synchrony with global climate change following the Mid-Pliocene climatic optimum are discussed as well.

2.2.2. Preservation patterns of Late Cenozoic fluvial deposits

According to the large data collection of the International Geoscience Programme (IGCP) 449 (Global Correlation of Late Cenozoic Fluvial Deposits) from years 2000 to 2004, three main patterns of fluvial sedimentation and valley evolution over Neogene and Quaternary timescales can be recognised:

1) Extensive *terrace staircases* formed as a result of regional uplift, leading to river incision into existing fluvial sediments deposited under similar condition during different climatic cycles. Hereby, important hiatuses coincide with incision below the base level of the pre-existing deposits (Bridgland and Westaway, 2008a; Bridgland and Westaway, 2008b; Westaway et al., 2009). Terrace staircases dominate the global fluvial archive, being widespread all over the world but the best documented sequences are from Europe such as those of the rivers Thames, Somme, Maas, Allier/Loire, Vltava, Dniester, Don and Volga (see references in Bridgland and Westaway, 2008b).

2) *Stacked fluvial sequences* in superposition with numerous hiatuses found in regions with ongoing subsidence such as sedimentary basins subsiding under their depositional load. Here, fluvial aggradation with no or only minor amounts of river incision has lead to accumulation of sediments over long periods of time (Westaway et al., 2009). This pattern is much less widespread than terrace staircases, found e.g. along the lower Rhine or in the Cilician basin offshore of southern Turkey (see references in Bridgland and Westaway, 2008b).

3) *High-stability pattern* is characterized by sporadic Late Cenozoic deposits preserved at or close to modern valley-floor level and generally corresponds with ancient (Archaean) cratonic crust. In this pattern, the preservation of fluvial deposits is related to river diversion rather than to incision. Examples for such pattern are peninsular India, the Vaal-Orange system in South Africa and along the Lower Volga draining into the Caspian Sea (see references in Bridgland and Westaway, 2008b).

As this is the case in other system occurring in the nature, combined forms within one fluvial system can be found as well (Bridgland and Westaway, 2008a; Bridgland and Westaway, 2008b). Fig. 1 shows the different patterns of fluvial sequences as a response to climate in combination with different rates of regional uplift.

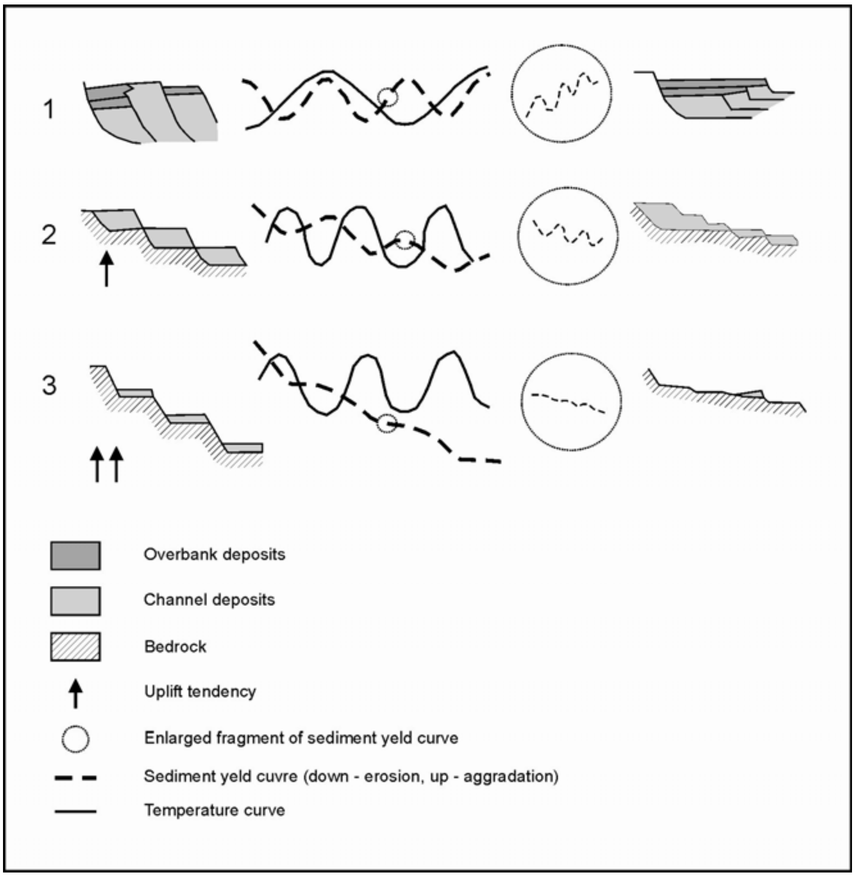

Fig. 1 Fluvial response to Quaternary climatic cycles in uplifting mountain areas; 1) Tectonically stable areas; 2) Areas with slight tectonic uplift; 3) Areas with intense tectonic uplift. Middle column: Overlapping of glacial–interglacial cycles (down=cold, up=warm) and variations between erosion (down) and aggradation (up); Left column: Typical sequences of terraces bodies; Right column: Enlarged fragments of a curve with the second-order rhythmic climatic variations and their reflection in alluvial sequences (Starkel, 2003; modified).

2.2.3. Active tectonics

Active surface deformation such as faulting, folding or tilting (Fig. 2) leads to different rates of uplift/subsidence within one fluvial system, depending on its intensity compared to regional uplift. As a response to active surface deformation, rivers can change their drainage pattern, whereas the most sensitive indicator is the change in valley floor profile and longitudinal profile of a stream. Tectonic activity can also be recognised by variability in the thickness of fluvial deposits along the river profile (Schumm et al., 2002).

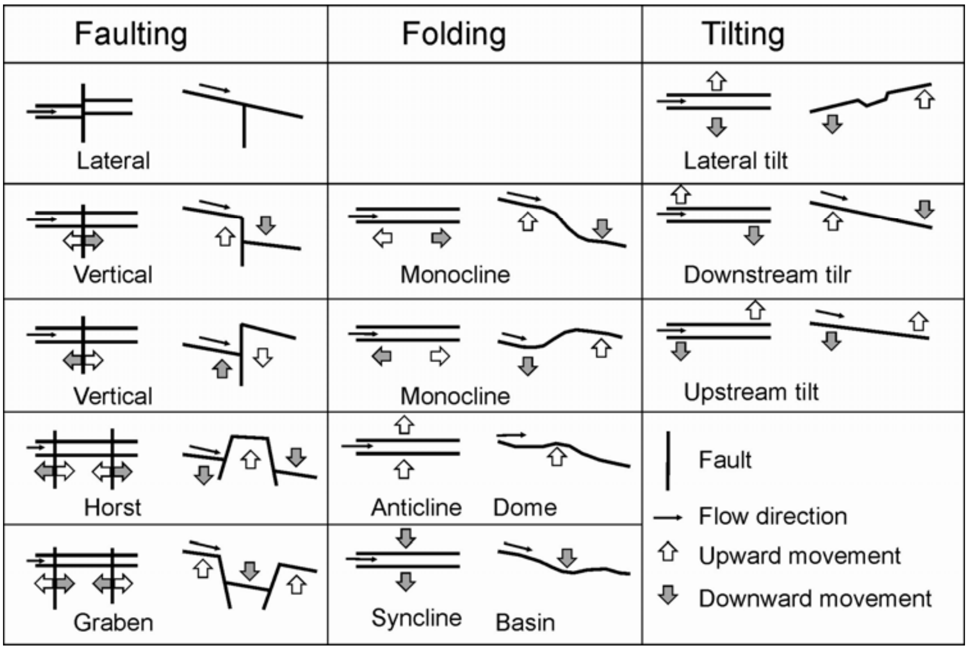

Fig. 2 Surface deformation by faulting, folding and lateral tilting. Left column: plan view; Right column: cross-section. Displacement greatly exaggerated. (from Schumm et al., 2002)

There are several important works dealing with fluvial sequences as evidence for Late Cenozoic landscape and climatic evolution worldwide, discussing both the influence of climatic factors and regional tectonics on the morphological build up of river valleys (e.g. Starkel, 2003; Vandenberghe, 2003; Bridgland and Westaway, 2008a; Bridgland and Westaway, 2008b; Gibbard and Lewin, 2009 or Westaway et al., 2009). The influence of tectonics as well as the question to which extent we can separate the role of climate and tectonics in the forming of river valleys are extensively discussed in the studies of Westaway et al. (2009) and Starkel (2003).

3. Upper Cenozoic fluvial history of the Bohemian Massif

In the Bohemian Massif, two main periods of fluvial development during the Upper Cenozoic are recognized: the Lower Miocene period and the Upper Pliocene-Holocene period, starting after the Gauss/Matuyama paleomagnetic reversal (Tyráček, 2001; Tyráček and Havlíček, 2009). Terrace sequences of the Labe (Elbe) and Vltava systems dominate the fluvial record in Bohemia, allowing the reconstruction of climate and landscape evolution of the area (Tyráček et al., 2004)

3.1. Lower Miocene

The drainage pattern of Miocene rivers was different from that of modern rivers, with southern, south-eastern and eastern parts of the Bohemian Massif draining to the Alpine and Carpathian foredeeps (Central Paratethys), respectively. Streams of the remaining parts of the Bohemian Massif drained into the large fresh-water lakes located in the north-western part of the today´s Czech Republic. The so-called "Bohemian threshold" as part of the main European watershed between the German-Polish Sea and the Central Parathetys Sea was separating these two drainage areas (Fig. 3) (Tyráček, 2001; Tyráček and Havlíček, 2009).

The Lower Miocene period is characterized by up to 100 m thick unterraced gravel bodies deposited under subtropical climate, today preserved only as fragmented spreads on plateaus and interfluves. The deposition is considered to be continuous, although the occurrence of Miocene gravels at different altitudes in Central Bohemia suggests gradual incision of the streams. The deposits consist of mature well-sorted quartz, quartzite and varicoloured lydite (Proterozoic metamorphic rock found in the Bohemian Massif) gravel, which allow an easy distinction from younger gravel deposits in overlapping areas (Tyráček, 2001; Tyráček and Havlíček, 2009).

In the area of the present day Budějovice and Třeboň basins, Middle Miocene sediments of the Mydlovary Formation were deposited in fluvial and fluvio-lacustrine environments, depending on the relative elevation of the region to Paratethys (Řeháková, 1963; Kvaček and Teodoridis, 2007).

Sandy and gravely fluvial strata of the St. Marein-Freischling Formation in the SE Bohemian Massif of Lower Austria represent Oligocene to Lower Miocene fluvial sediments deposited in a braided channel system (Nehyba and Roetzel, 2010). The fluvial system is described as a network of relatively shallow streams with seasonal fluctuations in discharge.

A general transport from west to east is supposed for the main fluvial system, which finally turned to the south in the surroundings of Horn. Provenance analyses of sediments allow identifying the South Bohemian Batolith and the Moldanubian zone as their source rocks.

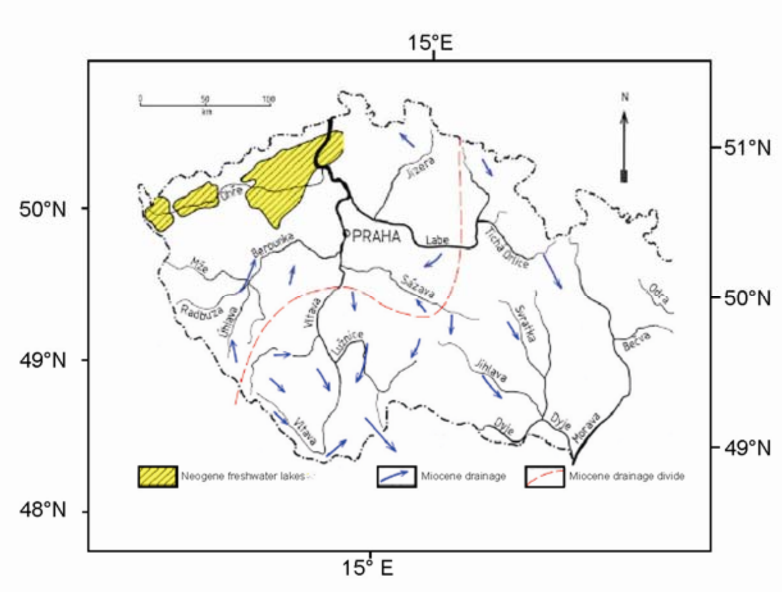

Fig. 3 Modern river network of the Bohemian Massif compared with the reconstructed Miocene flow pattern. At this time, upper reaches of the rivers Vltava and Labe drained into the Paratethys Basin in southeastern direction (from Tyráček and Havlíček, 2009).

During the more than 10 million years long break in deposition, Miocene sediments were incorporated into the "Bohemian peneplain", which can be regarded as the starting level for the modern drainage pattern (Tyráček and Havlíček, 2009).

The present day drainage pattern was probably first formed in the Pliocene, when tectonic uplift of the southwestern parts of the Bohemiam Massif forced the streams to drain to the north. Until then, the uppermost reaches of the Vltava River drained to the south (Balatka and Sládek, 1962). Recent uplift of the Vltava River headwater region is also indicated by the river long section showing a convex-up profile along its upper reach (Fig. 6).

3.2. Late Pliocene-Holocene

The onset of the next phase of fluvial deposition in the Bohemian Massif corresponds to the start of cyclic alternation of glacials and interglacials typical for the Quaternary. The incision of the newly formed river network into the old peneplain probably started already in the Late Pliocene, which is considered as the time when these cyclic fluctuations have started (Tyráček and Havlíček, 2009).

This period is characterised by alternating phases of fluvial erosion and deposition resulting from the climatic cyclicity that, in combination with the regional uplift, resulted in the formation of terrace staircases. Thanks to the fact, that the inner part of the Bohemian Massif was never glaciated, even the oldest deposits and relief forms remained preserved (Tyráček, 2001). The oldest terrace deposits are situated more than 100 m above the modern floodplains, indicating the approximate depth of local fluvial erosion in the Quaternary (Balatka and Kalvoda, 2008).

3.3. Morphostratigraphy of Late Pliocene-Holocene terraces

Since the Late Pliocene, three phases of valley formation in the Bohemian Massif can be recognised based on the relative position of terraces above the recent floodplain (Tyráček, 2001; Tyráček and Havlíček, 2009) (Fig. 4). A similar scheme with modifications resulting from regional differences can be applied to terrace sequences all over the world (Gibbard and Lewin, 2009):

1) Pliocene to Early Pleistocene (high-terrace groups)
2) Middle Pleistocene (middle-terrace groups)
3) Late Pleistocene (low-terrace groups).

3.3.1. Pliocene to Early Pleistocene

During this phase, the formation of the modern drainage pattern and the terracing of fluvial sediments were initiated. *High-terrace groups* were formed in a braided-river environment by streams flowing freely upon the old peneplain in wide, shallow valleys (Tyráček, 2001; Balatka and Kalvoda, 2008).

3.3.2. Middle Pleistocene

The relicts of *middle-terrace groups* occur within the river valleys at different altitudes at the slopes of river banks being usually of smaller vertical extent, but thicker than the high terraces (Tyráček and Havlíček, 2009). The onset of this phase is connected with an acceleration of river downcutting and increased rates of regional uplift in post-Archaean crust in every continent except of Antarctica since ~ 0.9 Ma. This change is documented in fluvial sequences worldwide, being not only a European phenomenon (Westaway et al., 2009). The mechanism of this change is not yet completely understood but it is usually explained as a shift from the 40 ka cycles (Laplace period) with relatively mild glacials to the 100 ka cycles (Milankovic period) characterized by drastic climate changes - also called the "Mid-Pleistocene Revolution" - close to the Matuyama/Brunhes paleomagnetic reversal (Fig. 4). This change, connected with increased erosion rates, is considered to be responsible for the increase of uplift rates and provides a linkage between Quaternary climate and landscape evolution (Bridgland and Westaway, 2008a; Tyráček and Havlíček, 2009).

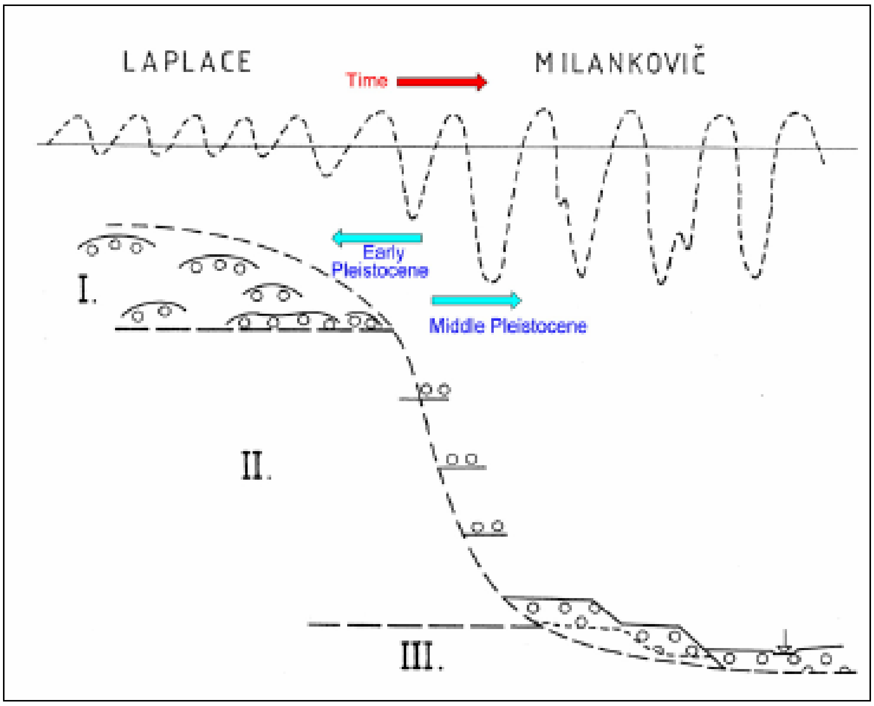

Fig. 4 Schematic profile across a typical upland river valley in the Bohemian Massif with the morphostratigraphic position of I) High (Pliocene - Lower Pleistocene), II) Middle (Middle Pleistocene) and III) Low (Lower Pleistocene) terrace groups (from Tyráček and Havlíček, 2009). Morphologically, the most pronounced switch is the change from Laplace- to Milankovic cycles at the beginning of Middle Pleistocene.

3.3.3. Late Pleistocene to Holocene

The *low-terrace group*, usually assigned to the late Pleistocene and Holocene, is developed in close vertical distance to present-day river floodplains, comprising two or three gravel aggradations separated by several phases of river incision (Tyráček, 2001).

Such a pattern can be also observed along the course of the rivers Vltava and Malše in the Budějovice basin.

4. Vltava River

The Vltava River forms the biggest fluvial system in the Bohemian Massif with a length of ca. 377 km and a catchment area occupying more than 27,000 km^2 on Czech territory (Linhartová and Zbořil, 2006). It is a right-hand tributary of the river Labe, which flows to the North Sea. The river is formed at the confluence of Studená Vltava and Teplá Vltava in the Šumava (Bohemain Forest) mountains south of Volary at an elevation of ca. 715 m asl. Its biggest tributary is the river Sázava with a length of ca. 226 km (Fig. 5).

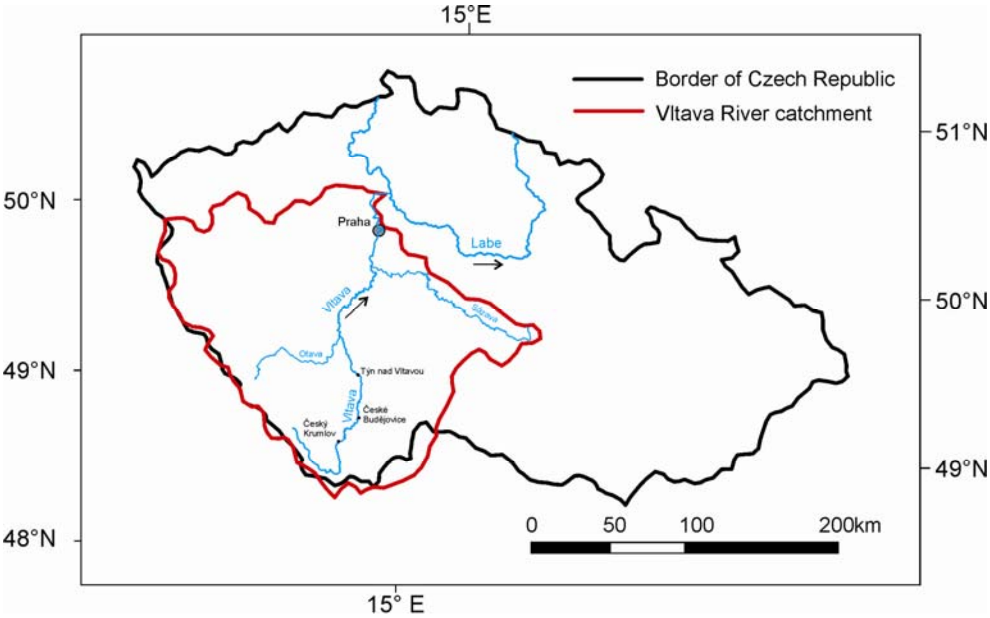

Fig. 5 Catchment borders of Czech rivers, highlighting the catchment area of the Vltava River (from Linhartová and Zbořil, 2006)

4.1. Previous studies about Vltava terrace sequences

A detailed overview of the literature dealing with the mapping of Vltava terraces along the whole river course is given in Balatka and Sládek (1962) and in Tyráček (2001). Therefore in this section, only the most relevant studies are mentioned.

Longitudinally, the Vltava terrace sequence can be subdivided into two parts: the upper reach and the lower reach, whereas the dividing point varies. In the study of Balatka and Sládek (1962), the upper reach is considered from the source to the confluence with Otava and the lower reach down to the confluence with Labe. Záruba (1977) describes in detail the terraces section downstream of Týn nad Vltavou, where the terraces are horizontally and vertically much better developed than the terraces along the upper course. In more recent studies (Tyráček et al., 2004; Balatka and Kalvoda, 2008), authors also deal mainly with the terraces along the lower course downstream of Týn nad Vltavou.

Terrace sequences along the upper course gained much less attention and the authors focused in their studies mainly on their morphology. Chábera and Novák (1975) describe the section between Český Krumlov and the Budějovice basin, where the Vltava River flows through a deep narrow valley in the crystalline and the terraces are preserved only as small remnants on the steep slopes. The morphology and some other characteristics such as gravel petrography of Vltava River terraces in the Budějovice basin are described in the study of Chábera (1965). The terrace sequence further downstream between the basin and Týn nad Vltavou (confluence with Lužnice), which is morphologically similar to that upstream of the basin, is described in the study by Chábera and Novák (1976). These studies accord in complaining about the difficulties connected with mapping of Vltava terraces in this area due to their small horizontal and vertical extent. Table 1 gives an overview of terrace levels mapped in the studies mentioned above.

Interesting is the higher number of terrace levels between Hluboká nad Vltavou and Týn nad Vltavou mapped in the study by Chábera and Novák (1976).

Section	**Český Krumlov - Budějovice basin**		**Confluence Vltava-Malše**		**Hluboká n. Vltavou - Týn n. Vltavou**	
Author(s)/year	*Chábera, S. & Novák, V. (1975)*		*Chábera, S. (1965)*		*Chábera, S. & Novák, V. (1976)*	
“Donau”	I.	46-60	I.	48-55	I.	47-53
“Günz”	II.	34 - 44	II.	33-41	II.	33-39
“Mindel”	III.	16-20	III.	T: 20 B: 15	III.	T: 29 B: 17
					IV.	T: 21 B:10
“Riss”	IV.	T: 6-10 B: 1	IV.	T: 6 B: 2	Va.	T: 14 B: 8
					Vb.	T: 10 B: 3
					VI.	T: 4 B: -1
“Würm”	V.	T: 2 B: -2	V.	T: 2 B: -3	VII.	T: 2 B: -1

Tab. 1 Comparison of Vltava River terraces along the upper course, mapped by different authors. Numbers mark the relative elevation of terraces above Vltava water level in meters. T – maximum elevation of terrace top, B – minimum elevation of terrace base.

In all mentioned studies, morphological characteristics such as longitudinal profiles and cross sections of the river valley, dip of the river valley, relative elevation of morphological terraces above water level was used. Morphological mapping was partly supported by sedimentological characteristics of the fluvial deposits, mostly by petrography of fluvial gravel.

Absolute dating of fluvial sediments was not used in any of the mentioned studies, neither in the detailed works about terraces along the lower course, nor in those dealing with the upper course.

4.2. Stream gradient along the Vltava River upper course

Along its upper course, the Vltava River flows in a deep narrow valley carved in metamorphic and magmatic rocks of the Moldanubian crystalline. Exceptions are the ca. 20-km-long section in the Budějovice basin filled with sediments of Cretaceous to Quaternary age and a section at the uppermost reach, where it flows through a tectonic depression of the Vltavice graben.

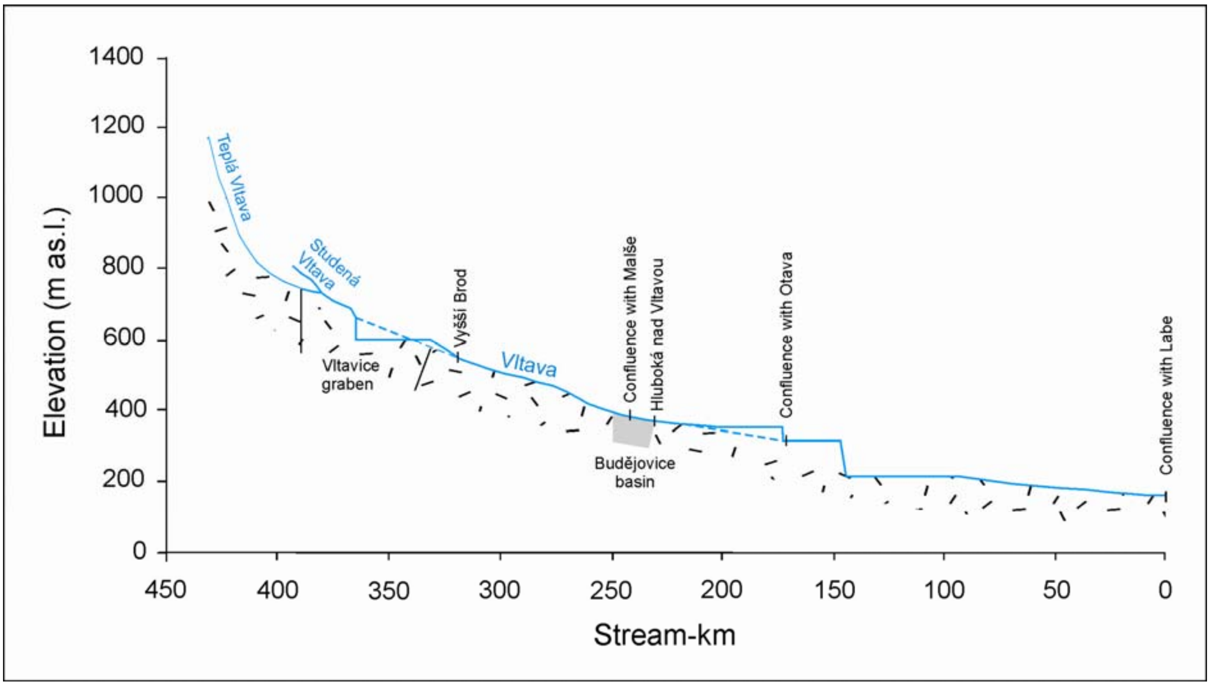

Fig. 6 Simplified longitudinal profile of the Vltava River from source down to the confluence with Labe with smoothing of the anthropogenic overprint by dams (after Linhartová and Zbořil, 2006; modified).

The stream gradient of the river changes throughout its upper course remarkably. Near the source of Teplá Vltava, the gradient is ca 26 ‰, decreasing to ca. 5 ‰ at the confluence with Studená Vltava (Fig. 6). Further downstream in the Vltavice graben, the gradient is surprisingly low, reaching only 0.4 ‰ until the dam in Lipno (stream-km ca. 330). The Vltavice furrov is probably a rest of an old depression from times, when the uppermost reaches of the Vltava River drained to the south and the 2.5-km-short section downstream the dam in Lipno with a gradient of 27 ‰ represents the old watershed. As a result of backward erosion and the Pliocene tectonic uplift of blocks south of the today´s Vltava River course, the uppermost reaches were connected to the rest of the present-day river.

Between Vyšší Brod (stream-km ca. 320) and the southern border of Budějovice basin, where the river incises in the crystalline bedrock of the Bohemian Massif, the mean stream gradient is 2.2 ‰. In the Budějovice basin (between Boršov nad Vltavou and the confluence with Malše at stream-km ca. 240), the stream gradient is smaller, reaching only 1.6 ‰. After leaving the Budějovice basin north of Hluboká nad Vltavou (stream-km 229) until the confluence with Otava, the river flows in a narrow valley again, which is deeply incised in the crystalline basement. Interestingly, the mean stream gradient of this section is remarkably small with only 1 ‰ (Balatka and Sládek, 1962).

Since the focus of this thesis is on the upper reach of the river, a detailed description of lower reaches will be omitted.

4.3. Vltava tributary in the Budějovice basin: Malše

The 91.7 km long river Malše is a right-hand tributary of the river Vltava with a source in Austria. After a 5.2 km long section through the Austrian territory, the river flows 19.7 km along the border between Austria and Czech Republic and then 66.8 km in the Czech territory until the confluence with Vltava in the Budějovice basin.

The terrace sequence of the river Malše is described in the study by Novák (1990), who recognises five terrace levels and assigned them to the main glacials Würm (V. level - valley floor terrace), Riss (IV. level - lower terrace), Mindel (III. level), Günz (II. level) and Donau (I. level).

5. Methods

5.1. Mapping of fluvial terraces in the study area

In previous studies (Chábera, 1965; Chábera and Novák, 1976), fluvial terraces in Budějovice basin and adjacent areas north of the Hluboká fault were assigned to the main glacial periods Würm, Riss, Mindel, Günz and Donau according to their relative elevation above the Vltava water level. These data as well as data from the Geological map 1:25 000 (Základní Geologická Mapa ČSSR 1:25.000, 1982) (Fig. 7) needed to be revised.

Methods used for mapping the Pleistocene fluvial terraces of the rivers Vltava and Malše in this thesis include the geomorphologic analysis of a high-resolution digital elevation model (DEM), interpretation of borehole data and mapping of outcrops.

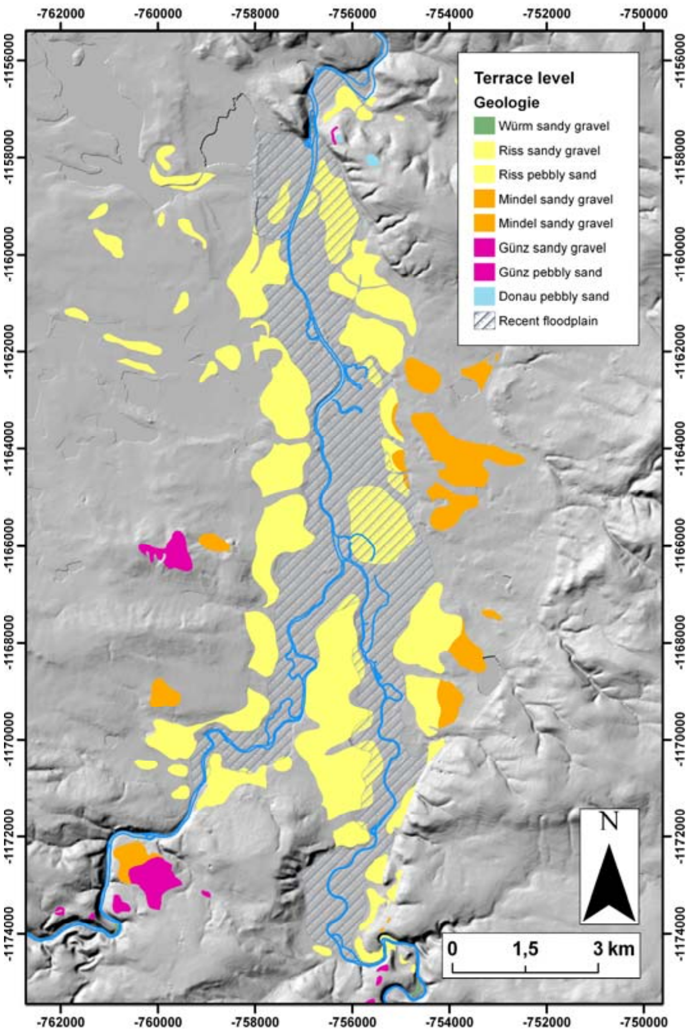

Fig. 7 Terrace levels assigned to the main glacial periods Würm, Riss, Mindel, Günz and Donau according to the Geological map of the Czech Republic 1:25.000 (Základní Geologická Mapa ČSSR 1:25.000, 1982)

5.1.1. High-resolution DEM

For detailed geomorphologic analyses, a high-resolution digital elevation model (DEM) was inevitable. This was constructed from digital contour lines, geodetic points and lines representing the river banks and lakes (Fig. 8). The geodetic points and the river banks were digitized from the Czech topographic map 1:10.000. The digital contour lines with a contour interval of 2 meters were produced by the Czech Office for Surveying, Mapping and Cadastre (COSMC) by digitizing the topographic map 1:10 000. At the moment they provide the most precise elevation information for this area.

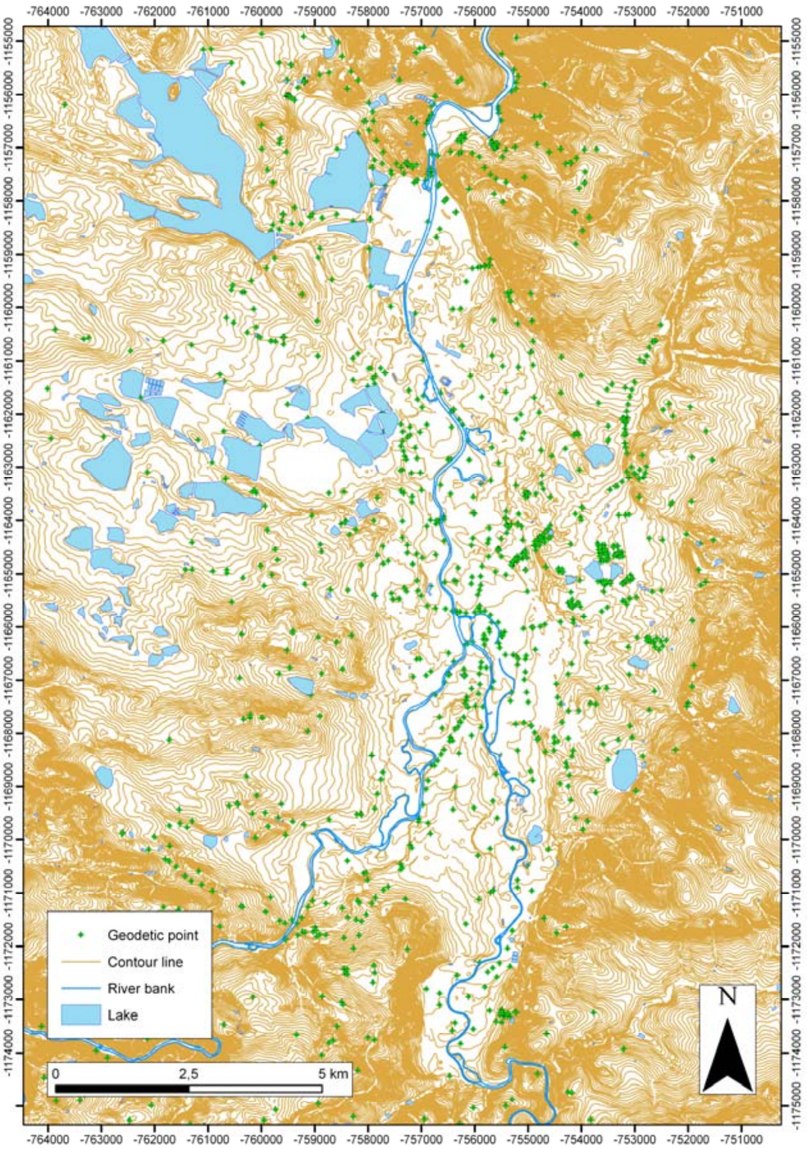

Fig. 8 Data used for the interpolation of the higher resolution DEM: Digital contour lines, geodetic points, river banks and lakes.

To build a proper DEM, the digital contour lines had to be revised, manually adjusted and completed. After these corrections a 10 m-resolution raster was build with the 3D Analyst Toolbox in ArcMap. In this way a DEM we produced, which provides the most precise information on the topography available for the region (Fig. 9). Comparison of the new dataset with the previously used 30 m DEM shows the very significant differences between these two models (Fig. 10).

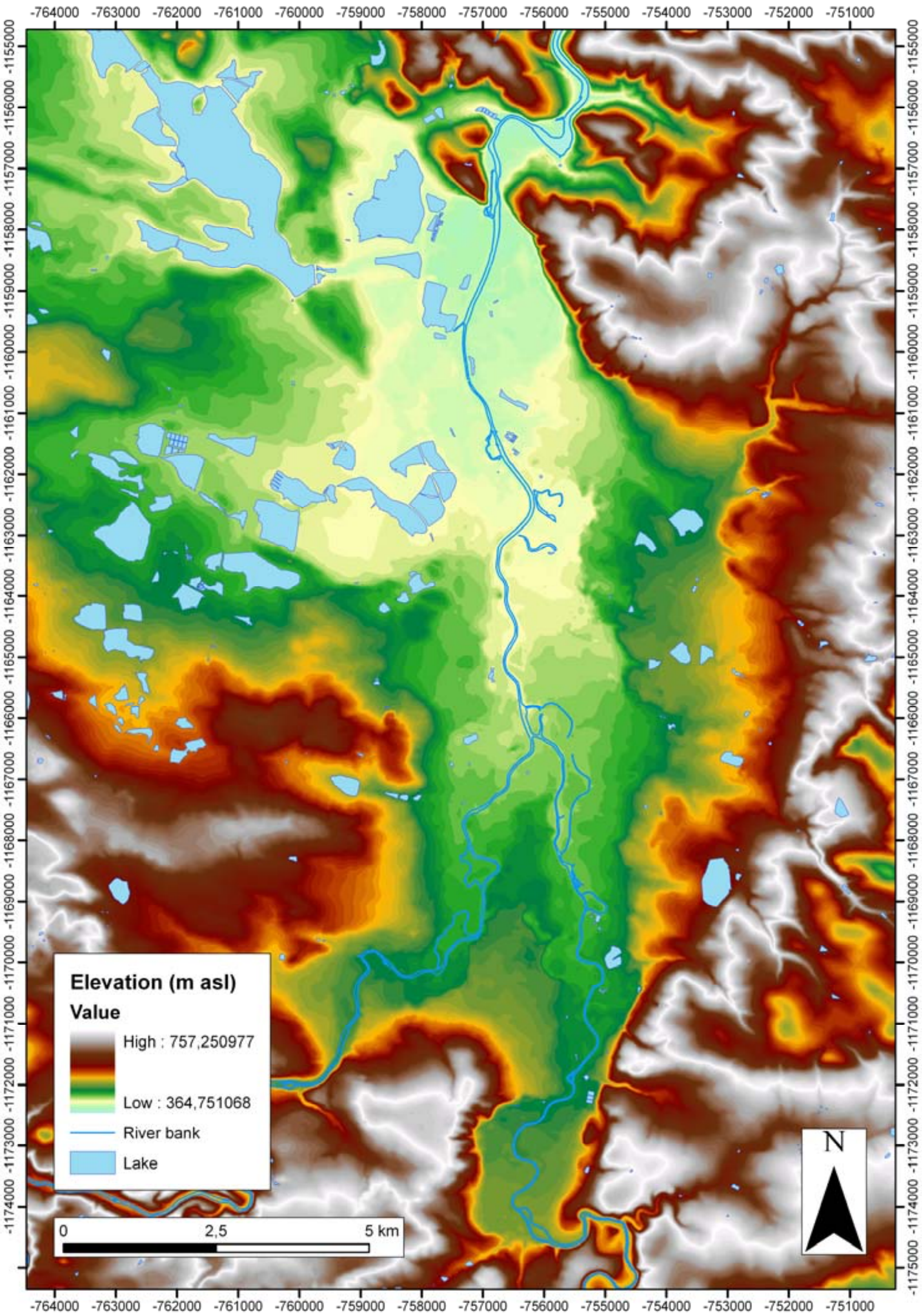

Fig. 9 Digital elevation model (DEM) of the Budějovice basin with 10 m grid resolution.

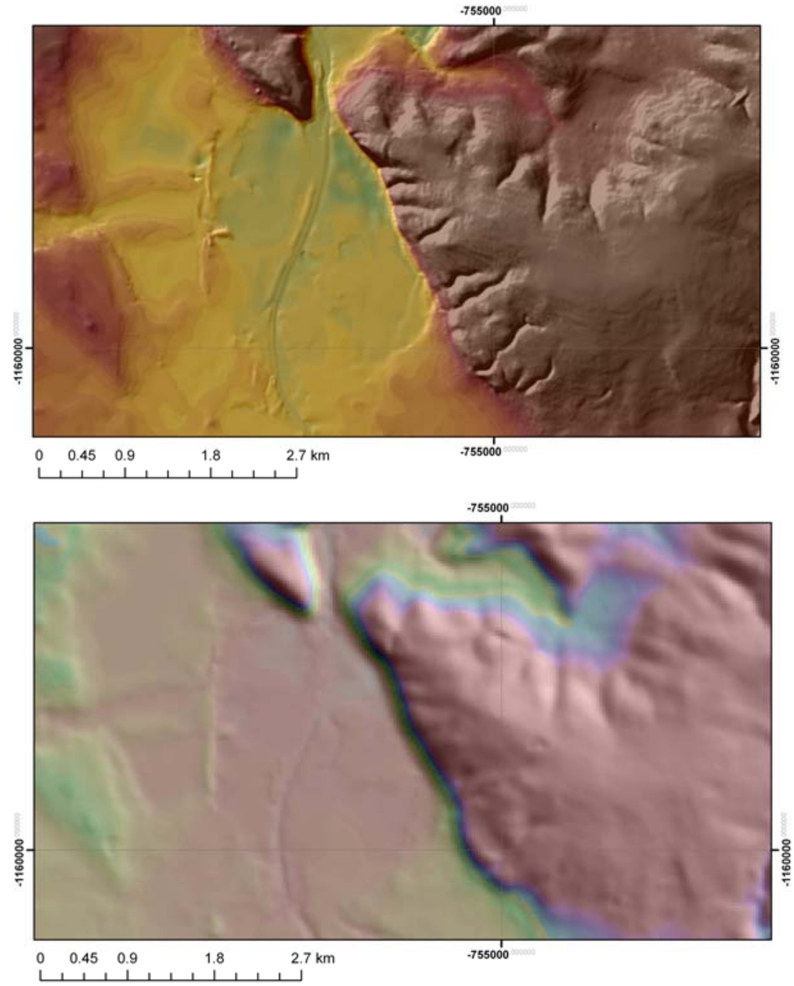

Fig. 10 Comparison of a 10-m-resolution DEM and a 30-m-resolution DEM.

5.1.2. Geomorphologic analysis

Morphological terraces were identified by field mapping supported by the high-resolution DEM and derivates computed from the DEM such as hillshade and slope values using two classes with slope values < 3° and > 3°. The resulting map highlights flat surfaces which may correspond to fluvial terraces as well as slopes, which partly correspond to terrace risers (Fig. 11).

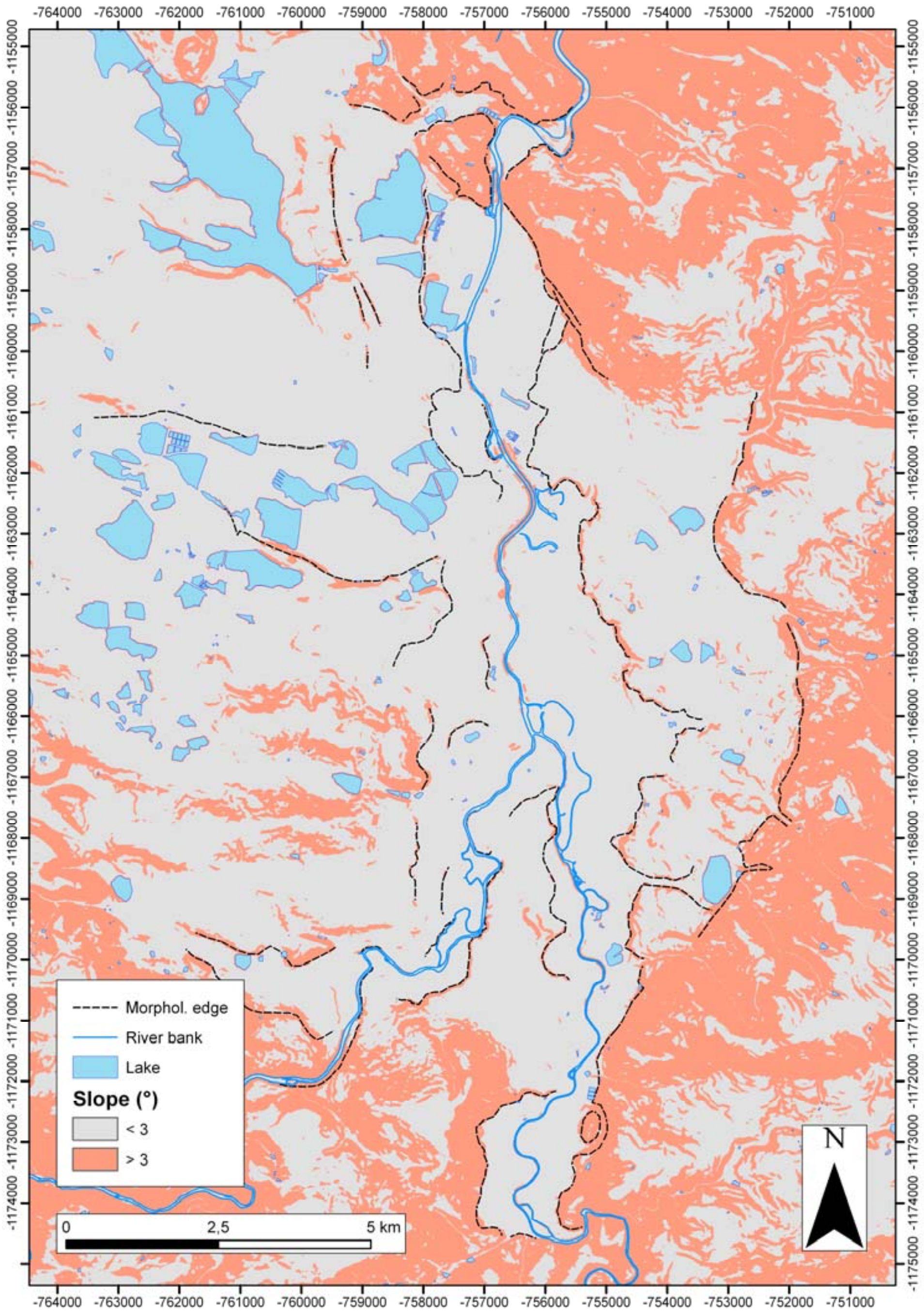

Fig. 11 Topographic slope computed from a high resolution DEM and morphological edges interpreted from these data used to identify terraces with flat surface topography and separating terrace risers. See text for explanation.

Additionally, georeferenced historic map sheets of the Austrian Second Military Survey (Timár et al., 2006) were used to obtain information about the geomorphologic situation in the study area of the years 1836-1842, primarily about the former courses of the rivers Vltava and Malše prior to their regulation (Fig. 12). The georeferenced map sheets of the First and Second Military Survey provide a very exact base map for investigating geomorphological features in a landscape with little anthropogenic changes. This was particularly valuable for studying river courses, morphological scarps and the location of morphological terraces. Since the georeferencing accuracy is < 10 m, data from these map sheets can be integrated into the geomorphologic studies providing information about the geomorphologic situation in the study area from times with less anthropogenic impact on geomorphological features than today.

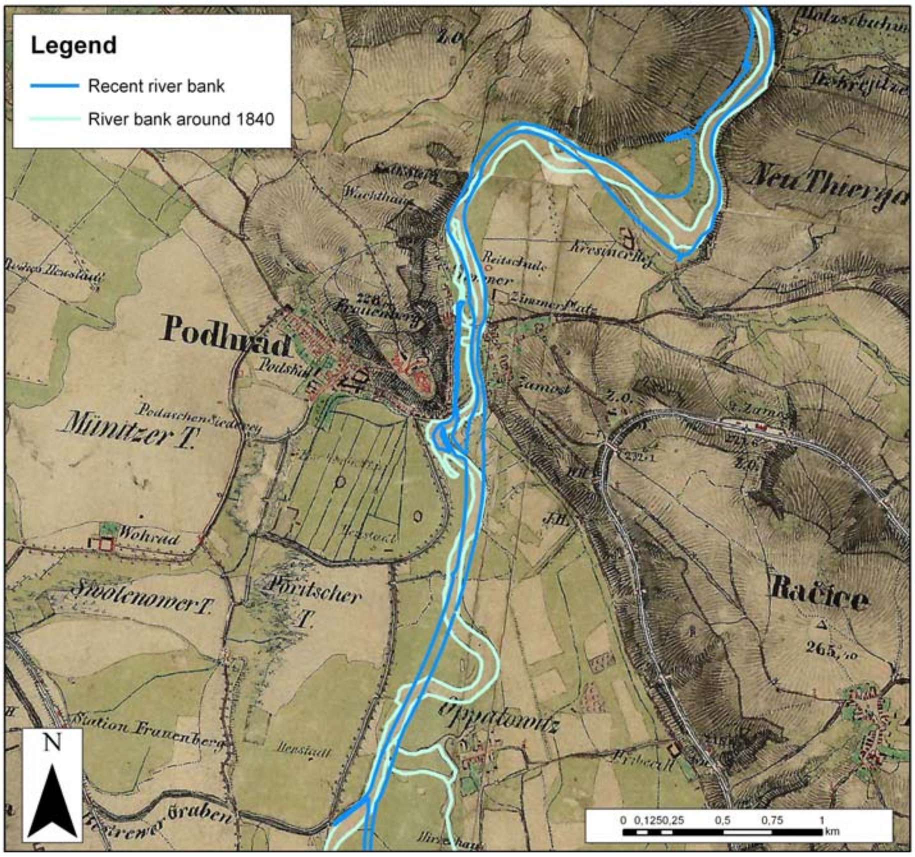

Fig. 12 Historical map of the Austrian 2nd Military Survey of the Habsburg Empire showing the historical course of the un-dammed Vltava River in the 1840s. The ancient course of the river is compared to the recent river bank.

5.1.3. Interpretation of borehole data

In a GIS-project, data from the DEM were combined with data from boreholes to model the horizontal and vertical extent of fluvial terraces in the study area.

Since the morphology of the study area was substantially modified by periglacial cryoturbation, soli- and gelifluction, fluvial terraces above the recent floodplain do not appear as distinct features with horizontal surfaces and steep risers, but as slopes gently tilted towards the modern river (see Fig. 9). The identification of separate terrace levels was therefore possible only by the definition of the terrace base from drilling profiles.

More than 1000 drilling profiles were collected from the archive of the Czech Geological Survey (Geofond) and additionally, 41 drillings were conducted in course of the field survey to reveal the thickness of the Quaternary sediment cover and to collect samples.

By analyzing lithological profiles from borehole data, sandy gravel was identified as the marker lithology characteristic for fluvial terraces. Since fine-grained Pleistocene fluvial sediments in the study area could not be distinguished from Miocene and Cretaceous ones only by looking at the profile descriptions from the archive, fluvial coarse gravel was regarded as the only sediments type of clearly fluvial origin. The base of a fluvial terrace in a particular area was then derived from the base of fluvial gravel in drillings.

5.1.4. Calculating the relative elevation of terrace base

5.1.4.1. Vltava longitudinal profile

The longitudinal profile of the mean water level of the recent Vltava River and its thalweg has been constructed as a base for terrace mapping and further geomorphological analyses. Two datasets were used for constructing a longitudinal profile of the Vltava River across the study area: a relatively new dataset comprising 230 individual cross section of the river bed obtained between river-km 226 and 250 from the Vltava waterways Management (Povodí Vltavy - http://www.pvl.cz/en; personal data acquisition) (Dataset 1) and one dataset including data on the mean water level and the elevation of the river bed from the year 1973 between river-km 200 and 320 (Dataset 2).

Both dataset have their advantages and disadvantages.

Dataset 1 includes very detailed information about the shape of the river bed in the form of cross sections with a mean length of about 100 m. The spacing of the cross sections along the river is about 300 m, but only data for the reach between stream-km 226 and 250 were available (Fig. 13). Along the cross sections, the elevation of up to 20 points is given to get precise information about the shape of the river bed, including the elevation of the water level. For each point, X/Y-coordinates and the elevation are given. From each cross section, the point with the lowest elevation was taken as the elevation of the river bed. Data from these cross-section had to be digitized into the geographic reference frame.

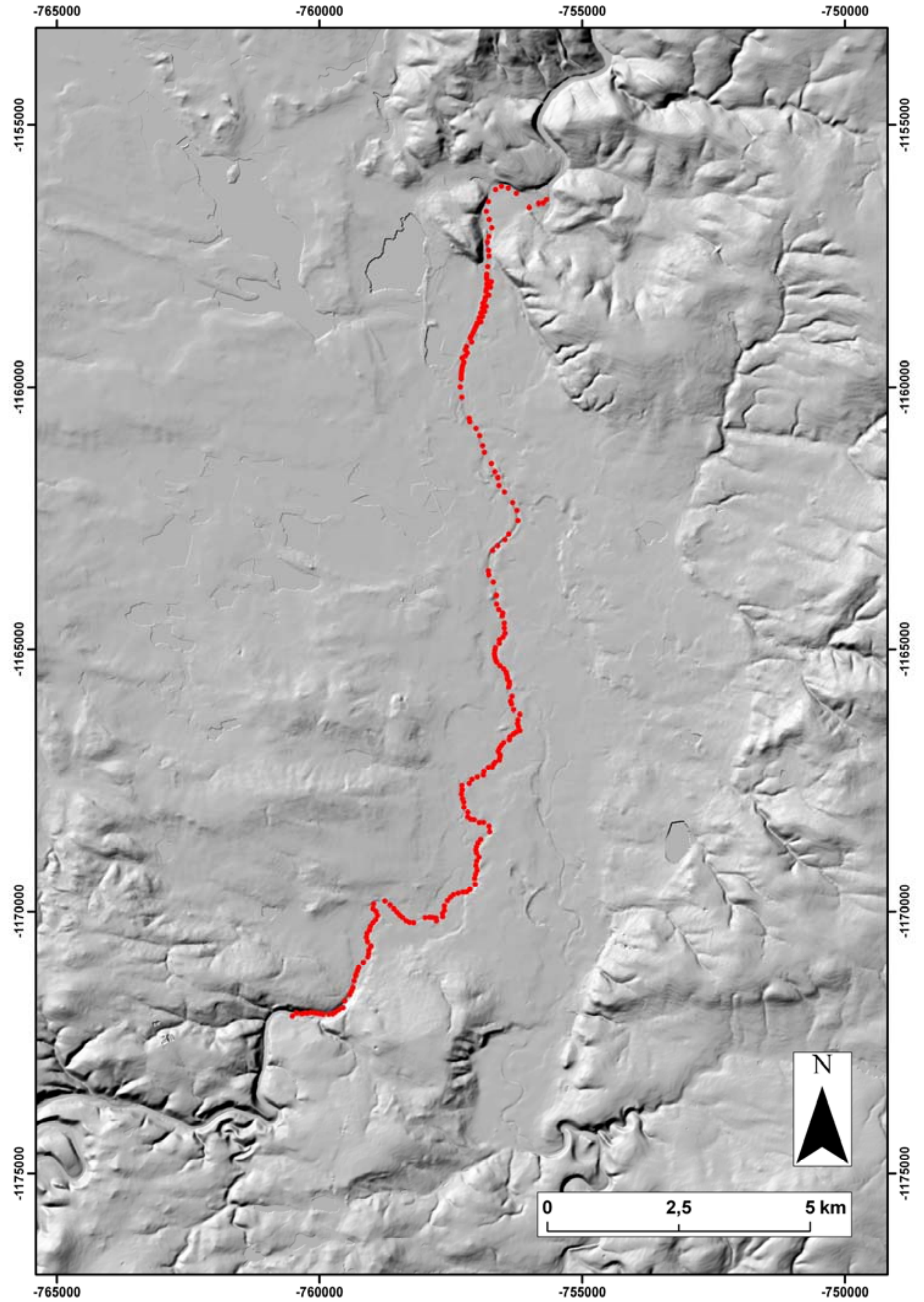

Fig. 13 Location of the longitudinal section along the Vltava River in the Budějovice basin showing the high density of datapoints in Dataset 1.

Although the resulting longitudinal profile is very precise, it cannot be used for further interpretations as the original stream gradient as well as the river bed are strongly altered by dams that have been constructed after about 1930 (Fig. 14). For further use, the longitudinal river profile would have to be drastically smoothed to a curve omitting these anthropogenic structures.

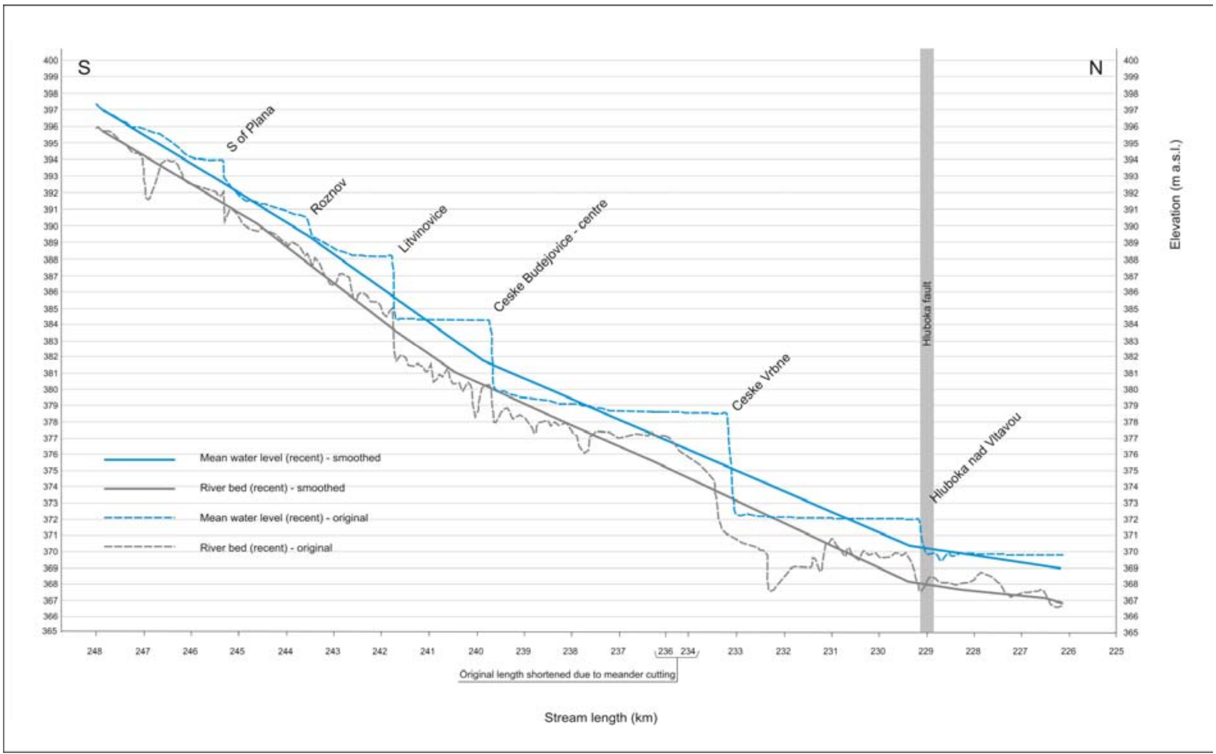

Fig. 14 Longitudinal section along the Vltava River in the Budějovice basin using the Dataset 1 (Vltava Waterways Management; http://www.pvl.cz/en; Data obtained 2010). Note the strong anthropogenic influence on the river thalweg by dams build along the river.

The *Dataset 2* from 1973 shows a quite low density of data points along the course of the river (reaching distances of up to 2 km), but includes a larger section of the river (Fig. 15). The information for each point in this dataset is reduced to the elevation of the water level (not every point) and that of the river bed but in spite of that, this dataset turned out to be better applicable for further analyses. There are some small steps in the longitudinal profile of the river caused by major dams, but the anthropogenic imprint is not so distinctive (Fig. 16).

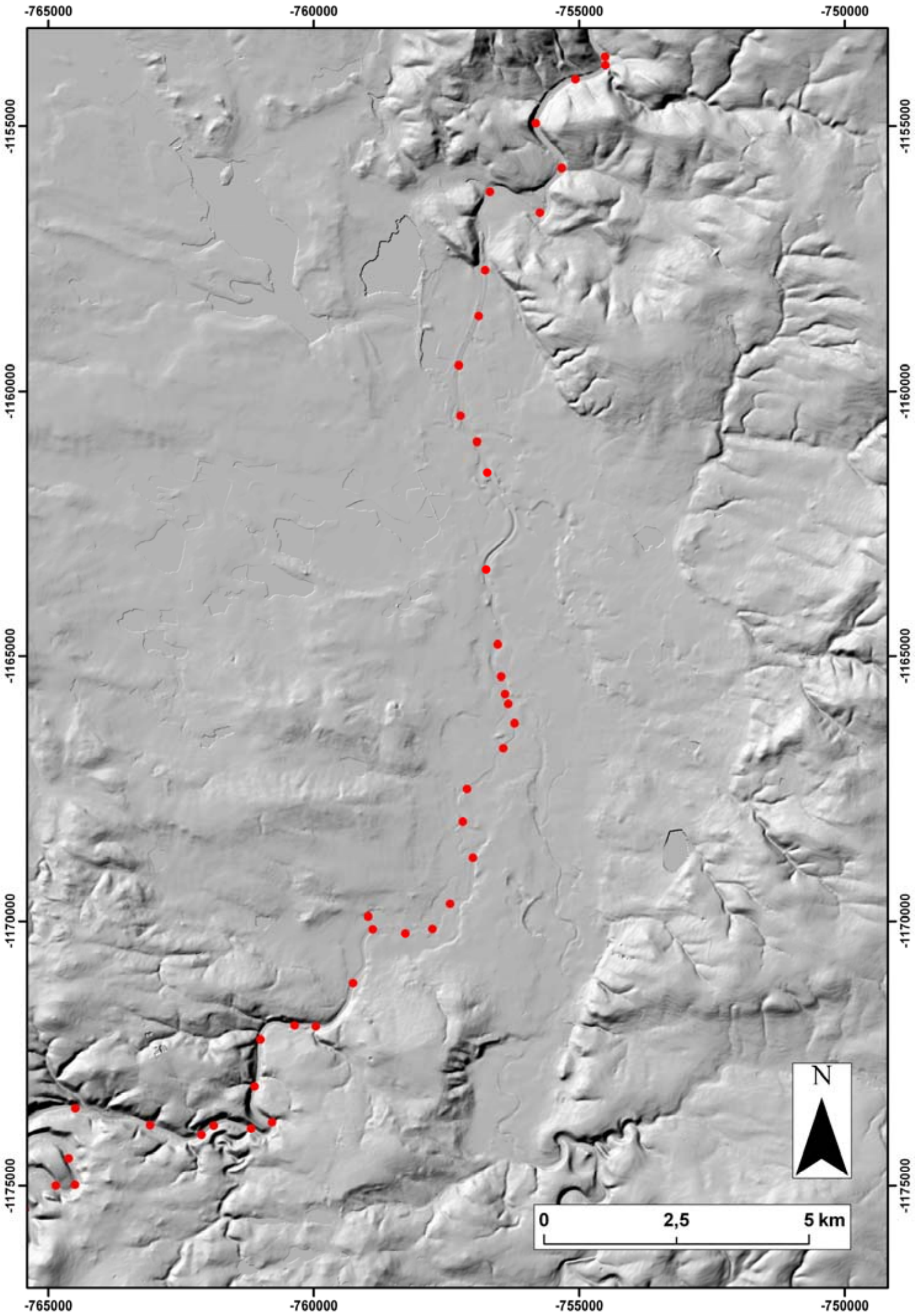

Fig. 15 Location of the longitudinal section along the Vltava River in the Budějovice basin showing the lower density of datapoints in Dataset 2.

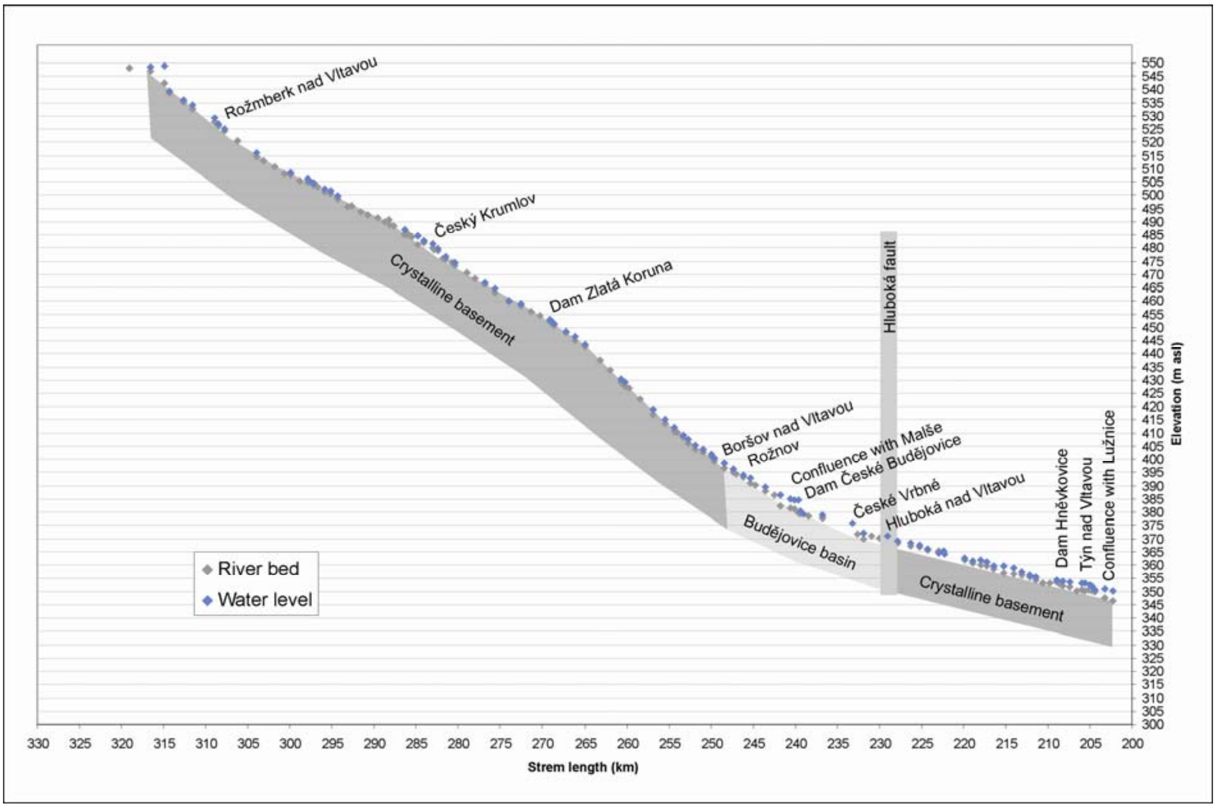

Fig. 16 Longitudinal profile of the Vltava River between stream-km 200 and 330 based on the Dataset 2. Note the low anthropogenic influence compared to Dataset 1. The lower stream gradient in the Budějovice basin and the reaches downstream of the Hluboká fault compared to the reaches upstream of the basin can be observed as well.

5.1.4.2. Calculating a surface representing the Vltava water level

In the next step, a surface representing the Vltava water level was modelled and used for calculating the relative elevation of gravel base. After smoothing the small steps in the longitudinal profile of the Vltava River, the elevation of the water level was assigned to data points along the river in an ArcGIS project. After this step, lines were drawn perpendicular to the river profile, attributed with the water level at the crossing point (Fig. 17). From these lines, a triangulated irregular network (TIN) was created, which afterwards was converted to a raster dataset (Fig. 18).

This surface, representing the Vltava water level as a polygon, was used for calculating the relative elevation of the gravel base above the recent Vltava water level.

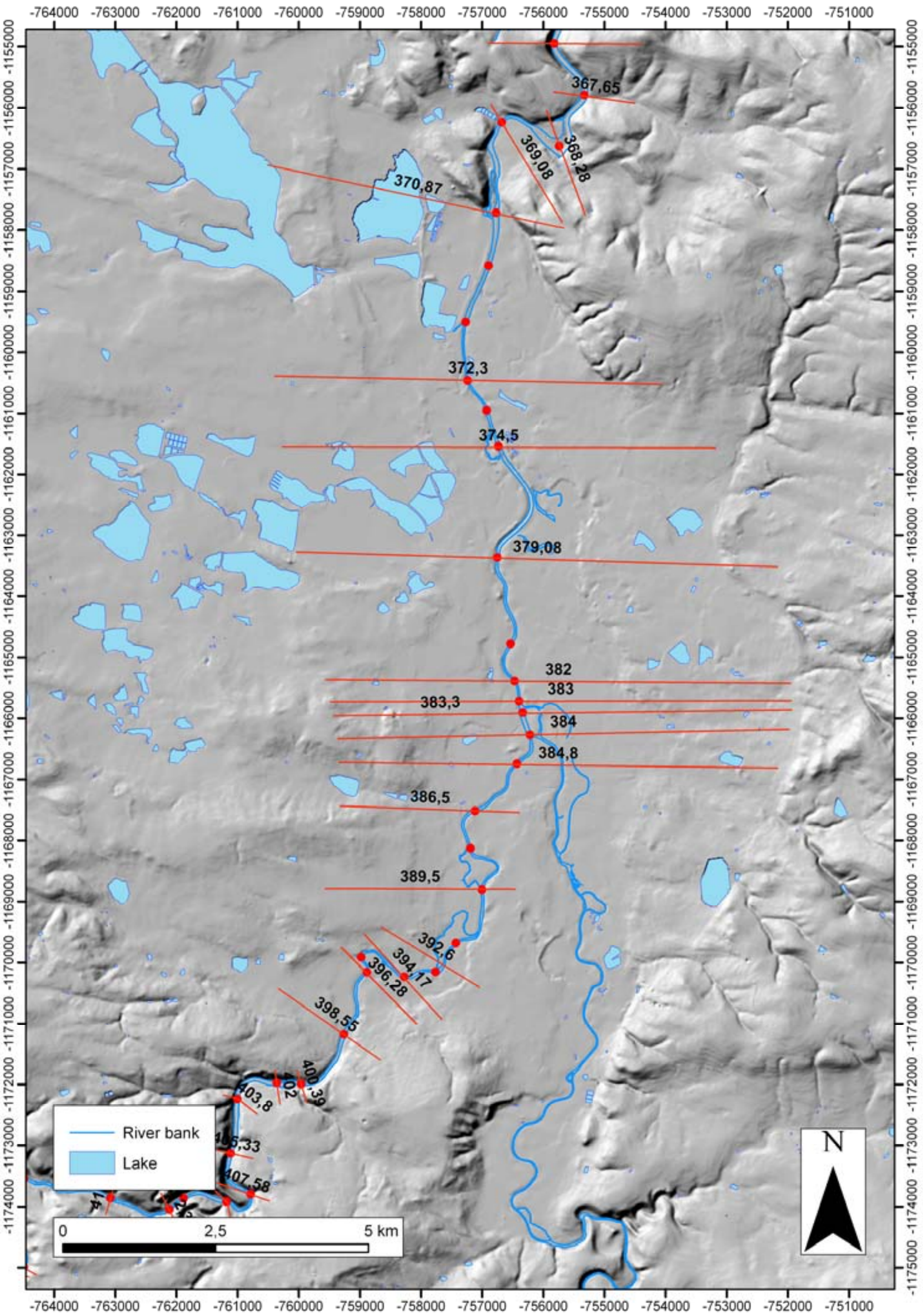

Fig. 17 Lines representing the Vltava water level perpendicular to the river course. At points not crossed by lines, only the information about the elevation of the river bed was available.

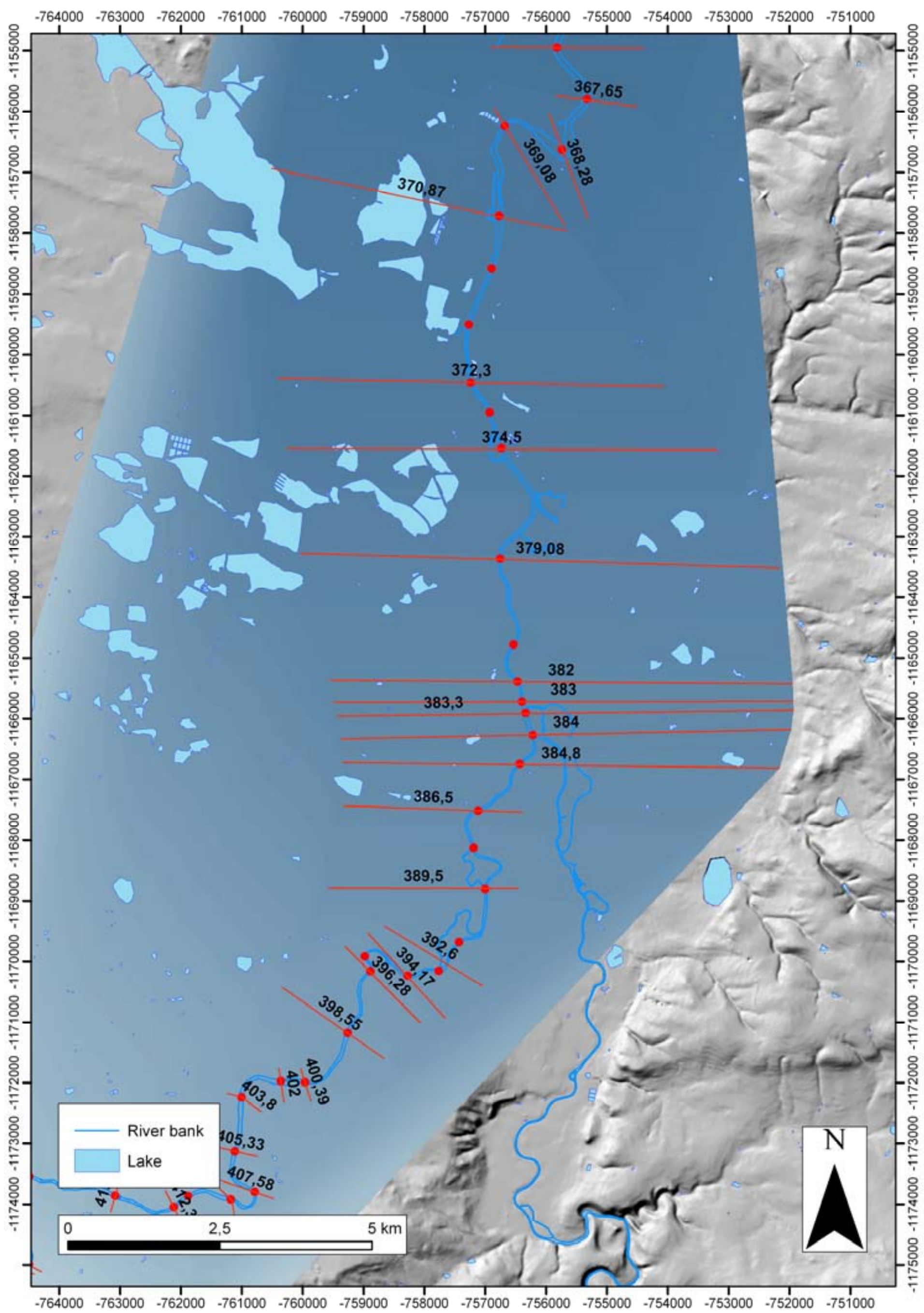

Fig. 18 Surface representing the Vltava water level used for calculating the relative elevation of gravel base.

Points representing the absolute elevation of the gravel base derived from drilling data were converted to raster format. Then, the relative elevation was calculated with the "raster calculator" by substracting the absolute elevation of the water level from absolute elevation of the gravel base. Afterwards, the results of the calculation in the raster format were again converted to point features (Figs. 19 and 20).

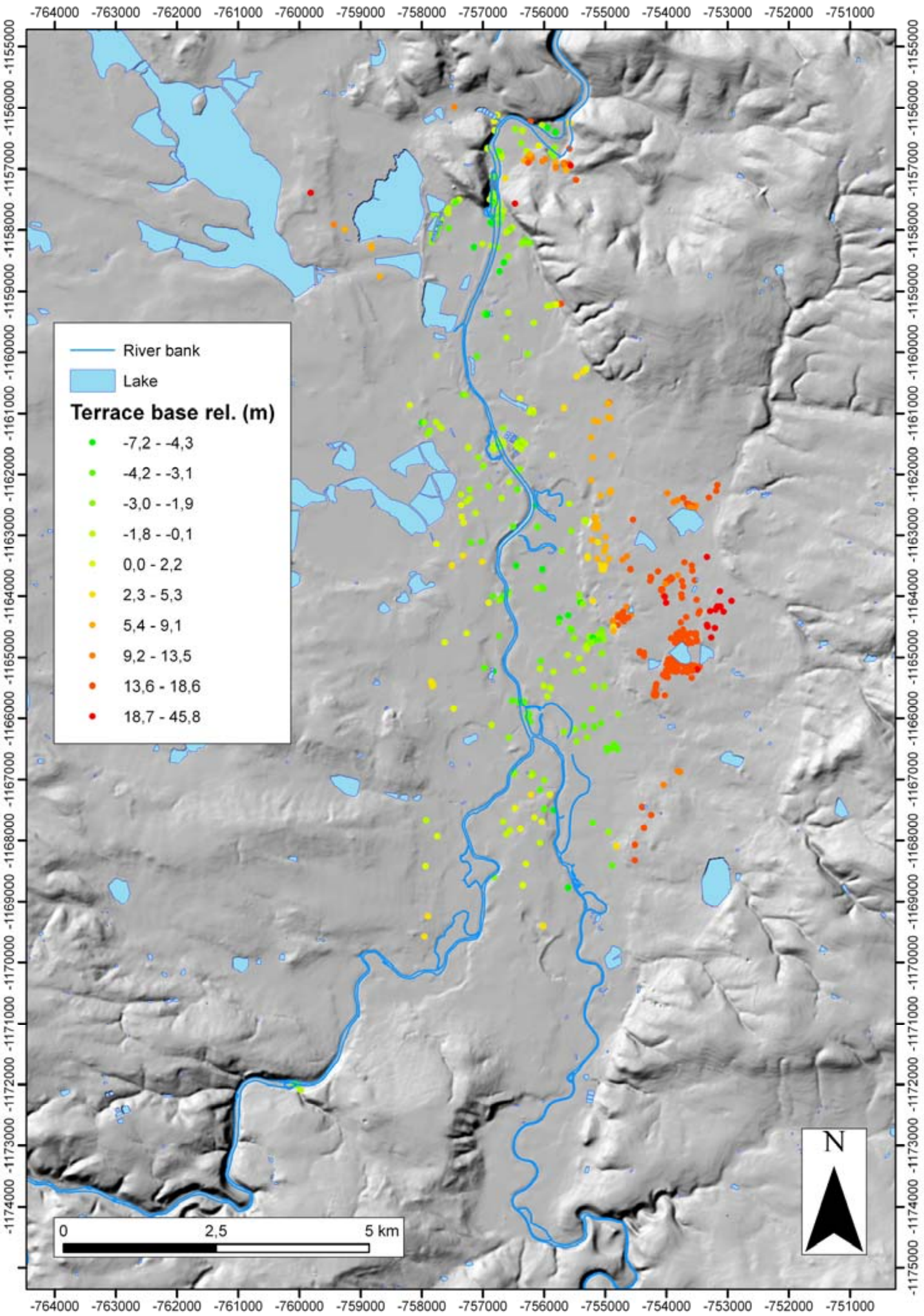

Fig. 19 Relative elevation of the gravel base in meters above the Vltava water level calculated from the surface representing the Vltava water level and drilling data.

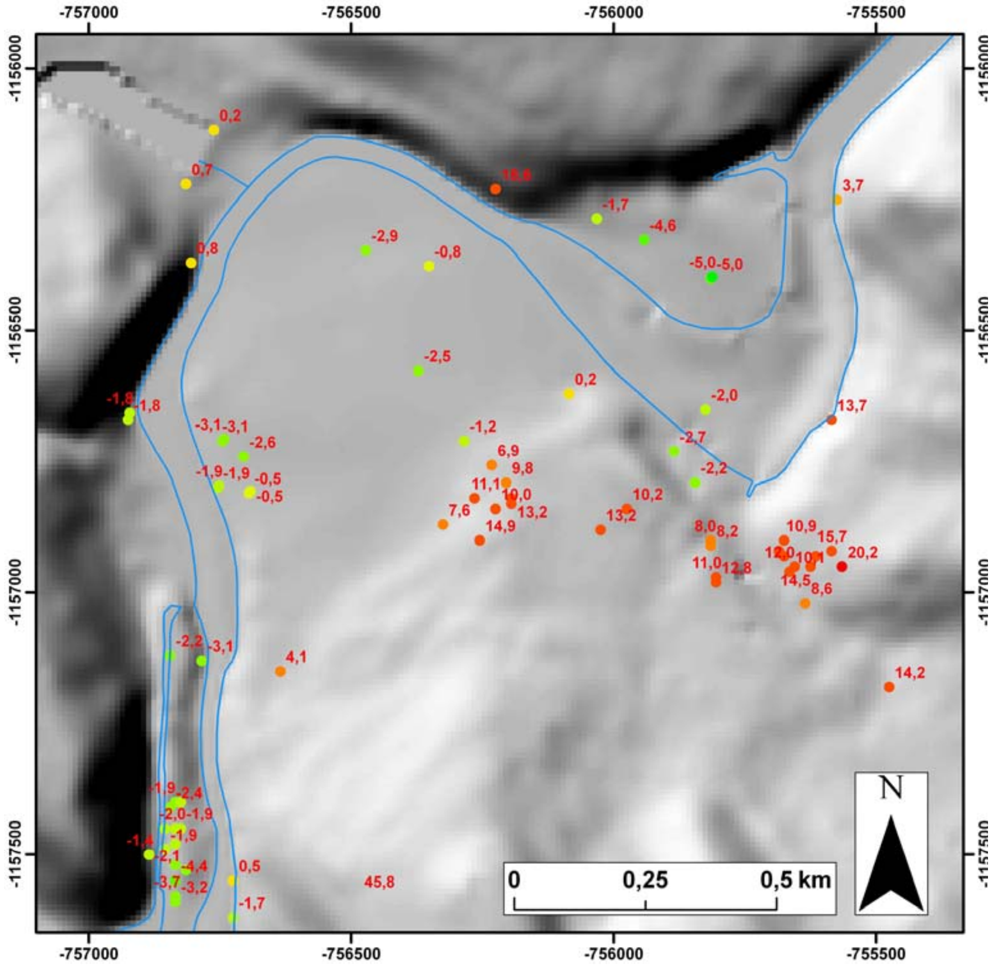

Fig. 20 Relative elevation of the base of fluvial gravel above Vltava water level in meters derived from drillings and outcrops. These data in combination with the DEM were used to map terrace levels in the vicinity of Hluboká nad Vltavou.

5.2. Sediment-petrography

Sedimentological analyses were necessary to distinguish the different types of clastic sediments of the Budějovice basin since the visual differentiation between Quaternary fluvial sands and gravel, Miocene and Cretaceous sediments is difficult and highly ambiguous. This created the need to find petrological characteristics of Quaternary fluvial sediments, which can be used to distinguish them from Cretaceous and Miocene deposits as well as from other Quaternary deposits. All of these are widespread in this area and lithologically very similar to each other. The methodology and results are described in the study by Homolová and Decker (submitted) (Appendix A).

The study introduces a new method to easily distinguish fine-grained Quaternary and pre-Quaternary sediments from the north-eastern part of the Budějovice basin using standard sedimentological techniques such as X-ray powder diffraction on bulk samples as well as heavy mineral analysis. There are significant differences in the mineralogical composition as well as the heavy mineral content of both sediment groups. The main bulk components of pre-Quaternary sediments are quartz, alkali-feldspar, muscovite, and kaolinite, reflecting longer periods of chemical weathering. Quaternary deposits additionally contain less weathering resistant plagioclase and chlorite and only small amounts of kaolinite. Quaternary sediments transported by the Vltava River generally contain significant amounts of amphiboles, which are missing in recent alluvia of its tributaries. The mineralogical compositions as well as the heavy mineral suites of analysed sediments in general reflect the lithological properties and the duration of weathering processes the sediments underwent. The results of this study help to distinguish Quaternary from pre-Quaternary deposits of the Budějovice basin in places, where optical characteristics of sediments do not allow this and to distinguish different types of Quaternary sediments, mainly those transported by the Vltava River and its small local tributaries.

5.3. Fault analysis using tectonic geomorphology

To follow the neotectonic activity of the near regional faults, several tools of tectonic geomorphology were used as indicators for potential vertical or lateral displacement along the faults like Valley-Floor Width to Valley-Height ratio, Stream Length-Gradient index, Hypsometric Integral, Mountain-Front sinuosity etc. A detailed description of the analyses and the results is given in the study by Popotnig et al. (submitted) (Appendix B).

The NW-SE striking Hluboká fault and the NNE-SSW striking Rudolfov fault in southern Bohemia are part of a late Variscan fault-system and were repeatedly re-activated in Mesozoic, Miocene and Pliocene times. The faults form the NE and SE margin of the Budějovice basin filled with up to 340 m thick Cretaceous to Quaternary sediments and overlying the hanging wall of the fault system.

We compared two hill slopes crossing the faults and one slope which is not directly fault-controlled. We used several morphological parameters to investigate small tributaries of the Vltava river which cut into crystalline basement units. All creeks are similar in hydrological conditions and the common base level formed by the Vltava river. Morphological differences in valley shapes are therefore likely a result of different uplift of the crystalline basement with respect to the sedimentary basin.

All calculated geomorphic parameters characterize the hill slope crossing the Hluboká fault as a very straight mountain-piedmont junction in the vicinity of the fault and the morphology as influenced by uplift along the fault. The values are significantly different than those observed at the other two hill slopes. The marked convex-up thalweg sections with single large knickpoints close to the Hluboká fault are supporting the data as well as an isoline map of vertical crustal movements in the surrounding area of the Budějovice basin (Vyskočil, 1973).

Values observed at the north facing slope of Račice mountain and at the hill slope crossing the Rudolfov fault are of similar range and therefore may classify both slopes as of moderate tectonic activity. Observations of thalweg sections show the small difference in the concave profiles passing into convex profiles for the north facing slope, but concave-convex and convex thalweg sections and slightly higher Stream Length (SL) values for the hill slope crossing the Rudolfov fault.

5.4. Luminescence dating of sediments in the study area

To derive absolute ages of fluvial and other Quaternary sediments in the study area, which is inevitable for their stratigraphic assignment, samples were dated using the luminescence method.

Luminescence dating methods such as optically stimulated luminescence (OSL) or infrared stimulated luminescence (IRSL) allow dating the last exposure of sediment to sunlight and thus, the last event of transport and deposition. Two parameters have to be determined to derive a luminescence age. These are the equivalent dose (De, in Gy) and the dose rate (Do, in Gy/ka). The De measures the accumulated radiation dose in minerals such as quartz and feldspars and the dose rate is a measure of ionising radiation in the surrounding sediment. The environmental radiation, which is responsible for the dose accumulation in minerals, is mainly derived from the decay of naturally occurring radionuclides such as ^{232}Th, ^{238}U, ^{235}U and ^{40}K, and from the cosmic dose. The luminescence age is then calculated by dividing the equivalent dose by the dose rate.

Sediment samples analysed in this study were dated in two luminescence laboratories: The luminescence laboratory of the University of Natural Resources and Life Sciences (BOKU) in Vienna (Austria) and the Sheffield Centre for International Drylands Research (SCIDR) luminescence laboratory (Sheffield, UK).

Results from luminescence dating are described in Homolová et al. (2012) (Appendix C) and Homolová et al. (in preparation) (Appendix D).

6. Summary

This study presents results from mapping and dating of Pleistocene fluvial terraces along the Vltava and Malše rivers in the Budějovice Basin and adjacent areas. Additionally, new ideas on the late Pleistocene landscape development and the neotectonic history of the study area are presented.

After an introduction to fluvial sequences in general and the late Cenozoic fluvial history of the Bohemian Massif, all the methods used during the study are described in detail. The results are presented in four articles (1 published, 2 in review, 1 in preparation), given in appendices A to D.

The article by Homolová and Decker (Appendix A) describes sedimentological-petrological investigations of fine-grained deposits from the Budějovice Basin and the adjacent area north of the Hluboká Fault. The study presents a new method for clearly differentiating between Quaternary and Cretaceous/Miocene sediments; this uses simple sedimentological methods such as X-ray powder diffraction on bulk samples and heavy minerals analysis. Quaternary sediments transported by the Vltava River can be distinguished from those transported by its small local tributaries and from colluvia. The results of this study allow a clear assignment of fine-grained sediments to the different stratigraphic units occurring in the study area; this is useful for identifying and correlating Quaternary fluvial sediments across the area.

The study by Popotnig et al. (Appendix B) presents a geomorphological analysis of the Budějovice Basin using quantitative morphometric parameters to follow the neotectonic activity of the Hluboká and Rudolfov faults that delimit the basin to its Variscan crystalline basement. Calculated parameters include the mountain front sinuosity (Smf), stream length gradient (SL), valley floor width-to-height ratio (Vf), drainage basin shape (Rf), circularity index (C) and the basin elongation ratio (Bs), supported by interpretations of knickpoints and thalweg sections. All the calculated morphometric parameters indicate an uplift of the crystalline basements relative to the basin fill along both investigated faults. This is supported by geodetic data obtained from precise levelling (e.g. Vyskočil, 1973), suggesting relative vertical displacement rates of several tenths of a millimetre per year between the Budějovice Basin in the hanging wall and the Variscan basement in the footwall.

Results from mapping and dating of fluvial terraces of the rivers Vltava and Malše in the Budějovice Basin are presented in the study by Homolová et al. (2012) (Appendix C). By using a combination of methods including analysis of a high-resolution DEM, interpretation of borehole data and luminescence dating, five terrace levels (BB 1 to BB 5) were mapped. During the Pleistocene, the original morphology of the terrace staircase was smoothed by periglacial slope processes. The lowermost terrace level (BB 1), morphologically corresponding to the recent Vltava River floodplain, represents a complex sedimentary body with several distinct packages of river aggradation. Numerical ages of sediments from this terrace level range from ca. 90 ka to the Holocene. Dating of sediments from higher terraces was not possible because of the limitations of the luminescence method. The presence of stacked fluvial deposits of Pleistocene age underneath the recent floodplain points to ongoing subsidence or relative tectonic stability of the Budějovice Basin during the late Pleistocene.

Fluvial terraces of the Vltava River in the vicinity of Hluboká and Vltavou to the north of the Budějovice Basin are described in the study by Homolová et al. (Appendix D). The study area comprises parts of the Variscan crystalline basement forming the footwall of the Hluboká Fault. Five terrace levels (CB 1 to CB 5) were mapped using a combination of spatial data analysis, geomorphological mapping and analysis of drill profiles. As in the Budějovice Basin, the stacked sequence of the lowermost terrace level (CB 1) morphologically corresponds to the recent floodplain, showing luminescence ages from ca. 60 ka to the Holocene. Higher terrace levels do not appear as morphological terraces because their original morphology was smoothed by periglacial cryoturbation and geli- and solifluction. Dating of sediments from these terraces was not possible because of the limitations of the luminescence method.

A comparison of the lowermost terrace levels in the Budějovice Basin (BB 1) and the area north of the Hluboká Fault (CB 1) shows that there is no observable change in the thickness and relative elevation of the terrace base below the Vltava water level. What can be observed is the occurrence of ca. 37 ka and 14 ka old fluvial sediments in and above the recent floodplain in the area north of the fault, which we interpret as a vertical displacement of parts of the crystalline body along a NNE-SSW-striking branch of the Hluboká Fault. The data also show a mismatch in the relative elevation of higher terraces situated above the recent floodplain on both sides of the fault. These phenomena indicate a higher uplift rate in parts of the Variscan crystalline basement in the footwall of the Hluboká Fault relative to the sedimentary fill of the Budějovice Basin (hanging wall of the fault) during the late Pleistocene.

7. Zusammenfassung

Diese Arbeit präsentiert die Ergebnisse der Kartierung und Datierung von pleistozänen Flussterrassen der Vltava (Moldau) und Malše (Maltsch) im Budweiser Becken und angrenzenden Gebieten. Zusätzlich werden neue Ideen zur spätpleistozänen Landschaftsentwicklung und neotektonischer Geschichte des Untersuchungsgebiets vorgestellt.

Nach den einleitenden Kapiteln über fluviatile Abfolgen im Allgemeinen und der Beschreibung der spätkänozoischen Geschichte des Flussnetzes der Böhmischen Masse werden alle Methoden, die während der Arbeit verwendet wurden, im Detail vorgestellt.

Die Ergebnisse aller Untersuchungen werden in Form von vier Manuskripten (Appendix A bis D) vorgestellt.

Im Manuskript von Homolová und Decker (Appendix A) werden sediment-petrologische Untersuchungen an feinkörnigen Sedimenten des Budweiser Beckens und angrenzender Gebiete nördlich der Hluboká-Störung beschrieben. Die Studie präsentiert eine neue Methode zur eindeutigen Unterscheidung zwischen quartären und kretazischen/miozänen Sedimenten unter Verwendung einfacher sedimentologischer Methoden wie Röntgendiffraktometrie und Schwermineralanalyse. Zusätzlich können quartäre Moldausedimente von Sedimenten lokaler Tributärgerinne und von Kolluvien unterschieden werden. Die Ergebnisse dieser Studie erlauben eine klare Zuordnung von feinkörnigen Sedimenten zu den unterschiedlichen stratigraphischen Einheiten, die in dem Untersuchungsgebiet auftreten. Das ist vor allem für die Identifikation der lokalen Quartärbasis, sowie für die Korrelation von quartären Flusssedimenten über das ganze Untersuchungsgebiet von Bedeutung.

Die Studie von Popotnig et al. (Appendix B) präsentiert eine geomorphologische Analyse des Budweiser Beckens unter Verwendung von quantitativen morphometrischen Parametern zur Beurteilung der neotektonischen Aktivität der Hluboká- und Rudolfov-Störung. Diese zwei Störungen trennen das Becken von seinem variszischen kristallinen Untergrund. Die berechneten Parameter sind “mountain front sinuosity” (Smf), “stream length gradient” (SL), “valley floor width-to-height ratio” (Vf), “drainage basin shape” (Rf), “circularity index” (C) und das “basin elongation ratio” (Bs). Unterstützt werden die Ergebnisse durch die Interpretation von Knickpunkten und den „thalweg sections“. Alle berechneten morphometrischen Parameter deuten in Summe auf eine Hebung des kristallinen

Untergrundes relativ zur Beckenfüllung entlang beider untersuchter Störungen. Diese Beobachtungen werden durch geodetische Daten aus präzisen Nivellierungen (e.g. Vyskočil, 1973), die auf relative vertikale Versatzraten von mehreren Zehntel Millimeter pro Jahr zwischen dem Budweiser Becken in der Hangendscholle und dem variszischen Untergrund in der Liegendscholle hinweisen, unterstützt.

Die Ergebnisse der Kartierung und Datierung von Flussterrassen im Budweiser Becken werden in der Arbeit von Homolová et al. (2012) (Appendix C) vorgestellt. Durch die Kombination von Analysen eines hochauflösenden digitalen Höhenmodells, die Interpretation von Bohrungsdaten und Lumineszenzdatierung wurden fünf Terrassenstufen (genannt BB 1 und BB 5) kartiert. Die ursprüngliche Morphologie der Terrassenstufen wurde durch periglaziale Hangprozesse während des Pleistozäns geglättet. Die niedrigste Terrassenstufe BB 1 entspricht morphologisch der rezenten Überflutungsebene der Moldau und stellt einen komplexen Sedimentkörper mit mehreren Phasen fluviatiler Aufschüttung dar. Numerische Alter von Sedimenten aus diesem Terrassenkörper reichen von ca. 90 ka bis ins Holozän. Wegen Einschränkungen der Lumineszenzmethode war die Datierung von Sedimenten aus höheren Terrassenstufen nicht möglich. Das Auftreten von übereinander liegenden Flussablagerungen pleistozänen Alters unter der rezenten Überflutungsebene deutet auf eine fortschreitende Subsidenz beziehungsweise auf eine relative tektonische Stabilität des Budweiser Beckens während des Spätpleistozäns.

Flussterrassen der Moldau in der Umgebung von Hluboká nad Vltavou nördlich des Budweiser Beckens werden in der Arbeit von Homolová et al. (Appendix D) beschrieben. Das Untersuchungsgebiet umfasst Teile des kristallinen Untergrundes, welche die Liegenscholle der Hluboká-Störung bilden. Durch Analyse eines Höhenmodells, geomorphologische Kartierung und Analyse von Bohrprofilen wurden fünf Terrassenstufen (genannt CB 1 bis CB 5) kartiert. Ähnlich wie im Budweiser Becken entspricht die unterste Terrassenstufe CB 1, bestehend aus übereinander liegenden Sedimentschichten, morphologisch der rezenten Überflutungsebene. Die darin enthaltenen Sedimente zeigen Lumineszenzalter zwischen ca. 60 ka und dem Holozän. Höhere Terrassenstufen treten nicht als morphologische Terrassen auf, weil ihre ursprüngliche Form durch periglaziale Kryoturbation, Geli- und Solifluktion verändert wurde. Die Datierung von höheren Terrassen war mit der Lumineszenzmethode nicht möglich.

Bei einem Vergleich der niedrigsten Terrassenkörper im Budweiser Becken (BB 1) und im Gebiet nördlich der Hluboká-Störung (CB 1) kann man keinen Unterschied in der

Mächtigkeit und relativer Höhe der Terrassenunterkante unter dem heutigen Moldau-Wasserspiegel beobachten. Was man beobachten kann, ist das Auftreten von ca. 37 ka und 14 ka alten Flusssedimenten in und über der rezenten Überflutungsebene im Bereich nördlich der Hluboká-Störung. Dies wird als Folge eines vertikalen Versatzes von Teilen des kristallinen Körpers entlang einer NNO-SSW-streichenden Abzweigung der Hluboká-Störung interpretiert. Man kann auch einen Versatz von höheren Terrassenstufen über der rezenten Überflutungsebene auf beiden Seiten der Störung beobachten. Diese Phänomene können als Ergebnis von höheren Hebungsraten von Teilen des variszischen Kristallinuntergrundes in der Liegendscholle der Hluboká-Störung relativ zur Sedimentfüllung des Budweiser Beckens (Hangendscholle der Störung) während des Pleistozäns interpretiert werden.

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Appendix A

Homolová, D. and Decker, K. (submitted to "Austrian Journal of Earth Sciences"). Sediment-petrological investigations of clastic sediments in the vicinity of České Budějovice (Southern Bohemian Massif).

(submission date: 7.10.2012)

Sediment-petrological investigations of clastic sediments in the vicinity of České Budějovice (Southern Bohemian Massif)

Dana Homolová[a*], Kurt Decker[a]

a) Department of Geodynamics and Sedimentology, University of Vienna, Althanstrasse 14, 1090 Wien, Austria

Abstract

The study introduces a new method to easily distinguish fine-grained Quaternary and pre-Quaternary sediments from the north-eastern part of the Budějovice basin using standard sedimentological techniques such as X-ray powder diffraction on bulk samples as well as heavy mineral analysis. There are significant differences in the mineralogical composition as well as the heavy mineral content of both sediment groups. The main bulk components of pre-Quaternary sediments are quartz, alkali-feldspar, muscovite, and kaolinite, reflecting longer periods of chemical weathering. Quaternary deposits additionally contain less weathering resistant plagioclase and chlorite and only small amounts of kaolinite. Quaternary sediments transported by the Vltava River generally contain significant amounts of amphiboles, which are missing in recent alluvia of its tributaries. The mineralogical compositions as well as the heavy mineral suites of analysed sediments in general reflect the lithological properties and the duration of weathering processes the sediments underwent. The results of this study help to distinguish Quaternary from pre-Quaternary deposits of the Budějovice basin in places, where optical characteristics of sediments do not allow this and to distinguish different types of Quaternary sediments, mainly those transported by the Vltava River and its small local tributaries.

Zusammenfassung

Diese Studie präsentiert eine neue Methode zur einfachen Unterscheidung von feinkörnigen Quartären und prä-Quartären Sedimenten vom nordöstlichen Teil des Budweiser Beckens unter Verwendung von sedimentologischen Standardanalysen wie der Bestimmung der Gesamtmineralogie mit Röntgendiffraktometrie und Schwermineralanalyse. Beide Sedimentgruppen zeigen signifikante Unterschiede in mineralogischer Zusammensetzung

sowie im Schwermineralgehalt. Die wichtigsten Bestandteile des Gesamtmineralspektrums von prä-Quartären Sedimenten sind Quarz, Kalifeldspat, Muskovit und Kaolinit, die auf lange Phasen chemischer Verwitterung hinweisen. Quartäre Ablagerungen enthalten zusätzlich Anteile von weniger verwitterungsresistentem Plagioklas und Chlorit, aber nur geringe Mengen Kaolinit. Die quartären Sedimente der Moldau enthalten außerdem signifikante Anteile von Amphibolen. Der Amphibolgehalt unterscheidet die Moldauablagerungen von den rezenten Alluvien der lokalen Moldauzuflüsse. Die mineralogische Zusammensetzung sowie die Schwermineralspektren der Proben spiegeln die lithologischen Gegebenheiten in den Einzugsgebieten sowie die Dauer von Verwitterungsprozessen, denen die Sedimente ausgesetzt waren. Die Daten dieser Studie zeigen, dass sedimentpetrographischen Methoden eine sichere Unterscheidung von quartären von prä-quartären Ablagerungen im Budweiser Becken ermöglichen. Petrographische Charakteristika erlauben ausserdem, zwischen fluviatilen Sedimenten der Moldau und Ablagerungen kleiner, lokaler Zuflüsse zu unterscheiden.

1. Introduction

The sedimentary fill of the two southern Bohemian sedimentary basins - the Budějovice basin and Třeboň basin - is dominated by Cretaceous and Miocene deposits, with Quaternary sediments forming only a relatively thin layer of several meters thickness (Homolová et al., 2012). Cretaceous and Miocene sediments were extensively described in several studies with respect to their petrography (Slánská, 1963 and 1976) and paleontological content (Pacltová, 1961; Malecha and Pícha, 1963; Řeháková, 1963; Gabrielová et al.1964), but much less attention was paid to sediments of Quaternary age.

In most of the studies dealing with Quaternary sediments of the southern Bohemian basins, authors describe the morphology of terrace staircases formed by rivers crossing the basins (Chábera, 1965; Chábera and Vojtěch, 1972; Novák, 1990; Homolová et al., 2012), whereas the petrography of those sediments was mentioned only marginally and was reduced mostly to pebble analyses of fluvial gravel.

Extensive petrographic investigations on fluvial sediments of Bohemian rivers including grain size and pebble analyses as well as heavy mineral analysis were done by Kodymová (1960, 1962, 1963 and 1966), however, focusing solely on sediments from recent river alluvia. Sediments from Pleistocene terraces of rivers were analyzed only from very few locations along the middle and lower course of the river Vltava and until now, there are no data for other types of Quaternary sediments in the study area at all.

In the Budějovice basin as well as in the adjacent Třeboň basin, fine-grained sediments from Quaternary and pre-Quaternary units appear very similar, making their stratigraphic assignment problematic. This causes problems by analyzing drilling profiles in places, where Quaternary sands or gravels lay directly on Miocene or Cretaceous ones and only field methods are used.

In studies dealing with fluvial terraces of the rivers Vltava and Malše in the Budějovice basin (Chábera, 1965; Homolová et al., 2012) and Lužnice in Třeboň basin (Chábera and Vojtěch, 1972), authors identified only fluvial sandy gravel of the main rivers as the marker lithology of undoubtly Quaternary age. Sandy and silty fluvial sediments, frequently forming most of the bodies of Pleistocene terraces could not be distinguished from fine-grained deposits of Miocene or Cretaceous age leaving severe difficulties in correlating Pleistocene terraces and defining the thickness of Quaternary sediments.

Such correlations are, however, vital for understanding the Pleistocene fluvial history of the region and for regional correlations of terrace staircases along the Vltava and other rivers. Terrace correlations are further important for identifying potential vertical displacements at active faults in South Bohemia. Such analyses can as well be used to clearly distinguish between terrace sediments of the main rivers (Vltava and Malše) and alluvial fans deposited by their local tributaries.

A simple assignment of sediments to different stratigraphic units based only on the lithofacies is difficult, as fluvial sequences occur in Quaternary as well as in Miocene and Cretaceous successions and the facies are mostly not distinctive enough (Nehyba and Roetzel, 2010). A crucial task of this study was therefore to find a method to distinguish fine-grained sediments of Quaternary age from sediments of older stratigraphic units using sediment-petrologic analyses such as X-ray powder diffraction and/or heavy mineral analysis.

Another important issue of the present study was the characterisation of different types of Quaternary sediments, especially those originating from the Vltava River and its tributaries. The focus was on fluvial sand and gravel from the lowermost terrace level forming the recent floodplain as well as on recent alluvia from small Vltava River tributaries. By finding clear differences between these two types of sediments, one should be able to assign sediments of ambiguous morphological position either to the Vltava River or to its tributaries at the valley slopes along the Vltava River near tributary estuaries.

2. Regional setting

The Budějovice basin and the Třeboň basin, located east of it, are referred to as the South Bohemian basin system, situated on top of the Bohemian Massif. The characteristic elongated shape of both basins is determined by a system of faults striking predominantly NW-SE and NNE-SSW. The two basins are separated from each other by the fault-bounded basement high of the Rudolfov ridge (Fig. 1).

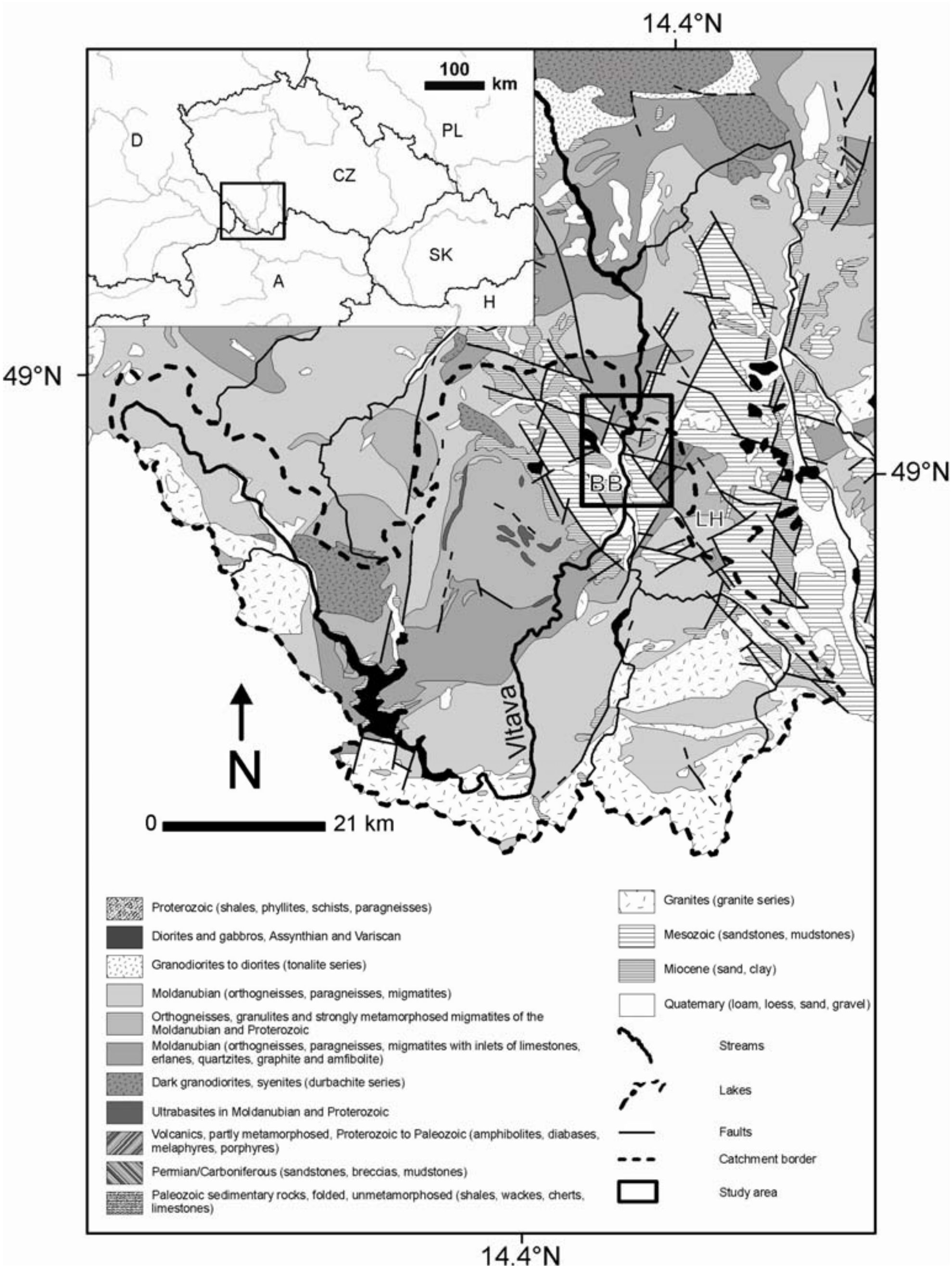

Figure 1 Geological map of southern Bohemia (modified after Cháb et al., 2007) and location of the study area (black rectangle). Dashed line marks the catchment area of the Vltava River upstream of Hluboká nad Vltavou. BB - Budějovice basin; LH - Lišov horst.

The study area comprises the Budějovice basin as well as areas northeast of the Hluboká fault. This fault delimits the sedimentary fill of the Budějovice basin from its Moldanubian crystalline basement to the northeast (Fig. 2).

The depocenter of the Budějovice basin is located in the eastern part of the basin, where the sediment thickness reaches approx. 340 m. The distribution and offset of Permian, Cretaceous and Miocene sediments allows reconstructing repeated reactivations of faults at or close to the basin margin. The activity of some of the faults may have continued into the Quaternary. Young vertical displacement is particularly indicated by geomorphological data from the Hluboká (Jáchymov) fault and the Rudolfov fault (Vyskočil, 1973 and 1979), which form the NE and E margin of the Budějovice basin.

The Moldanubian crystalline complex forming the basement of the Budějovice basin consists of Precambrian to Paleozoic highly metamorphosed mica-schists, gneisses and migmatites as well as of igneous rocks of the Central Bohemian and Moldanubian Plutons (Slánská, 1976). Upper Carboniferous and Lower Permian coal-bearing claystones and sandstones of the Blanice Graben east of the Hluboká fault represent the oldest unmetamorphosed sediments in this area (Suk et al., 1989).

The thickest stratigraphic unit of the Budějovice basin is the Upper Cretaceous Klikov Formation consisting of poorly sorted white, grey and reddish brown sands, sandstones and mudstones lying directly on the weathered crystalline basement and reaching a maximum thickness of 340 m (Slánská, 1976; Domácí et al., 1989). Based on a comparison of palynology, carpology and macroflora, these fresh-water, fluvio-lacustrine sediments are dated as Late Turonian to Santonian (Knobloch, 1985). The Klikov Formation is the most widespread stratigraphic unit of the southern Bohemian basins covering large areas of the Budějovice basin (Fig. 1). The main sediments source for the Klikov Formation during the Cretaceous were the kaolinite-rich eluvia of granitoides and sillimanite-biotite gneisses strongly weathered under the Late Cretaceous tropical and subtropical climate (Slánská, 1963). The main mineralogical components are quartz, feldspar (mainly microcline and orthoclase and very rarely plagioclase), mica (muscovite and biotite) and kaolinite. Organic matter, illite and limonite are present as well. Zircon, tourmaline, rutile, kyanite, anatase and opaque minerals dominate the heavy mineral spectra throughout the Klikov Formation. Less weathering resistant minerals such as apatite, andalusite, garnet, amphiboles and minerals of the epidote group only occur locally near basement rocks and faults (Slánská, 1976).

The Miocene strata are represented by two stratigraphic units: the Zliv Formation and the Mydlovary Formation. Their very similar paleontological content suggests that they were deposited in close time intervals (Svoboda, 1966). Sediments of these formations either directly overlie crystalline basement or Cretaceous sediments.

The Zliv Formation reaching a maximal thickness of 15 m comprises grayish-green sandy clays at the base coarsing upward into sandstones and conglomerates. These are often strongly silicified in the upper part. The mineralogical composition is similar to the Klikov Formation but with a significant amount of montmorillonite (Svoboda, 1966). Zircon, tourmaline, rutile and opaques are the most abundant heavy minerals, followed by minor amounts of kyanite, staurolite and andalusite. In earlier studies, the Zliv Formation was considered as the uppermost part of the Cretaceous Klikov Formation, later it was assigned to the Miocene (Ottnangian), based on the diatomaceous flora similar to that of the Mydlovary Formation. Beside shells of fresh-water diatoms, brackish and marine species are preserved as well (Svoboda, 1966).

Consisting of grayish-green clayey sands and sandstones to olive-green clays with layers of dark-grey coaly clays, xylites and greenish diatomaceous clays, the Mydlovary Formation, up to 60 m thick, covers only small areas mainly in the north-western part of the Budějovice basin (Svoboda, 1966). These well-sorted sediments consist mainly of quartz, kaolinite, illite, montmorillonite, organic matter and, in places, calcite. Beside stable ones, less stable heavy minerals such as amphiboles, andalusite, epidote or sillimanite are found in the heavy mineral spectra of the Mydlovary Formation as well (Slánská, 1963).

The Pliocene is represented by the Ledenice Formation distributed in both the Budějovice basin and the Třeboň basin as well as on the crystalline basement. The 15 - 20 m thick succession consists of light-grey, bluish-grey, dark grey and greenish predominantly kaolinic and highly sandy clays (Svoboda, 1966). It has been dated to the Pliocene based on palynological data (Pacltová, 1963) and diatoms (Řeháková, 1963).

Quaternary sediments are represented by fluvial sandy gravels and pebbly sands of the rivers Vltava and Malše, alluvial fans of their tributaries, solifluction loams and loess loams deposited on slopes surrounding the basin. Sandy overbank deposits are found in recent floodplains of the two main rivers as well as along their tributaries (Domácí et al., 1989; Suk et al., 1989; Vrána et al., 1990).

In course of the Pleistocene and probably further to the past, the two main rivers Vltava and Malše accumulated terrace bodies of different horizontal and vertical extent covering large areas in the southeastern part of the Budějovice basin (Fig. 2). The former terrace staircase was subsequently smoothed by periglacial geli- and solifluction processes which took place during the last glacial period and most probably during all cold stages before. The lowermost terrace level corresponding morphologically with the recent floodplain represents a complex sediments body build up of several distinct packages of river aggradation with ages ranging between approx. 90 ka to the Holocene (Homolová et al., 2012). Alluvial fans found mainly along the morphologically pronounced Hluboká fault scarp at the north-eastern basin margin were deposited by the small right-hand tributaries of the rivers Vltava and Malše (Fig. 2).

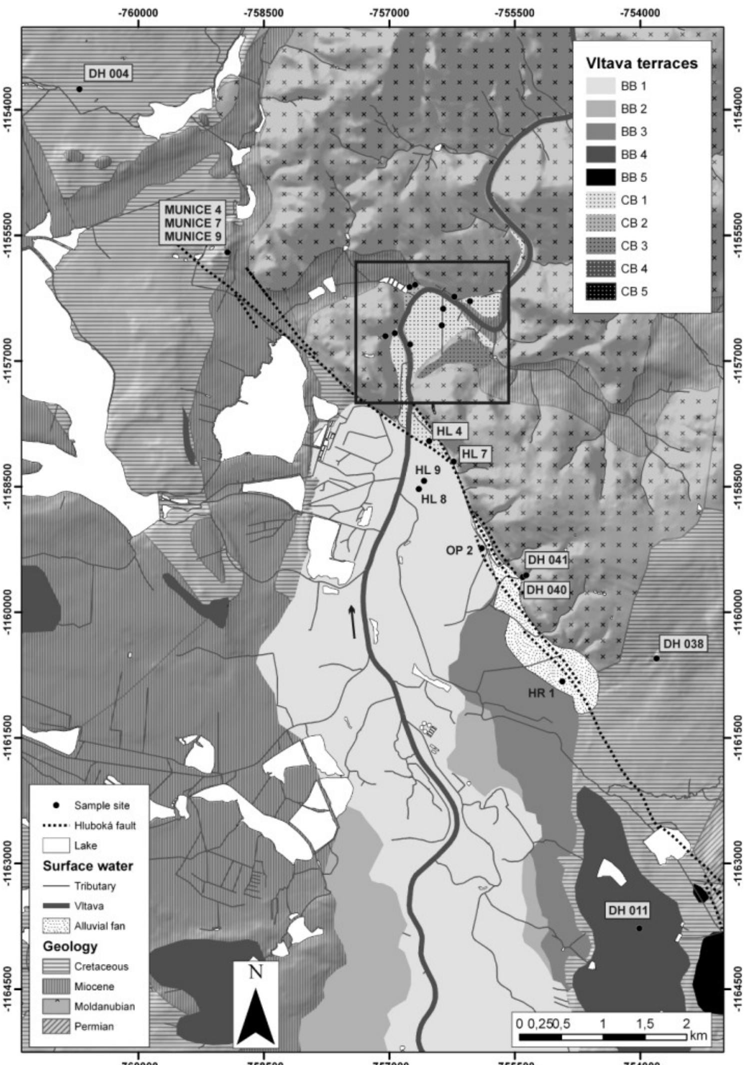

Figure 2 Location of sample sites underlain by a hillshade view of a digital elevation model (DEM) and a simplified geological map showing the main stratigraphic units of the study area. The extent of Vltava river terraces in the Budějovice basin and north of the Hluboká fault is taken from Homolová et al. (2012). Black rectangle shows the extent of the close-up view shown in Fig. 3.

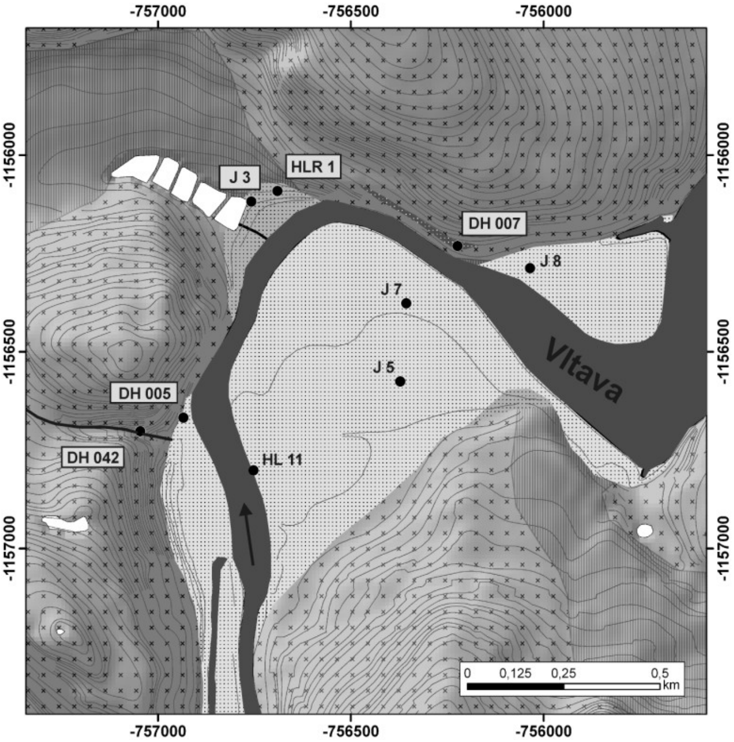

Figure 3 Close-up view of the area N of the Hluboká fault with the location of sample sites and 10-m contour lines highlighting the morphology of the area. For legend see Fig 2.

The lithological composition of the fluvial sediments deposited by the two main rivers reflects the bedrock properties of their catchments. The sediments therefore consist mainly of subangular to well-rounded clasts of Moldanubian crystalline rocks such as quartz, orthogneiss, granite, granulite, migmatite, amphibolite, eclogite, schist, aplite, quartzite or pyroxenic hornfels (Kodymová, 1960). In contrast, the composition of material deposited by the tributaries is much less variable consisting only of local lithologies such as quartz, sillimanite-biotite gneiss, leucocratic migmatite as well as clasts of Cretaceous and Permian sedimentary fragments, which survived the short transport. An example for such deposits is the sandy gravel of Kyselá voda in the vicinity of Úsilné consisting of quartz, gneiss and mudstone clasts from the Permian (Špaček et al., 2011).

In recent alluvia of the rivers Vltava and Malše, the heavy mineral spectrum is dominated by amphiboles with significant amounts of garnet, sillimanite, kyanite, epidote, andalusite, titanite and staurolite (Kodymová, 1966).

3. Methods

3.1. Sampling

Samples for sediment analyses were taken from twelve drill cores, six outcrops and from alluvia of small Vltava tributaries. Sampling locations and site types are shown in Figs. 2 and 3 and Table 1. The position of samples within drilling cores and outcrop profiles is summarized in Figs. 4 and 5. Samples not shown in that figures (DH 004/2, DH 038/2, MUNICE 4, 7 and 9 as well as DH 040, 041, 042/1, and 042/2) were sampled surface near and therefore only the location is given.

Sample site	Site type	X[a]	Y[a]	Lat (N)	Long (E)	Z surface (m asl)
DH 004	Claypit	-760703.4	-1153753.3	14.386111°	49.079722°	404.0
DH 005	Outcrop	-756934.3	-1156667.9	14.442778°	49.058333°	372.3
DH 007	Outcrop	-756223.0	-1156231.1	14.451667°	49.063056°	389.0
DH 011	Outcrop	-754011.4	-1163773.7	14.495556°	49.998611°	399.0
DH 038	Sandpit	-753805.4	-1160552.0	14.492500°	49.027500°	435.0
DH 040	Streambed	-755405.0	-1159581.0	14.468889°	49.034167°	410.0
DH 041	Streambed	-755363.0	-1159558.0	14.469444°	49.034444°	412.0
DH 042	Creek cutting	-757046.0	-1156702.0	14.441389°	49.058056°	388.0
HL 4	Drilling	-756523.8	-1157955.1	14.450833°	49.047500°	373.2
HL 7	Drilling	-756230.3	-1158202.2	14.455278°	49.045556°	373.0
HL 8	Drilling	-756647.5	-1158528.6	14.449039°	49.041455°	373.6
HL 9	Drilling	-756583.6	-1158431.9	14.450111°	49.042664°	373.0
HL 11	Drilling	-756752.2	-1156801.5	14.445556°	49.057500°	372.1
HLR 1	Drilling	-756690.1	-1156091.0	14.445000°	49.063889°	376.7
HR 1	Drilling	-754931.5	-1160825.8	14.476880°	49.023138°	387.3
J 3	Drilling	-756757.8	-1156117.9	14.444167°	49.063611°	375.3
J 5	Drilling	-756371.8	-1156575.7	14.450278°	49.060000°	371.4
J 7	Drilling	-756356.1	-1156376.7	14.450000°	49.061667°	371.5
J 8	Drilling	-756035.2	-1156287.4	14.454167°	49.062778°	371.0
MUNICE 4, 7, 9	Outcrop	-758934.0	-1155702.5	14.413889°	49.064722°	400.0
OP 2	Drilling	-755893.8	-1159235.2	14.460572°	49.036141°	374.2

Table 1 Sample sites location data.
[a]X-Y (m) stand for Jednotná trigonometrická síť katastrální (JTSK) system used in the Czech Republic.

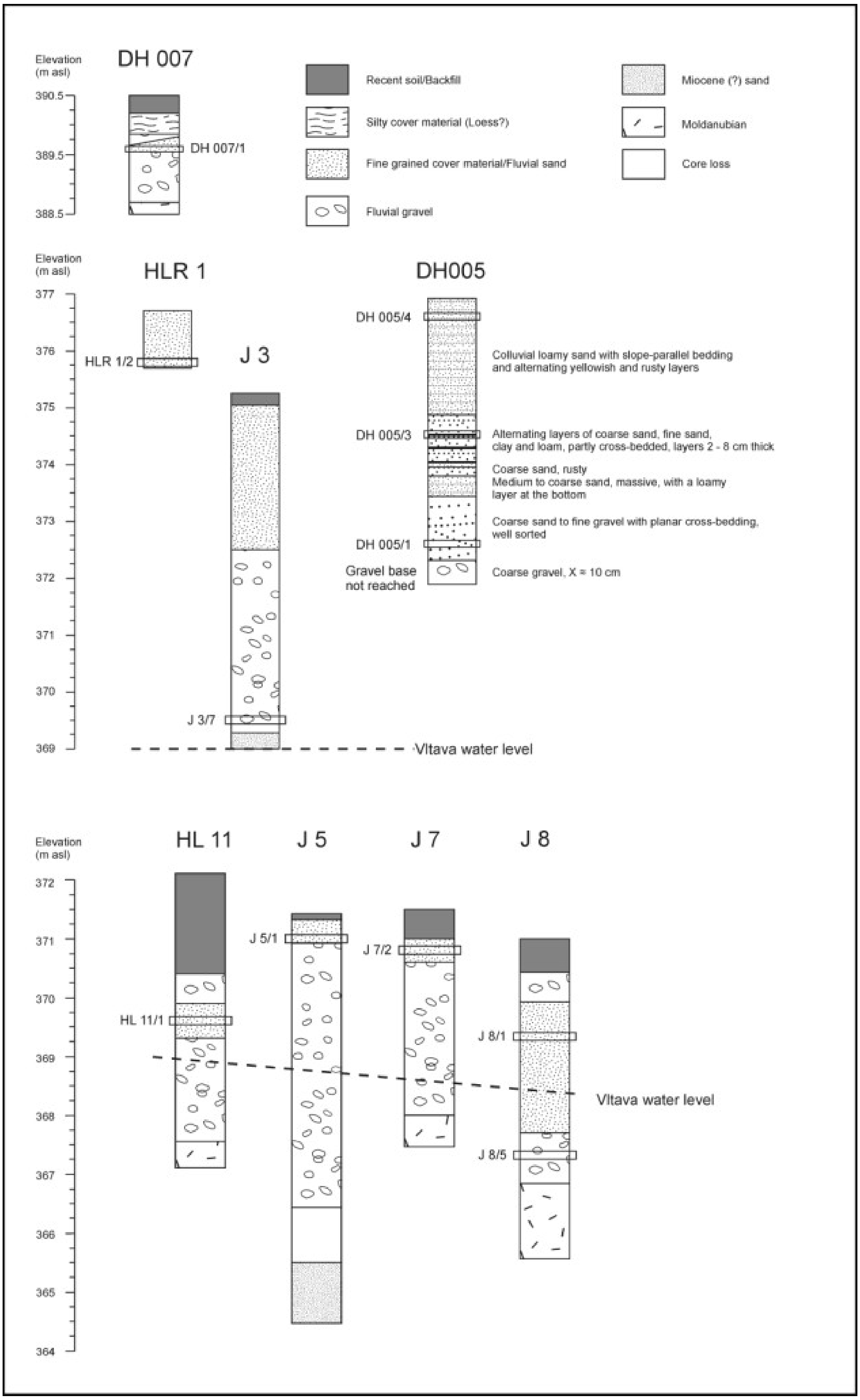

Figure 4 Lithological profiles of boreholes and outcrops situated in and above the recent Vltava River floodplain N of the Hluboká fault with the position of analyzed samples.

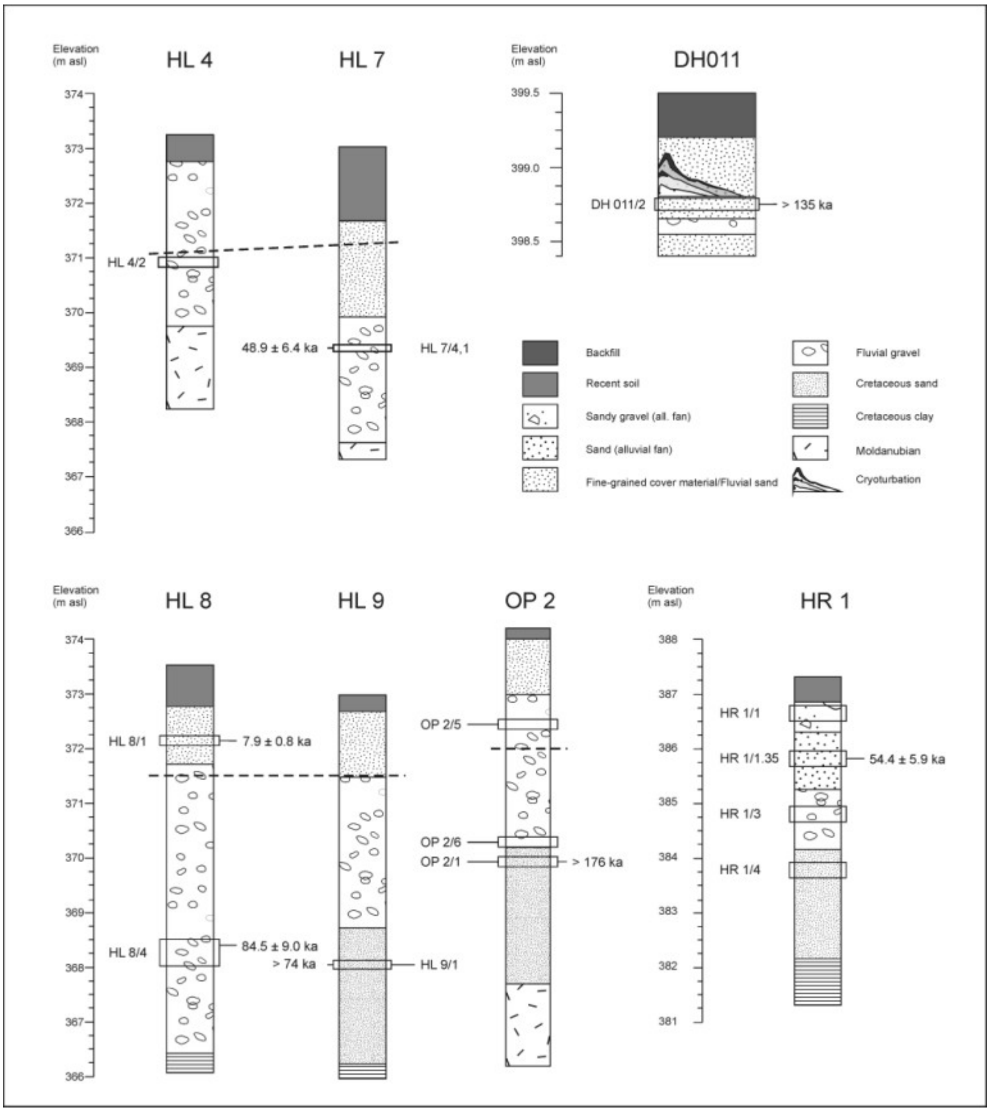

Figure 5 Lithological profiles of boreholes and the outcrop DH 011 situated in and above the recent Vltava River floodplain in the Budějovice basin with the position and luminescence ages (from Homolová et al., 2012) of analyzed samples. Dashed line represents the mean Vltava water level.

We collected samples from all sediment types of pre-Quaternary and Quaternary including Cretaceous and Miocene sandstones, claystones, clay, and sand and Quaternary fluvial gravel and sand of the river Vltava, sediments of small Vltava tributaries as well as other Quaternary deposits (Table 2).

3.2. Grain size and color

The grain size of unconsolidated sediments was estimated in the field and not further analyzed in detail. Such a method is considered to be sufficient as according to various studies (Slánská, 1963; Huber, 2003), similar sediment types can be found in all different stratigraphic units occurring in the study area. This characteristic can not be used for a clear assignment of sediments to the different stratigraphic units. A detailed grain size analysis would therefore not significantly improve the overall conclusion of this study.

The color of all air-dried samples was determined using the Munsell Soil Color Charts (MUNSELL COLOR, 2000).

3.3. Bulk mineralogy

32 samples from various stratigraphic units were analyzed with X-ray powder diffraction to resolve their mineralogical composition. The samples were first dried in a drying chamber at 60 °C for 24 hours, milled in a vibration mill for two to five minutes and analyzed in a Panalytical PW 3040/60 X´Pert PRO X-ray diffractometer (CuKα radiation, 40 kV, 40 mA, continuous scan, step size 0.02, 5s per step). Fifteen samples (Table 3) were subsequently treated with ethylene glycol and analyzed to better resolve their clay mineral content.

In the result section, main minerals and mineral groups are distinguished including quartz, alkali-feldspars (summarizing microcline and orthoclase), plagioclase (mainly albite), biotite, muscovite, kaolinite, amphiboles, and smectite minerals.

3.4. Heavy mineral analysis

For heavy mineral analysis, samples were first treated with diluted acetic acid for 7 days, wet sieved to separate the fraction 0.063 - 0.4 mm, and dried in a drying chamber at 60 °C for 24 hours. Heavy minerals were separated from the light fraction by gravity separation in a funnel using tetrabrom-ethane ($C_2H_2Br_4$) with a density of 2.94 g/cm^3. The separated minerals were subsequently washed with acetone and dried. The washed and dried heavy minerals were then dispersed on a glass microscope slide covered with canada balsam with a light refraction value of 1.54, and covered with a thin cover glass.

Heavy minerals were studied using a polarization microscope. For quantitative analysis, 200 non-opaque grains per sample were counted using the ribbon counting method. The number of opaque grains was noted as well.

Nine heavy mineral separates were powdered in an agate mortar and analyzed with the diffractometer to identify their main components and to cross-check the results of the microscope analyses.

4. Results

4.1. Cretaceous and Miocene sediments

4.1.1. Grain size and color

Samples assigned to Cretaceous and Miocene collected from outcrops and drillings show a relatively large variability in sediment/rock type, grain size, and color. This accounts for both Miocene and Cretaceous sediments. The sediment/rock type ranges from clay/claystone through sand to more or less consolidated sandstones cemented with clay (Table 2). White, shades of grey, yellow and reddish brown dominate the color spectrum.

	Sample name	Depth below surface (m)	Stratigraphy/ Sediment origin	Sediment type/ Grain size	Color value	Color name	Lithofacies
Pre-Quaternary	DH 038/2	0.0	Klikov formation, C[a,b]	Sand/Sandstone	10 YR 8/1	White	Quartz fine gravel (< 10 mm) cemented with kaolinite
	DH 004/2	0.0	Klikov formation, C[a]	Clay/Claystone	10 YR 7/2 5 YR 6/4	Light gray Light reddish brown	Compact clay to claystone intercalated with layers of grey sandstone
	MUNICE 4	3.0	Zliv formation, M[a,c]	Clay	2.5 Y 6/2	Light yellowish gray	Grey clay
	MUNICE 7	3.0	Zliv formation, M[a]	Sandstone	10 YR 8/1	White	Quartz fine gravel (< 10 mm) in clayey matrix
	MUNICE 9	2.0	Zliv formation, M[a]	(Sandy) clay	5 Y 5/2	Olive gray	Shale
	HL 9/1	4.8	Klikov formation, C	Sand	2.5 Y 7/3	Pale yellow	Silty fine sand
	OP 2/1	4.1	Klikov formation ,C	Sand	10 YR 8/1	White	Silty medium sand
	HR 1/4	3.6	Klikov formation, C	Sandy fine gravel	10 YR 7/6	Yellow	Fine gravel (< 10 mm) cemented with sandy clay
Quaternary	DH 007/1	0.9	Q[e], CB[f] 4	Sand	10 YR 5/4	Yellowish brown	Silty coarse sand with fine gravel
	DH 011/2	1.0	Q, BB[g] 4	Sand	2.5 Y 6/3	Light yellowish brown	Silty coarse sand to fine gravel
	J 3/7	5.8	Q, CB 2	Pebbly sand	10 YR 6/6	Brownish yellow	Silty coarse sand with clasts < 6 cm
	J 5/1	0.5	Q, CB 1	Sand	10 YR 5/6	Yellowish brown	Silty medium sand, compacted
	J 7/2	0.7	Q, CB 1	Sand	2.5 Y 6/6	Olive yellow	Coarse sand, light silty with a few clasts < 4 cm, micaceous
	J 8/1	1.7	Q, CB 1	Sand	2.5 Y 7/3	Pale yellow	Silty medium to coarse sand, compacted
	J 8/5	3.7	Q, CB 1	Sandy gravel	2.5 Y 6/3	Light yellowish brown	Sandy gravel, clasts < 15 cm; matrix of sand to fine gravel
	HL 11/1	2.5	Q, CB 1	Sand	10 YR 6/6	Brownish yellow	Silty fine sand, micaceous
	DH 005/1	-0.3	Q, CB 1 cover sand	Sand	10 YR 6/4	Light yellowish brown	Coarse sand with fine gravel, loose
	DH 005/3	-2.2	Q, CB 1 cover sand	Sand	10 YR 6/6	Brownish yellow	Coarse sand, light silty, loose
	DH 005/4	-4.2	Q, colluvium	Sand	10 YR 7/6	Yellow	Silty medium to coarse sand, loose, colluvium
	HLR 1/2	0.9	Q, CB 2 cover sand	Sand	10 YR 6/4	Light yellowish brown	Silty fine to medium sand with very fine gravel
	HL 4/2	2.3	Q, BB 1	Sandy gravel	10 YR 6/6	Brownish yellow	Coarse gravel, clasts < 10 cm in matrix of silty coarse sand to fine gravel

HL 7/4.1	4.1	Q, BB 1	Sandy gravel	2.5 Y 7/2	Light grey	Loamy medium gravel, clasts < 5 cm, matrix of loamy fine sand to fine gravel
HL 8/1	1.4	Q, BB 1	Sand	10 YR 6/6	Brownish yellow	Silty fine to medium sand with very fine gravel
HL 8/4	4.9	Q, BB 1	Sandy gravel/ Pebbly sand	2.5 Y 7/4	Pale yellow	Silty fine sand with fine gravel
OP 2/5	1.8	Q, BB 1	Sandy fine gravel	2.5 Y 6/4	Light yellowish brown	Sandy gravel, clasts < 8 cm; matrix of sand to fine gravel
OP 2/6	3.3	Q, BB 1	Sandy fine gravel	2.5 Y 6/4	Light yellowish brown	Sandy gravel, clasts < 5 cm; matrix of sand to fine gravel
HR 1/1	0.7	Q, AF[h]	Sandy coarse gravel	10 YR 6/6	Brownish yellow	Sandy gravel, clasts < 7 cm; matrix of medium sand
HR 1/1.35	1.3	Q, AF	Sand	10 YR 7/6	Yellow	Silty medium sand
HR 1/3	2.6	Q, BB 3	Sandy gravel	10 YR 7/6	Yellow	Sandy gravel, clasts < 3 cm, partly cemented with clayey matrix
DH040	0.0	Q, TA[i]	Sandy gravel, angular	10 YR 5/3	Brown	Sandy angular medium gravel
DH041	0.0	Q, TA	Sandy gravel, angular	10 YR 4/4	Dark yellowish brown	Loamy coarse sand to fine gravel
DH 042/1	0.0	Q, TA	Sandy gravel, angular	10 YR 6/4	Light yellowish brown (black organic patches)	Silty coarse sand with organic material
DH 042/2	2.0	Q, TA	Sand	10 YR 6/3	Pale brown	Silty coarse sand with fine gravel

Table 2 Sample data: Depth, stratigraphy, sediment type/grain size, color and lithofacies.
[a] Stratigraphic assignment according to Geological map of the Czech Republic (Základní Geologická Mapa ČR 1:25.000, 1982).
[b] C - Cretaceous
[c] M - Miocene
[d] Pre-Q - Pre-Quaternary
[e] Q - Quaternary
[f] CB - Terrace level on crystalline
[g] BB - Terrace level in Budějovice basin (from Homolová et al., 2012)
[h] AF - Alluvial fan
[i] TA - Tributary alluvium

4.1.2. Bulk mineralogy

All samples of pre-Quaternary age contain mainly quartz, kaolinite, muscovite and except of DH 038/2, also significant amounts of alkali-feldspars. In Miocene samples MUNICE 4 and MUNICE 7, smectites are found as well (Table 3).

4.1.3. Heavy minerals

By looking at the heavy minerals spectra of pre-Quaternary sediments, a clear dominance of the stable minerals zircon and tourmaline is observed (Table 3, 4 and Fig. 9). In sample DH 038/2, anatase was recognised by X-ray powder diffraction (Fig. 6). Relatively unstable phases make up only max. 40 % of all non-opaque grains (Table 4). These are mainly staurolite, monazite, kyanite and epidote. The relative amounts of opaque grains in the heavy mineral spectra of Cretaceous and Miocene sediments are significantly higher than in samples of Quaternary age, exceeding 50 %. There are no significant differences between the heavy mineral spectra of Cretaceous and Miocene samples.

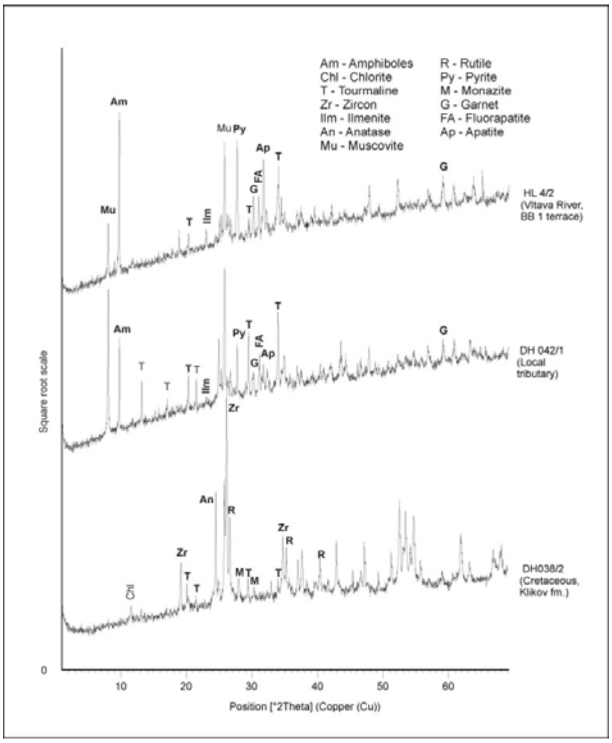

Figure 6 Diffractograms of heavy mineral separates. Note the dominance of stable minerals and the absence of amphiboles in the Cretaceous sample DH 038/2. See also the lower amount of amphiboles and higher amount of tourmaline in sample DH 042/1 (Vltava tributary) compared to sample HL 4/2 (Vltava River sediment). Bold printed minerals were detected in all diffractograms below.

4.2. Quaternary sediments

4.2.1. Grain size and color

The Quaternary Vltava River sediments are represented mainly by sand, sandy gravel and pebbly sand with subangular to well-rounded larger clasts, whereas the recent creek alluvia mainly consist of angular sandy gravel or sand. Alluvial fan material and other Quaternary sediments are mostly sandy, with variable content of coarser grains. In general, Quaternary sediments are uncemented and much less consolidated than Miocene or Cretaceous sediments.

Concerning the color, a large variety of yellow and brown can be observed in all sediment types (Table 2).

4.2.2. Bulk mineralogy

All samples of Quaternary age consist of quartz, alkali-feldspars (microcline and orthoclase), plagioclase and mica (muscovite and/or biotite). Only very low amounts of kaolinite and smectites were found.

Sediments from the recent Vltava floodplain south and north of the Hluboká fault also contain significant amounts of chlorite and amphiboles. The high content of amphiboles is identified in both, diffraction patterns of bulk samples and in the heavy mineral spectra (Table 3). Older terrace deposits in the Budějovice basin deposited on Cretaceous sediments (DH 011/2, HR 1/3) and recent alluvia of small Vltava tributaries near Hluboká nad Vltavou (DH 040, DH 041, DH 042/1 and DH 042/2) are missing the amphibole-peak in their diffraction patterns of bulk samples. Samples J 3/7 and HLR 1/2 from the terrace level CB 2 north of the Hluboká fault show only low amphibole contents (Table 3). No chlorite has been found in Vltava River terrace deposits situated above the recent floodplain.

Stratigraphy		Sample name	Bulk components	Main heavy minerals (> 5%)
Klikov fm., Cretaceous		**DH 038/2**	Q[a], Alk-Fsp[b], Kao[c], Mus[d]	Zr[j], Ru[k], T[l], Ky[m], Mo[n]
		DH 004/2[EG]	Q, Alk-Fsp, Kao, Mus	Zr, Ru, T
Zliv formation, Miocene		**MUNICE 4[EG]**	Q, Alk-Fsp, Kao, Mus, Bio[e], Sm[f]	T, Zr, Ru
		MUNICE 7[EG]	Q, Alk-Fsp, Kao, Mus, Sm	Zr, Mo, Tu, Ky
		MUNICE 9	Q, Alk-Fsp, Kao, Mus, Bio	T, Zr, Ru
Klikov fm., Cretaceous (This study)		**HL 9/1[EG]**	Q, Alk-Fsp, Kao, Mus, Sm	Zr, T, Ru, Mo
		OP 2/1[EG]	Q, Alk-Fsp, Kao, Mus, Bio, (Sm)	T, Zr
		HR 1/4	Q, Alk-Fsp, Kao, Mus, Bio	no data
Quaternary	**CB 4**	**DH 007/1**	Q, Alk-Fsp, Plag[g], Mus, Am[h], (Kao)	Am, Py[o]
	BB 4	**DH 011/2**	Q, Alk-Fsp, Plag, Mus, Kao	Am, T, Py, Zr, G[p], Si[q], Ep[r],
	CB 2	**J 3/7**	Q, Alk-Fsp, Plag, Mus, Kao	G, Am, T, Si, Ap[s]
	CB 1	**J 5/1[EG]**	Q, Alk-Fsp, Plag, Mus, Am, Chl[i], (Kao)	no data
		J 7/2[EG]	Q, Alk-Fsp, Plag, Mus, Bio, Am, Chl	Am, G, Ap, T, Ep
		J 8/1[EG]	Q, Alk-Fsp, Plag, Mus, Am, Chl, (Kao)	Am, Py, T, Zr
		J 8/5[EG]	Q, Alk-Fsp, Plag, Mus, Am, Chl	Am, G, Ep, Ap, Si
		HL 11/1[EG]	Q, Alk-Fsp, Plag, Mus, Am, Chl, (Kao)	no data
	CB 1 cover	**DH 005/1[EG]**	Q, Alk-Fsp, Plag, Bio, Am, (Chl)	Am, G, T, Zr
		DH 005/3	no data	Am, G, Ap
	Colluvium	**DH 005/4[EG]**	Q, Alk-Fsp, Plag, Bio, Kao, (Am, Sm)	Am, G, T
	CB 2 cover	**HLR 1/2**	Q, Alk-Fsp, Plag, Mus, Bio, Kao, (Am)	Am, G, T, Ap, Py
	BB 1	**HL 4/2**	Q, Alk-Fsp, Plag, Mus, Am, Chl	Am, G, T, Ep, Si
		HL 7/4.1	Q, Alk-Fsp, Plag, Mus, Am, Chl	Am, G, T, Si
		HL 8/1[EG]	Q, Alk-Fsp, Plag, Mus, Am, Chl, Kao	Am, Ep, T, G
		HL 8/4[EG]	Q, Alk-Fsp, Plag, Mus, (Am, Chl)	no data
		OP 2/5[EG]	Q, Alk-Fsp, Plag, Mus, Bio, Am, Chl	Am, G, Si, T
		OP 2/6	Q, Alk-Fsp, Plag, Mus, Kao	no data
	Alluvial fan	**HR 1/1**	Q, Alk-Fsp, Plag, Mus, Kao	no data
		HR 1/1.35	Q, Alk-Fsp, Plag, Mus, Am, Kao	Am, G, Ep
	BB 3	**HR 1/3**	Q, Alk-Fsp, Plag, Mus, Kao	Am, G, Zr, Ep, T
	Tributary alluvia	**DH 040**	Q, Alk-Fsp, Plag, Mus, Bio, Chl, Kao,	Am, G, T, Zr, Py, Ep
		DH 041	Q, Alk-Fsp, Plag, Mus, Bio, Chl, Kao,	Am, G, T, Zr
		DH 042/1	Q, Alk-Fsp, Plag, Mus, Bio, Kao	T, G, Am, Ap, Ep
		DH 042/2	Q, Alk-Fsp, Plag, Bio, Chl, Kao	T, Ep, Am, Ap, G, Si

Table 3 Bulk mineralogy and heavy mineral spectra of analyzed samples.
[a] Q - Quartz; [b] Alk-Fsp - Alkali Feldspars; [c] Kao - Kaolinite; [d] Mus - Muscovite; [e]Bio - Biotite; [f] Sm - Smectite; [g] Plag - Plagioclase; [h] Am - Amphiboles; [i] Chl - Chlorite; [j] Zr - Zircon; [k] Ru - Rutile; [l] T - Tourmaline; [m] Ky - Kyanite; [n] Mo - Monazite; [o] Py - Pyroxene; [p] G - Garnet; [q] Si - Sillimanite; [r] Ep - Epidote group; [s] Ap - Apatite; EG - sample treated with etylene glycol

4.2.3. Heavy minerals

The heavy mineral spectra of Quaternary sediments are much more variable than those of pre-Quaternary samples, showing a clear dominance of relatively unstable minerals. These are mainly amphiboles and garnets from non-opaques and ilmenite from opaques (identified using X-ray diffraction) (Table 4, Fig. 6). Other compounds are pyroxenes (mainly enstatite and diopside), minerals of the epidote-group, sillimanite, andalusite and apatite. The relative amounts of heavy mineral components are variable according to different factors such as the horizontal or vertical position of the sample within the former river bed. The stable minerals zircon, rutile and tourmaline make up only up to 15 % of all non-opaque grains.

The relative amounts of opaque grains in the heavy mineral spectra of Quaternary sediments are significantly lower than in samples of pre-Quaternary age, lying under 40 % (Table 4). Older terrace deposits in the Budějovice basin (DH 011/2 and HR 1/3) show slightly higher amounts of opaque and strongly weathered grains, probably because of a higher content of reworked Cretaceous material on which the terraces are deposited. Samples from local tributaries in the vicinity of Hluboká nad Vltavou (DH 042/1 and DH 042/2) show larger relative amounts of stable minerals, mainly tourmaline, and slightly lower contents of amphiboles.

Stratigraphy		Sample/ Mineral	Opaque	Non-opaque	Tour-maline	Zircon	Rutile	Mona-zite	Stau-rolite	Garnet colour-less	Garnet pink	Apatite	Titanite	Silima-nite	Kyanite	Epidote group[a]	Anda-lusite	Pyroxene group[b]	Amph. misc[c]	Amph. brown	Amph. green	Others	Un-known	Sum
Klikov fm. Cretaceous		DH 038/2	49.9[d]	50.1	10.0[e]	49.0	20.0	8.0	0.5	0.5	0.0	0.5	0.0	0.5	8.0	2.0	0.0	0.0	0.0	0.5	0.0	0.5	0.0	100.0
		DH 004/2	55.3	44.7	43.5	28.0	16.0	2.0	1.5	2.5	0.0	0.0	0.0	0.0	3.0	1.5	0.0	0.0	0.0	0.0	0.0	2.0	0.0	100.0
Zliv fm. Miocene		MUNICE 4	64.5	35.5	20.0	28.0	23.0	0.0	0.5	1.0	0.0	0.0	0.0	0.0	0.0	3.0	0.0	0.0	0.0	0.0	0.0	0.0	24.5	100.0
		MUNICE 7	90.2	9.8	9.0	65.5	3.0	11.0	0.5	0.0	0.0	0.0	0.0	0.0	5.0	0.0	1.5	0.0	0.0	0.0	0.0	1.5	3.0	100.0
		MUNICE 9	54.5	45.5	68.0	18.0	7.0	0.0	3.0	0.0	0.0	0.0	0.0	1.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	100.0
Klikov fm. (This study)		HL 9/1	70.0	30.0	23.0	39.0	18.5	9.0	0.5	0.0	0.0	1.0	0.0	0.0	3.5	1.0	0.0	0.0	0.5	2.0	0.0	1.0	1.0	100.0
		OP 2/1	14.7	85.3	85.0	6.5	1.0	0.0	3.5	0.0	0.0	0.0	0.0	1.5	2.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	100.0
Quaternary	CB 4	DH 007/1	10.9	89.1	3.0	3.0	1.5	0.0	0.5	1.0	0.0	4.0	0.0	3.5	1.5	1.0	1.0	15.0	43.5	10.0	5.5	1.0	5.0	100.0
	BB 4	DH 011/2	33.1	66.9	8.0	7.0	1.5	0.0	0.5	7.0	0.0	0.5	1.5	7.0	3.0	6.5	4.5	7.5	20.0	9.5	4.0	1.0	11.0	100.0
	CB 2	J 3/7	21.9	78.1	19.0	2.0	1.5	3.0	1.0	21.0	2.5	9.0	0.0	10.5	2.5	2.5	0.0	0.0	10.5	8.5	1.0	0.0	5.5	100.0
	CB 1	J 7/2	22.5	77.5	6.0	1.0	0.5	0.5	0.5	18.0	2.0	8.0	0.0	2.0	1.0	6.0	1.5	3.5	10.5	23.0	10.5	0.0	5.5	100.0
		J 8/1	22.9	77.1	7.0	7.0	3.5	0.0	0.5	3.5	0.0	0.0	0.5	3.5	0.0	3.5	0.0	9.0	11.0	29.0	17.0	0.5	4.5	100.0
		J 8/5	12.7	87.3	0.5	3.0	0.0	0.0	0.0	11.0	2.5	6.5	0.5	6.5	0.5	9.0	0.5	2.5	16.5	21.5	8.5	1.5	9.0	100.0
	CB 1 cover	DH 005/1	23.1	76.9	5.0	5.0	2.5	1.5	0.5	20.5	0.0	3.0	0.0	1.5	1.5	3.0	0.0	2.5	12.5	18.0	17.5	1.0	4.5	100.0
		DH 005/3	35.5	64.5	4.0	4.0	2.0	0.0	0.5	13.0	0.5	7.0	0.5	2.0	2.5	2.0	0.0	4.0	31.5	9.0	11.5	0.5	5.5	100.0
	Colluvium	DH 005/4	37.9	62.1	10.5	0.0	0.5	0.0	0.5	12.0	0.5	4.5	0.0	4.5	0.5	2.5	1.0	3.0	33.0	8.5	13.5	0.0	5.0	100.0
	CB 2 cover	HLR 1/2	23.0	77.0	8.0	4.0	3.0	2.0	0.5	17.0	1.0	5.0	1.0	2.0	0.0	0.0	2.0	5.0	16.5	14.0	10.0	1.0	8.0	100.0
	BB 1	HL 4/2	29.8	70.2	6.0	4.0	0.5	0.5	0.5	18.5	6.0	4.0	0.5	5.0	1.0	6.0	1.0	4.0	9.0	15.5	11.0	1.5	5.5	100.0
		HL 7/4.1	13.8	86.2	14.0	4.5	0.0	0.0	0.5	14.0	5.5	4.0	0.0	10.0	3.5	3.0	4.0	0.5	10.0	15.0	8.5	0.0	3.0	100.0
		HL 8/1	20.6	79.4	7.0	3.0	1.0	0.5	0.5	6.0	0.5	0.5	0.0	3.0	1.0	9.0	1.0	2.0	11.0	30.5	22.0	0.5	1.0	100.0
		OP 2/5	8.3	91.7	5.0	1.5	0.0	0.0	0.5	11.5	1.0	4.0	0.0	5.5	0.5	4.0	3.0	3.0	23.5	22.5	10.0	0.0	4.5	100.0
	Alluvial fan	HR 1/1.35	20.6	79.4	4.5	3.0	3.5	0.0	0.0	15.5	8.0	1.5	0.0	3.5	1.5	10.0	1.5	0.0	23.0	16.0	2.5	0.0	6.0	100.0
	BB 3	HR 1/3	42.9	57.1	6.5	9.5	1.5	2.0	1.5	13.5	0.0	3.5	2.0	1.5	2.0	8.0	0.0	0.0	21.5	15.0	3.0	5.0	4.0	100.0
	Tributary alluvia	DH 040	29.6	70.4	8.0	5.5	2.0	2.5	0.5	20.0	0.5	3.5	0.0	2.5	1.5	5.0	0.0	5.5	11.5	11.0	16.5	1.5	2.5	100.0
		DH 041	29.8	70.2	11.5	10.0	3.0	2.5	0.5	24.5	0.0	2.0	0.0	4.5	1.0	1.5	0.0	0.0	24.0	3.0	8.5	0.0	3.5	100.0
		DH 042/1	36.5	63.5	31.0	3.5	0.5	2.0	0.5	20.5	2.5	10.5	0.0	3.5	1.0	6.5	1.0	0.0	14.0	1.5	1.5	0.0	0.0	100.0
		DH 042/2	6.5	93.5	22.0	4.5	2.5	3.0	0.5	11.5	0.0	12.0	0.0	5.5	4.0	18.5	0.0	0.0	10.0	2.5	2.5	1.0	0.0	100.0

Table 4 Heavy minerals spectra of analyzed samples

[a] Epidote group includes the minerals epidote, clinozoisite and zoisite

[b] Pyroxene group includes mainly enstatite and diopside (colourless and green)

[c] Miscellaneous amphiboles include mainly tremolite and actinolite

[d] Percent of all grains counted (opaques + non-opaques)

[e] Percent of 200 non-opaque grains counted

5. Discussion

5.1. General characteristics of pre-Quaternary and Quaternary deposits

The results of this study show that there are clear differences in the mineralogical composition as well as in the heavy mineral spectra of Quaternary and pre-Quaternary sediments. With the applied sediment-petrologic methods, a relatively fast discrimination between these two sediment groups can be achieved (Table 3).

Pre-Quaternary sediments contain mainly quartz, kaolinite, muscovite and alkali-feldspars. Most of the pre-Quaternary samples analyzed in this study are assigned to the Upper Cretaceous Klikov Formation (Table 3). The assignment is in accordance with the geological map of the study area (Základní Geologická Mapa ČSSR 1:25.000, 1982). The high amounts of kaolinite and the absence of less stable minerals such as plagioclase and amphiboles serve as an evidence for tropical and subtropical kaolinic weathering that took place in the study area during the Late Cretaceous and Miocene (Slánská, 1976; Nehyba and Roetzel, 2010). The samples MUNICE 4, MUNICE 7, and MUNICE 9, bearing significant amounts of smectites, most probably belong to the Miocene Zliv Formation. This is also in accordance with the geological map of the study area (Základní Geologická Mapa ČSSR 1:25.000, 1982). None of the samples analysed in this study can be assigned to the Miocene Mydlovary Formation.

Compared to pre-Quaternary deposits, Quaternary sediments contain beside quartz, alkali-feldspars and mica also plagioclase and only low amounts of kaolinite (Table 3). Most of the Vltava River sediments contain significant amounts of chlorite and amphiboles. The presence of less stable minerals as well as the small amounts of kaolinite in Quaternary sediments rule out long periods of chemical weathering and are clearly in line with the young age and weathering conditions of these deposits.

By looking at the heavy minerals spectra of pre-Quaternary and Quaternary deposits, a clear dominance of ultra stable minerals can be observed in the first group (Fig. 7 and 8). This can be interpreted as a result of long-term weathering and dissolution of unstable heavy minerals during the Cretaceous and Neogene. In Quaternary deposits, relatively unstable minerals such as amphiboles and garnet are the main components of the heavy mineral suites. In this case, the weak recent chemical weathering has had almost no effect on the mineralogical composition of the young clastic sediments (Kodymová, 1963) and therefore a much broader spectrum of heavy minerals is preserved.

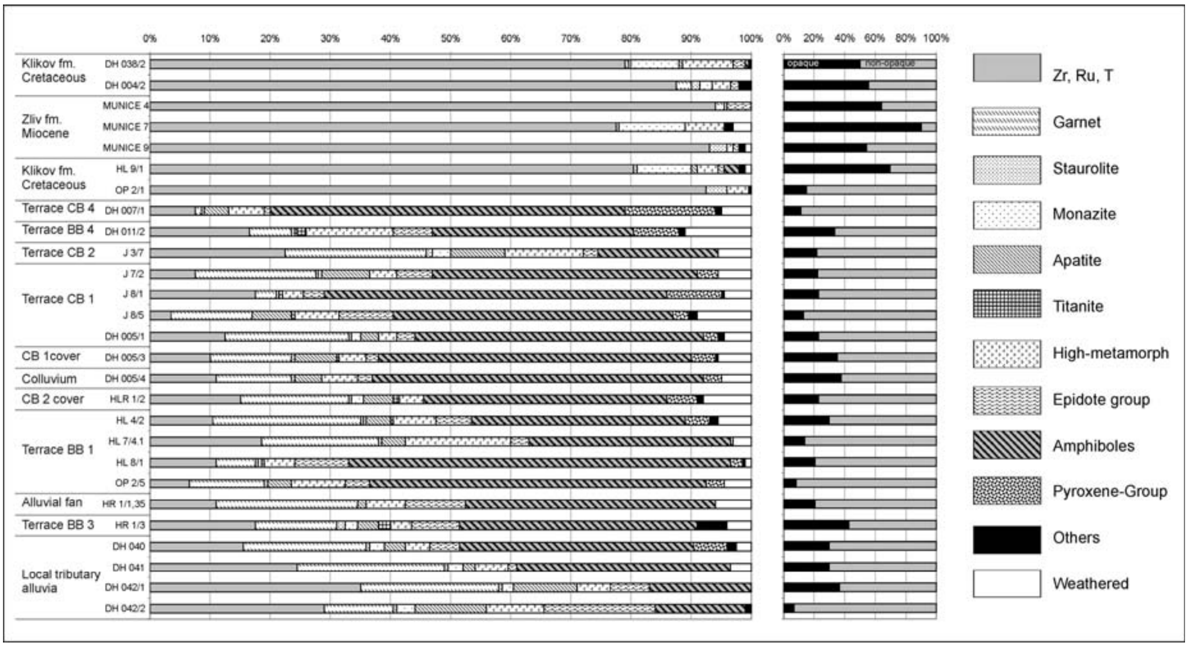

Figure 7 Distribution of non-opaque heavy minerals (simplified) and relative amounts of opaques and non-opaques in the heavy mineral suites of analyzed samples. The group "High-metamorph" includes andalusite, kyanite and sillimanite. Note the dominance of stable minerals zircon, rutile and tourmaline (Zr, Ru, T) in pre-Quaternary sediments as well as the dominance of amphiboles in Quaternary sediments transported by the Vltava River.

The observations described above were proved by statistical analyses of heavy mineral distributions of samples assigned to Quaternary and Miocene/Cretaceous, showing significant differences between these two groups (Fig. 8 and Table 5). The results of the T-Tests for both groups (Quaternary and Miocene/Cretaceou) are very convincing, even though the number of samples in both groups was relatively small (7 in the group "Miocene/Cretaceous" and 20 in the group "Quaternary").

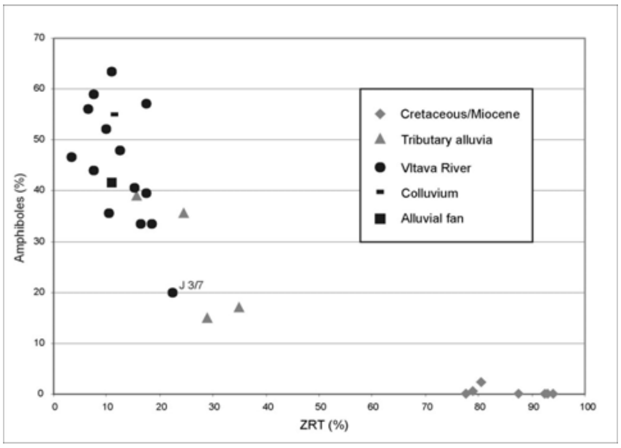

Figure 8 Discrimination diagram showing the relationship between the content of weathering resistant heavy minerals zircone (Z), rutile (R) and tourmaline (T) and amphiboles in all analyzed samples of Quaternary and Cretaceous/Miocene age. Based on this relationship, a clear assignment of samples to these two groups can be done.

Mineral	T-Test	T-Value	Significance
Garnets	Welch	-9.035	0.000
Zircon, Rutile, Tourmaline	Student	20.959	0.000
Sillimanite	Student	-3.977	0.001
Amphiboles	Welch	-13.312	0.000
Apatite	Student	-3.498	0.002

Table 5 T-Test for the groups "Quaternary" and "Miocene/Cretaceous"

The remarkable presence of amphiboles in bulk samples as well as in heavy mineral suites of Vltava River sediments is assigned to the high abundance of amphibole-bearing lithologies such as amphibolites, granulites and some igneous rocks (plutons, some orthogneisses etc) (Slánská, 1963) found in the source area of the river (see Fig. 1). The source areas of local tributaries are significantly smaller and built up by leucocratic migmatites, biotite gneisses and sillimanite-biotite gneisses, which in places are partly migmatized (Základní Geologická Mapa ČSSR 1:25.000, 1982). These lithologies deliver mainly sillimanite, garnet and tourmaline with minor amounts of apatite, epidote, monazite, opaques, and titanite (Vrána et al., 1990). The significantly lower amounts of amphiboles in both the bulk samples and the heavy mineral suites as well as the higher amounts of tourmaline in samples DH 042/1 and DH 042/2 (Fig. 7) underline the strong influence of local lithologies on the mineralogical composition as well as on the heavy mineral content of these sediments. The significantly higher amount of tourmaline in recent creek alluvia compared to Vltava river sediments was proved with a T-Test by Student (T-Value: -3.358; Significance: 0.003). Characteristic is also the absence of chlorite in local creek alluvia and alluvial fan material.

Chronologic scale			Stratigraphic unit	Thickness	Sediment type	Bulk components	Heavy minerals	Dating method
Quaternary	Holocene		Recent creek alluvia	x	Sand, angular gravel	Quartz, Alkali-Fsp, Plagioclase, Muscovite, Kaolinite, Chlorite	Reflecting the local lithologies, mainly unstable minerals	Not dated
Quaternary	Holocene		Vltava overbank sediments	2	Clay to sand	Same as BB 1	Same as BB 1	OSL/IRSL (Homolová et al., 2012)
Quaternary	Pleistocene	Late	Solifluction loams	3	Unsorted reworked material with variable grain size	Quartz, Alkali-Feldspar, Plagioclase, Mica, Kaolinite	Amphiboles, Garnet, Apatite, Sillimanite, Kyanite, Epidote, Andalusite, Zircone, Tourmaline, Rutile	OSL/IRSL (Homolová et al., 2012)
Quaternary	Pleistocene	Late	Alluvial fans	15	Unsorted reworked material with variable grain size	Quartz, Alkali-Feldspar, Plagioclase, Mica, Kaolinite	Amphiboles, Garnet, Apatite, Sillimanite, Kyanite, Epidote, Andalusite, Zircone, Tourmaline, Rutile	OSL/IRSL (Homolová et al., 2012)
Quaternary	Pleistocene	Late	Vltava River terraces: BB 1	8	Fluvial sandy gravel and pebbly sand	Quartz, Alkali-Feldspar, Plagioclase, Muscovite, Amphiboles, Chlorite	Amphiboles, Garnet, Apatite, Sillimanite, Kyanite, Epidote, Andalusite, Pyroxenes, Zircone, Tourmaline, Rutile	OSL/IRSL (Homolová et al., 2012)
Quaternary	Pleistocene	Early - Middle	Vltava River terraces: BB 2	5	Fluvial sandy gravel and pebbly sand	No data	No data	Not dated (approx. assignment based on relative elevation above recent Vltava floodplain)
Quaternary	Pleistocene	Early - Middle	Vltava River terraces: BB 3	3	Fluvial sandy gravel and pebbly sand	No data	No data	Not dated (approx. assignment based on relative elevation above recent Vltava floodplain)
Quaternary	Pleistocene	Early - Middle	Vltava River terraces: BB 4	4	Fluvial sandy gravel and pebbly sand	Quartz, Alkali-Feldspar, Plagioclase, Muscovite, Kaolinite	Amphiboles, Garnet, Sillimanite, Kyanite, Epidote, Andalusite, Pyroxenes, Zircone, Tourmaline	Not dated (approx. assignment based on relative elevation above recent Vltava floodplain)
Quaternary	Pleistocene	Early - Middle	Vltava River terraces: BB 5	3	Fluvial sandy gravel and pebbly sand	no data	no data	Not dated (approx. assignment based on relative elevation above recent Vltava floodplain)
Neogene	Pliocene		Ledenice Fm.	10	Sandy clays	Quartz, Illite, Limonite (Huber, 2003)	no data	Palynomorphs (Pacltová, 1963), diatoms (Řeháková, 1963)
Neogene	Miocene		Mydlovary Fm.	85	Sands, clays, silts, diatomites, lignites	Quartz, Kaolinite, Illite, Montmorillonite, Organic matter, Calcite (in places) (Slánská, 1976)	Zircon, Tourmaline, Rutile, Amphiboles, Andalusite, Epidote, Sillimanite (Slánská, 1963)	Palynomorphs (Pacltová, 1963), diatoms (Řeháková, 1963); Diatoms (Řeháková, 1963)
Neogene	Miocene		Mydlovary Fm. / Zliv Fm.	< 20	Sands, clays, silicificated sandy clays, sandstones, pebbly conglomerates	Same as Klikov Fm. but with montmorillonite (Svoboda, 1966)	Zircon, Tourmaline, Rutile, Kyanite, Opaques, Anatase, Garnet, Epidote, Monazite, Staurolite, Sillimanite, Spinel, Titanite (Huber, 2003)	Diatoms (Řeháková, 1963)
Mesozoic	Upper Cretaceous		Klikov Fm.	~ 340	Claystones and kaolinitic sandstones	Quartz, Alkali-Feldspars, Mica (muscovite and biotite), Kaolinite (Slánská, 1976)	Main minerals: Zircon, Tourmaline Accesories: Garnet, Apatite, Rutile, Kyanite, Monazite, Staurolite (Slánská, 1976)	Palynomorphs, seeds and fruits, macroflora (Knobloch, 1985)
Paleozoic--Precambrian			Moldanubian		Crystalline basement			

Figure 9 Stratigraphic chart of the NE part of the Budějovice basin. Thickness of pre-Quaternary sedimentary units is derived from the Geological map 1:25.000 (Základní Geologická Mapa ČSSR 1 : 25.000, 1982), thickness of Quaternary units derived from Homolová et al., 2012.

Figure 9 gives an overview of all stratigraphic units occurring in the Budějovice basin with their basic characteristics including age, thickness, sediment type, bulk and heavy minerals components. The dating methods are shown as well.

5.2. Application of obtained data for stratigraphic assignment of sediments

The results of this study can be applied to samples of doubtful stratigraphic assignment, where optical characteristics were not sufficient for defining their age. A clear line dividing Quaternary from pre-Quaternary sediments can be drawn in drilling profiles OP 2 and HL 8 - HL 9 by looking at the mineralogical composition of samples from these drilling cores (Fig. 10). Samples of pre-Quaternary age (OP 2/1 and HL 9/1) contain mainly quartz, kaolinite and muscovite with a certain amount of alkali-feldspars and smectites. Quaternary sediments additionally contain plagioclase, chlorite and amphiboles. In the profile OP 2, a decrease of plagioclase, chlorite and amphiboles and an increase of kaolinite with depth are recorded. The heavy mineral spectra of those samples underline these results.

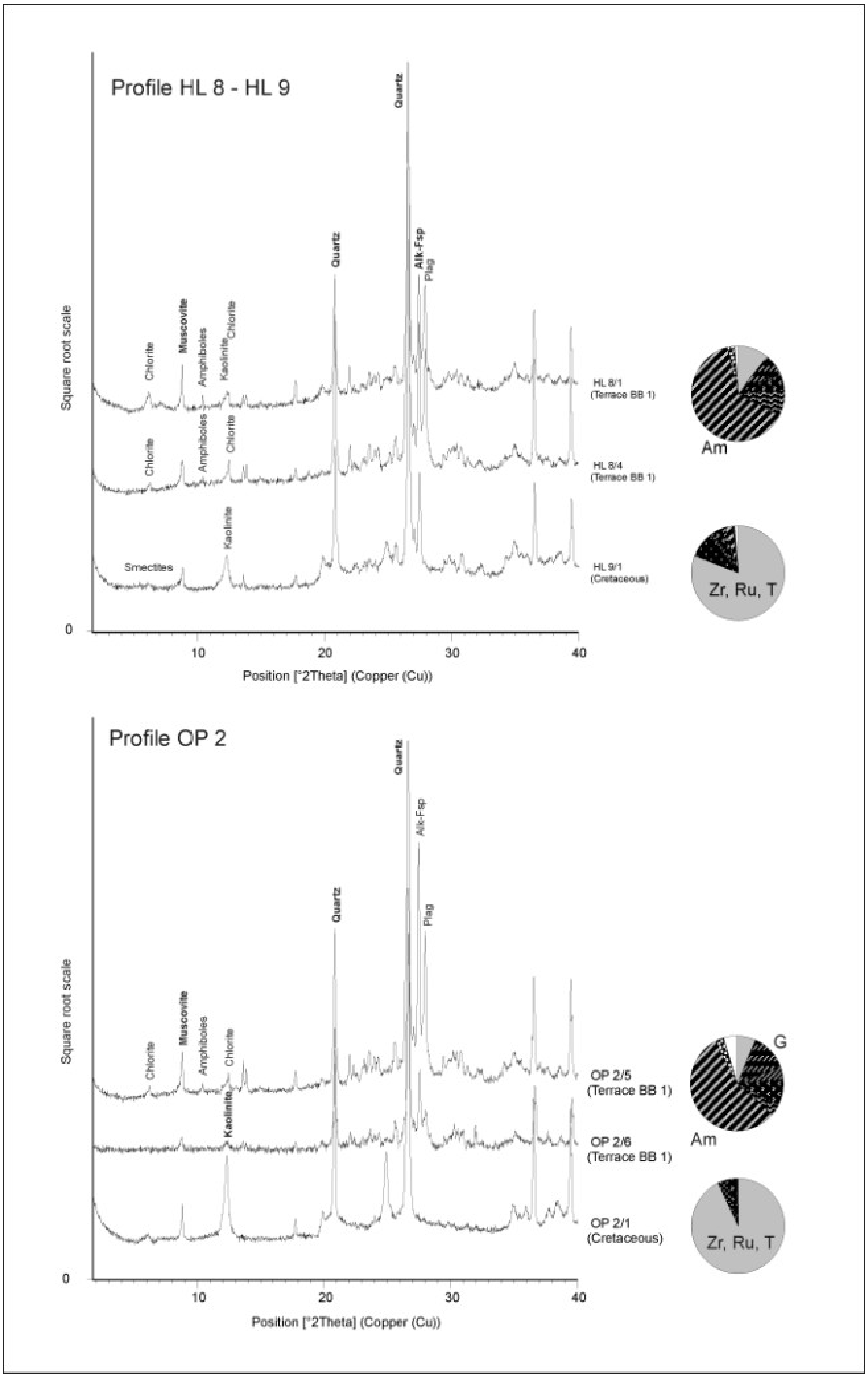

Figure 10 Diffractograms and heavy mineral composition of samples in drillings HL 8, HL 9 and OP 2. Note the different mineralogical content of Quaternary (HL 8/1, HL 8/4, OP 2/5 and OP 2/6) and pre-Quaternary samples (HL 9/1 and OP 2/1). The heavy mineral spectra underline the stratigraphic assignment of the samples. Alk-Fsp - Alkali feldspars; Plag - Plagioclase; Am - amphiboles; Zr, Ru, T - Zircon; Rutile; Tourmaline; G - garnet.

Samples HL 9/1 and OP 2/1 from the Vltava river floodplain with luminescence ages of > 74 ka and > 176 ka (Homolová et al., 2012) can be therefore clearly assigned to the pre-Quaternary. They probably represent the Cretaceous Klikov Formation underlying the Quaternary fluvial gravels in this area. The samples also contain small amounts of smectites, but this can be probably assigned to the fact, that they are overlain by several meters of Quaternary deposits, from which the smectites could have been washed down.

A more complicated situation is observed in the profile HR 1, exposing sediments of a large alluvial/colluvial fan which was deposited on top of an old Vltava River terrace. In the uppermost two meters of the profile, unsorted subrounded coarse gravel mixed with sand (HR 1/1) is underlain by silty sand, probably representing redeposited Vltava River fluvial sediments. The presence of amphiboles in the bulk sample of HR 1/1.35 dated by the luminescence method to 54.4 ± 5.9 ka (Homolová et al., 2012) serves as an evidence for that. The alluvial fan material is underlain by a remnant of an old Pleistocene terrace (sample HR 1/3) and Cretaceous coarse sand (HR 1/4) (Fig. 11). According to the mineralogical composition of the samples, the base of Quaternary can be put between the samples HR 1/3 and HR 1/4.

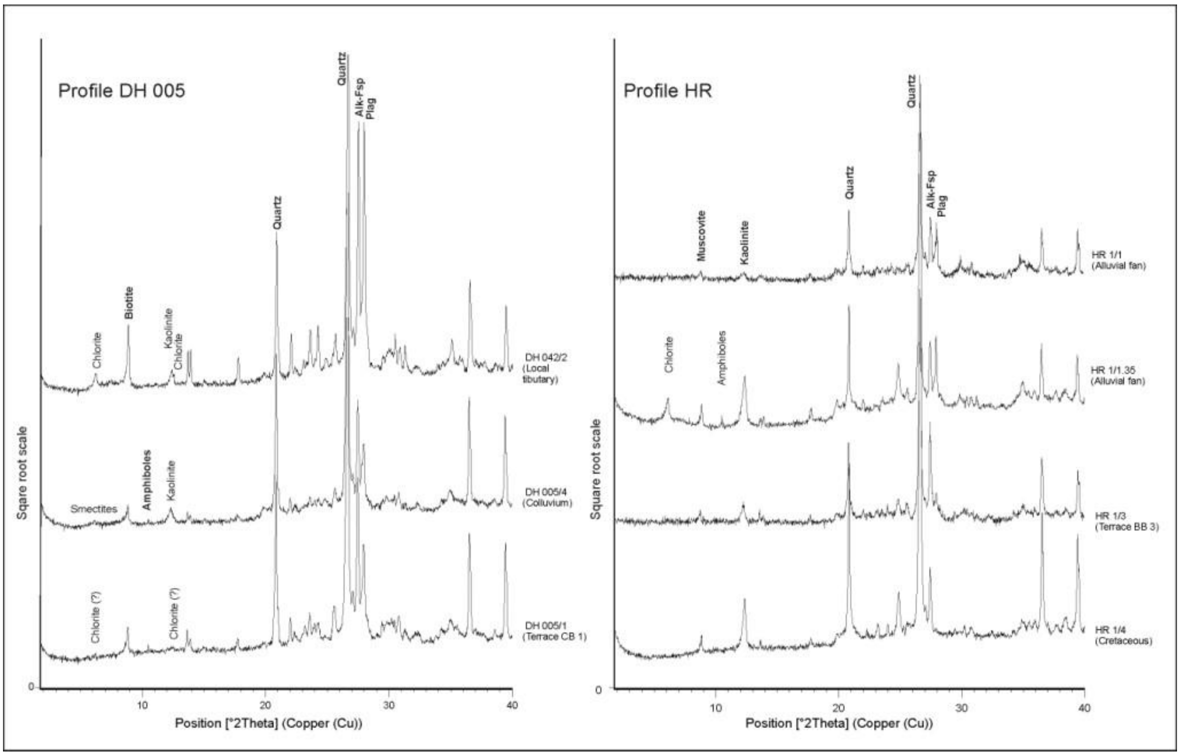

Figure 11 Diffractograms of samples from outcrop DH 005 and a sandy tributary alluvium DH 042. Note the missing amphibole peak in sample DH 042/2. The profile HR is revealing sediments of an alluvial fan (HR 1/1, HR 1/1.35) deposited on fluvial gravel from terrace BB 3 (HR 1/3) and Cretaceous sandstone (HR 1/4). Alk-Fsp - Alkali Feldspars; Plag - Plagioclase.

Within the different types of Quaternary sediments, some remarkable differences in mineralogical composition and heavy mineral spectra are observed as well.

In lowermost parts of the profile DH 005 we can see well sorted, cross-bedded fluvial coarse sand overlying sandy gravel (DH 005/1). This layer is covered by ~ 50 cm of medium to coarse sand with plane lamination, and about 90 cm of intercalated 2 to 5 cm thick layers of medium and coarse sand, silt and shale (DH 005/3) (Fig. 4). The whole succession shows a general fining-up trend and is interpreted as fluvial channel fill overlain by high stage flood deposits. In the upper parts of the profile, the fluvial succession is overlain by alternating layers of fine and medium sand partly containing humus and displaying thick lamination and laminae (DH 005/4). Showing a dip of 10° to 20°, parallel to the actual slope, this succession is interpreted as a colluvium.

Based on the presence of amphiboles in the bulk sample of the coarse sand overlying the fluvial gravel (DH 005/1), this was transported by the river Vltava. Small amounts of amphiboles were also found in the colluvial material (DH 005/4). This was probably originally transported by the Vltava River and later redeposited by periglacial slope processes. In samples from the tributary (DH 042/2) (Figure 11), the amphibole peak is missing. This makes the major difference between sediments originating from the Vltava River and from its tributaries. The heavy mineral composition is showing significantly higher contents of tourmaline compared to the Vltava sediments, pointing to the stronger influence of the local lithology.

6. Conclusion

The study presents sediment-petrological characteristics of clastic sediments from the Budějovice basin and adjacent areas. With the help of basic sedimentological methods such as X-ray powder diffraction of bulk samples and heavy mineral analysis, a clear determination of pre-Quaternary and Quaternary sediments is possible. There are significant differences in the mineralogical composition of bulk samples as well as in the heavy mineral spectra of both sediment groups. The bulk components of pre-Quaternary sediments are predominantly quartz, alkali-feldspar, muscovite and kaolinite as a result of long-lasting weathering processes. In contrast, Quaternary sediments additionally contain the less weathering resistant minerals plagioclase and chlorite and only small amounts of kaolinite, ruling out longer periods of chemical weathering. Vltava River sediments further contain significant amounts of amphiboles, which are missing in recent alluvia of the local Vltava tributaries, alluvial fan material and some older terrace deposits. In general, the mineralogical composition and heavy mineral suites of the analyzed sediments reflect the lithological properties of their source areas as well as the duration of weathering processes these sediments underwent.

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Appendix B

Popotnig, A., Homolová, D., and Decker, K. (submitted to "Geomorphology"). Morphometric analysis of a reactivated Variscan fault in southern Bohemian Massif (Budějovice basin, Czech Republic).

(submission date: 15.6.2012)

Morphometric analysis of a reactivated Variscan fault in southern Bohemian Massif (Budějovice basin, Czech Republic)

Angelika POPOTNIG [a,*], Dana HOMOLOVÁ [a], Kurt DECKER [a]

[a] Department of Geodynamics and Sedimentology, University of Vienna, Althanstraße 14, 1090 Vienna, Austria

Abstract

The NW-SE striking Hluboká fault and the NNE-SSW striking Rudolfov fault in southern Bohemia are part of a late Variscan fault-system and were repeatedly re-activated in Mesozoic, Miocene and Pliocene times. The faults form the NE and SE margin of the Budějovice basin filled with up to 340 m thick Cretaceous to Quaternary sediments and overlying the hanging wall of the fault system.

We compared two hill slopes crossing the faults and one slope which is not directly fault-controlled. We used several morphological parameters to investigate small tributaries of the Vltava river which cut into crystalline basement units. All creeks are similar in hydrological conditions and the common base level formed by the Vltava river. Morphological differences in valley shapes are therefore likely a result of different uplift of the crystalline basement with respect to the sedimentary basin.

All calculated geomorphic parameters characterize the hill slope crossing the Hluboká fault as a very straight mountain-piedmont junction in the vicinity of the fault and the morphology as influenced by uplift along the fault. The values are significantly different than those observed at the other two hill slopes. The marked convex-up thalweg sections with single large knickpoints close to the Hluboká fault are supporting the data as well as an isoline map of vertical crustal movements in the surrounding area of the Budějovice basin (Vyskočil, 1973).

Values observed at the north facing slope of Račice mountain and at the hill slope crossing the Rudolfov fault are of similar range and therefore may classify both slopes as of moderate tectonic activity. Observations of thalweg sections show the small difference in the concave

profiles passing into convex profiles for the north facing slope, but concave-convex and convex thalweg sections and slightly higher Stream Length (SL) values for the hill slope crossing the Rudolfov fault.

1. Introduction

The Bohemian Massif is part of the stable European platform in the Northern foreland of the Alpine-Carpathian fold-thrust belt, which traditionally was regarded as an exceptionally stable intra-continental region devoid of active deformation. This view was based on the very low level of historical seismicity (ACORN, 2004; Lenhardt et al., 2007) and regional GPS studies considering the Massif as part of Stable Europe (Bus et al., 2009). Post-Variscan tectonics in this crystalline basement complex were regarded to be restricted to the reactivation of Paleozoic fault systems (Brandmayr et al., 1995, 1997) in Cretaceous and Neogene times due to pre- and syn-collisional compression in the foreland of the evolving Carpathian–East-Alpine orogen (compare the review by Ziegler and Dèzes, 2007, and references therein).

This traditional view is challenged by geodetic studies identifying significant differential vertical (Vyskočil, 1979; Přibyl, 1995) and horizontal movements within the Bohemian Massif (Schenk et al., 2001) as well as by recent geomorphological and paleoseismological analysis of reactivated Paleozoic faults (Badura et al., 2007; Štěpančíková et al., 2010). These differential movements occur at the background of the continued large-scale uplift of the Bohemian Massif (Legrain and Stüwe, 2011).

Although southern Bohemia was intensively explored geologically (Němejc, 1956; 1962, Pacltová, 1961, Malecha et al., 1962, Malkovský, 1995, Ševčík, 2007, Schulmann, 2009) and geophysically (Košt'ák 1998, 2000, Košt'ák et al., 2006, 2011; Stemberk et al. 2010) only few studies in the 20th century investigated Quaternary and active vertical tectonic movements in the Budějovice basin (Vyskočil, 1973, 1984; Přibyl, 1995). In recent times the assessment of potentially active faults became an important topic in the course of seismic hazard analyses for the Bohemian Massif. Analyses focused on the region around the nuclear power plant of Temelín in Southern Bohemia investigating possible vertical tectonic movements at the faults bounding the Budějovice basin (Homolová et al., 2012; Popotnig et al., 2011). As part of a project to update the database for the seismic hazard assessment we analyzed the Hluboká fault northeast of the Budějovice basin, which is a segment of the Jáchymov (Joachimstal) shear zone (Fig. 1). In historical times several weak earthquakes ($M_L \leq 3.5$, epicental intensity $I_0 \leq 4.5$) were recorded near the basin. However these earthquakes were not significant for identifying the active tectonic structures. We therefore use quantitative geomorphic methods to evaluate possible active movements along the faults at the margins of the Budějovice basin focusing on the Hluboká fault (Fig. 2).

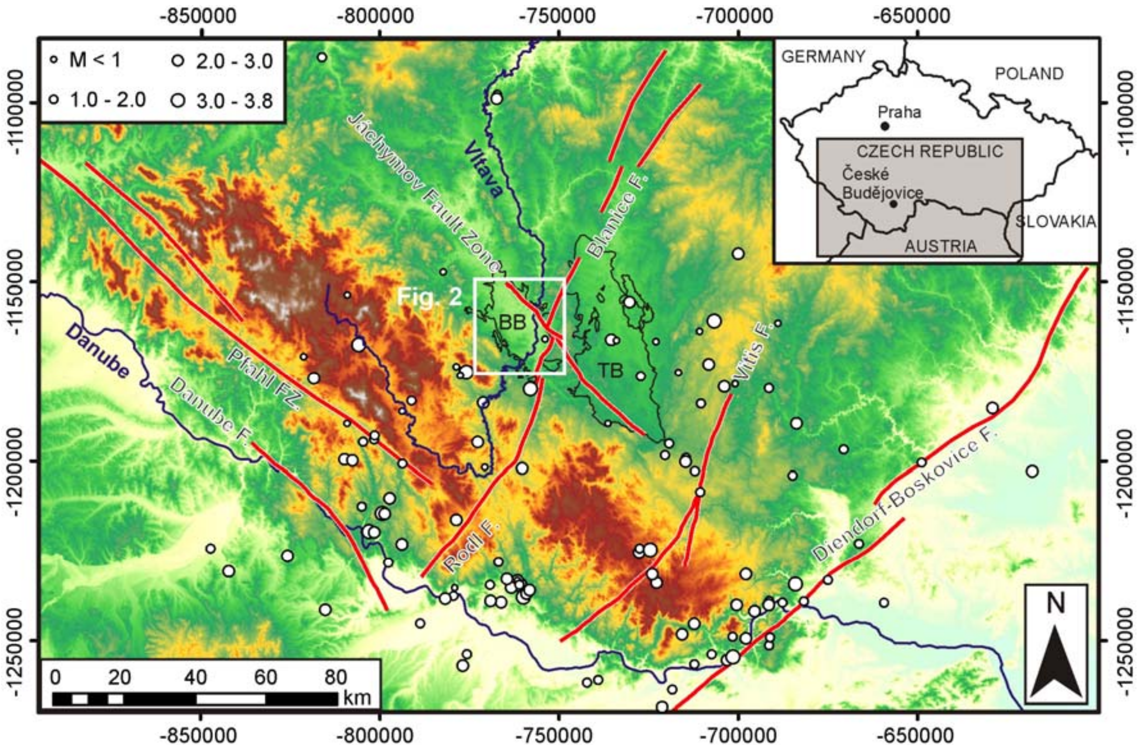


Figure 12. A digital elevation model (DEM) of southern Bohemia with schematic structural map of the main fault-systems modified after Geological map of Czech Republic 1:500,000 (Cháb et al., 2007) and Geological map of Austria 1:1,000,000 (Geologische Übersichtskarte der Republik Österreich: mit tektonischer Gliederung, 1964). Thin black lines represent the Budějovice basin (BB) and the Třeboň basin (TB) respectively. White rectangle represents the study area of the Budějovice basin. Displayed is the distribution of all earthquakes (M from <1 to 3.8) within South Bohemia after the Acorn CIP Catalogue, 2004.

Fluvial systems are known to be sensitive to the relative uplift/subsidence of fault blocks when vertical movements lead to significant base-level changes. The associated fluvial patterns and morphologies are described by a number of geomorphic parameters, which proved useful tools for identifying active vertical displacement (Keller, 1986; Keller and Pinter, 1996; Burbank and Anderson, 2001; Bishop, 2007), even in areas with low displacement rates (Pedrera et al., 2009). The most commonly used parameters are mountain front sinuosity (Smf), stream length gradient (SL), valley floor width-to-height parameter (Vf), drainage elongation ratio (Bs, Re), basin shape (Rf) and circularity index (C) along with stream profiles (see Tab. 1 and references therein). Single parameters as well as combinations of few parameters were successfully used in several studies on active tectonic mountain ranges (Delcaillau et al., 2010; Font et al., 2010; García-Tortosa et al., 2008; Gürbüz and Gürer, 2008; Bhatt et al., 2007; Pinter, 2005). However individual indices do not only respond to tectonic signals but also to other parameters like stream power, differential rock erodibility and climatic signals. To account for this complexity and to identify tectonic influences more clearly we analyzed all of the listed geomorphologic parameters for 16 subbasins at different slopes towards the Budějovice basin (Fig. 5).

We used a geographic information system (GIS) combining geological maps (Český geologický ustav Praha, Geologická Mapa ČR 1:25,000), topographic maps (Základní mapa České Republiky, 1:10,000; ZABAGED, 2009) and a digital elevation model with 10 m ground resolution for the morphological analyses. The DEM was created from digital contour lines with a 2 m contour interval, geodetic points and from lines representing river banks and lakes digitized from the analogue topographic map (Homolová et al., 2012). Where the resolution of maps and the DEM appeared insufficient, morphological features such as valley floor widths and slope angles were mapped in the field. As the study area is partly located in a densely populated area all analyzed drainage basins were surveyed in the field to identify possible anthropogenic features and overprints such as artificial drainages, peneplanations etc. Thereby we were able to identify the Hluboká fault scarp as a unique morphological feature in the Budějovice basin, which apparently results from vertical displacement at the fault.

2. Regional Geology

The Budějovice basin situated in Southern Bohemia (Fig. 1) is a sedimentary basin located on the Moldanubian crystalline complex of the Bohemian Massif. The Variscan crystalline basement is formed by Precambrian to Paleozoic rocks including highly metamorphosed mica schists, gneisses and migmatites as well as igneous rocks of the Central Bohemian and Moldanubian Plutons (Slánská, 1976; Fig. 2). The Upper Carboniferous and Lower Permian coal-bearing claystones and sandstones of the Blanice Graben represent the oldest un-metamorphosed sediments in the study area (Suk et al., 1989).

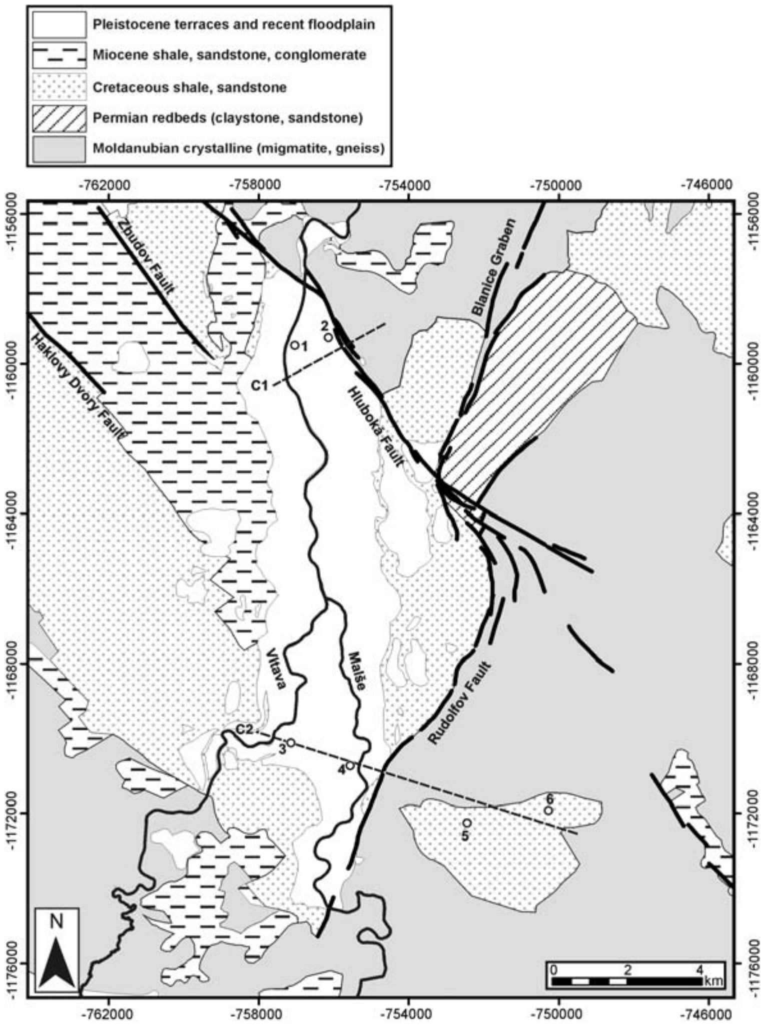


Figure 13. Simplified geological map of the study area featuring the different lithologies and major faults derived from geological maps marked by thick black lines. Dashed lines show locations of cross-Sections C1 and C2 in Figure 3, circles numbered 1-6 stand for boreholes in this area Borehole data according to Základní Geologická Mapa ČSSR 1:25,000 (1982).

The deposition of the sedimentary fill of the Budějovice basin started in Upper Cretaceous and continues intermittently until today. The depocenter of the basin is located in its south-eastern part where sediment thickness reaches up to about 350 m. With a thickness of 340 m, the Upper Cretaceous Klikov formation consisting of grey and red sandstones and mudstones is the thickest stratigraphic unit of the sedimentary basin fill (Svoboda, 1966; Slánská, 1976).

Miocene deposits are represented by up to 15 m thick layers of sandy clays, sandstones and conglomerates of the Zliv formation and up to 60 m thick sediments of the Mydlovary formation consisting of clayey sands, sandstones and clays (Svoboda, 1966).

Quaternary sediments in the study area mainly include fluvial sandy gravels and pebbly sands of the main rivers Vltava and Malše. Crossing the Budějovice basin from the south to the north, these rivers accumulated terrace bodies of different horizontal and vertical extent during the whole Pleistocene and probably further back in the past (Homolová et al., 2012). Solifluction loams and loess loams are covering older fluvial deposits on slopes gently dipping towards the recent floodplain as a result of intensive geli- and solifluction processes in course of the Pleistocene (Fig. 2). Alluvial fans of small Vltava and Malše tributaries are found along the morphological scarp of the Hluboká fault. Sandy overbank deposits are found in the recent floodplains of the two main rivers as well as along their tributaries (Domácí et al., 1989; Suk et al., 1989; Vrána et al., 1990).

The major fault geometry in the region surrounding the Budějovice basin is dominated by two major fault systems striking in NW-SE and (N)NE-(S)SW direction, respectively (Malkovský, 1987). The most important sinistral (N)NE-(S)SW striking fault is the Blanice-Rodl-fault zone, which parallels the Vitis - and Diendorf-Boskovice fault of the eastern part of southern Bohemia. The dextral NW-SE striking Jáchymov fault system parallels the Pfahl - and Danube fault (Fig. 1). The faults are interpreted as a conjugate set of ductile wrench faults formed by N-S directed compression during the late stage of the Variscan orogeny (280-290 Ma; Brandmayr et al., 1995, 1997; Wessely. 2006).

The elongated shape of the Budějovice basin is determined by the NW-SE striking dextral Hluboká fault, which is part of the Jáchymov fault zone, and the NNE-SSW striking Rudolfov fault. Structural studies indicate that displacement at the Hluboka fault initiated at low to very low metamorphic conditions in late Variscan times. The orientation of the fault is predefined by Variscan structural anisotropies (Váchal et al., 2009; Porpaczy, 2011). Repeated fault reactivation under brittle conditions occurred in Post-Cretaceous and post-Miocene times (Svoboda, 1966) and continued probably into the Quaternary (Váchal et al., 2009). This recurring tectonic activity is caused by N- to NW-directed shortening in the foreland of the Alpine Orogen, which continued into the late Pliocene–early Quaternary (Ziegler and Dèzes, 2007).

A 3D model of the Budějovice basin (Porpaczy et al., 2011) shows an asymmetric basin shape with a crystalline basement top gently dipping towards the Hluboká fault at the north-eastern border of the basin. The fault offsets the top of the crystalline basement for up to about 340 m. Seismic data show that the Hluboká fault consists of several sub-parallel fault branches, which steeply dip towards SW (Fig. 2). These branch faults are arranged in an en-echelon pattern paralleling the morphological scarp SE of Hluboká nad Vltavou (Fig. 3). The fault contact between crystalline basement and Cretaceous sediments is located approximately 50 to 150 m SW of the mountain front below Quaternary sediments within the Budejovice basin. The location of faults is reconstructed from borehole data (Fig. 2), seismic and field observations (Špaček et al., 2011; Porpaczy, 2011).

The Rudolfov fault forms the south-eastern boundary of the Budějovice basin delimiting the Cretaceous basin fill from crystalline basement rocks. Geological and geophysical data indicate several fault branches, which partly coincide with a morphological scarp as well.

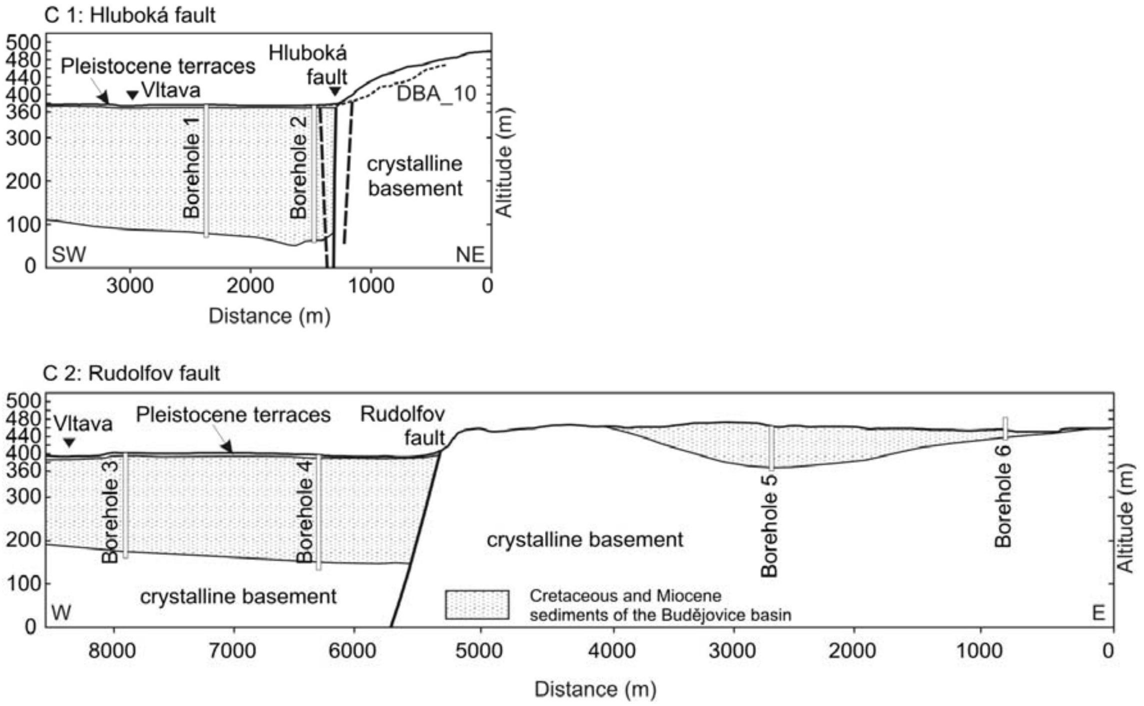


Figure 14. Schematic cross-sections C1 and C2 across the study area showing the Hluboká fault and Rudolfov fault uplifting the crystalline basement as well as the assumed contact between crystalline basement and Cretaceous and Miocene sediments.

3. Geomorphological Setting

The Budějovice basin with an average elevation of 370 to 390 m asl covers a size of about 250 km². It is surrounded by hill lands with the highest mountains reaching up to about 550 m asl. The basin has an elongate shape with a length of 48 km in NW-SE direction and 19 km width. It was located in the periglacial zone throughout the Pleistocene and never faced glacial erosion (Nývlt et al., 2011). Owing to its small size we can assume that the climatic conditions throughout the basin were always uniform. In the southeast, the basin is crossed by the river Vltava, the biggest fluvial system in the Czech Republic with a total length of approx. 377 km, and its right-hand tributary Malše (Fig. 4). Both form the receiving waters of the investigated creeks draining into the Budějovice basin.

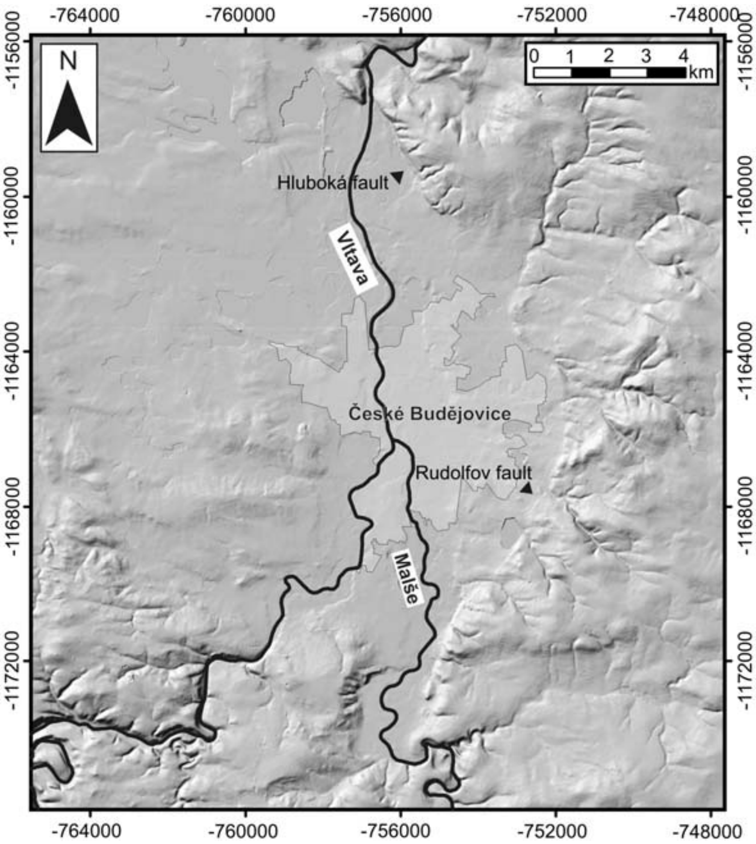


Figure 15. Hillshade view of a DEM showing the study area, highlighted is the extent of the town České Budějovice. You can clearly follow the lineaments of the faults as well as the embayed mountain front at western margin of the Budějovice basin.

The present day Vltava river valley in southern Bohemia was probably first formed in the Pliocene. The recent drainage pattern (Fig. 5) differs from that of Miocene times, when the streams of the S, SE and E part of the Bohemian Massif drained to the south (Tyráček, 2001). Subsequent tectonic movements forced the streams to drain to the north whereas the uppermost reaches of the Vltava river drained to the south until the lower Pliocene (Balatka and Sládek, 1962). Higher relative elevations of the highest fluvial gravels upstream and downstream of the Budějovice basin with respect to highest fluvial gravels in the basin itself points to the continuation of the relative uplift of the crystalline blocks surrounding the basin until today (Chábera and Novák, 1975). This assumption is supported by measurements of relative vertical movements of the crust in this area (Vyskočil, 1979).

In this study, three areas at the morphological basin margin named Slope A, Slope B and Slope C were chosen for morphometric analyses (Fig. 5). All investigated slopes are located on crystalline basement rocks with very similar lithologies: leucocratic migmatite and silimanite-biotite paragneiss (Slopes A and B at Račice mountain NE of the Budějovice basin) and biotitic migmatite and muscovite-biotite-silimanite paragneiss (slope C SE of the basin)

(Domácí et al., 1989; Suk et al., 1989; Vrána et al., 1990). All slopes cover relatively small areas (slopes A and B: about 4 km² each; slope C: approximately 65 km² including the subbasin DBC_07 and about 40 km² excluding DBC_07). Accordingly the average sizes of drainage basins at the different slopes are relatively small with 0.250 km² at slope A, 0.350 km² at slope B and 8.471 km² at slope C, respectively. The relatively large average area of the subbasins at Slope C results from subbasin DBC_07 with 27.9 km², which occurs to be the largest studied subbasin (see Fig. 5).

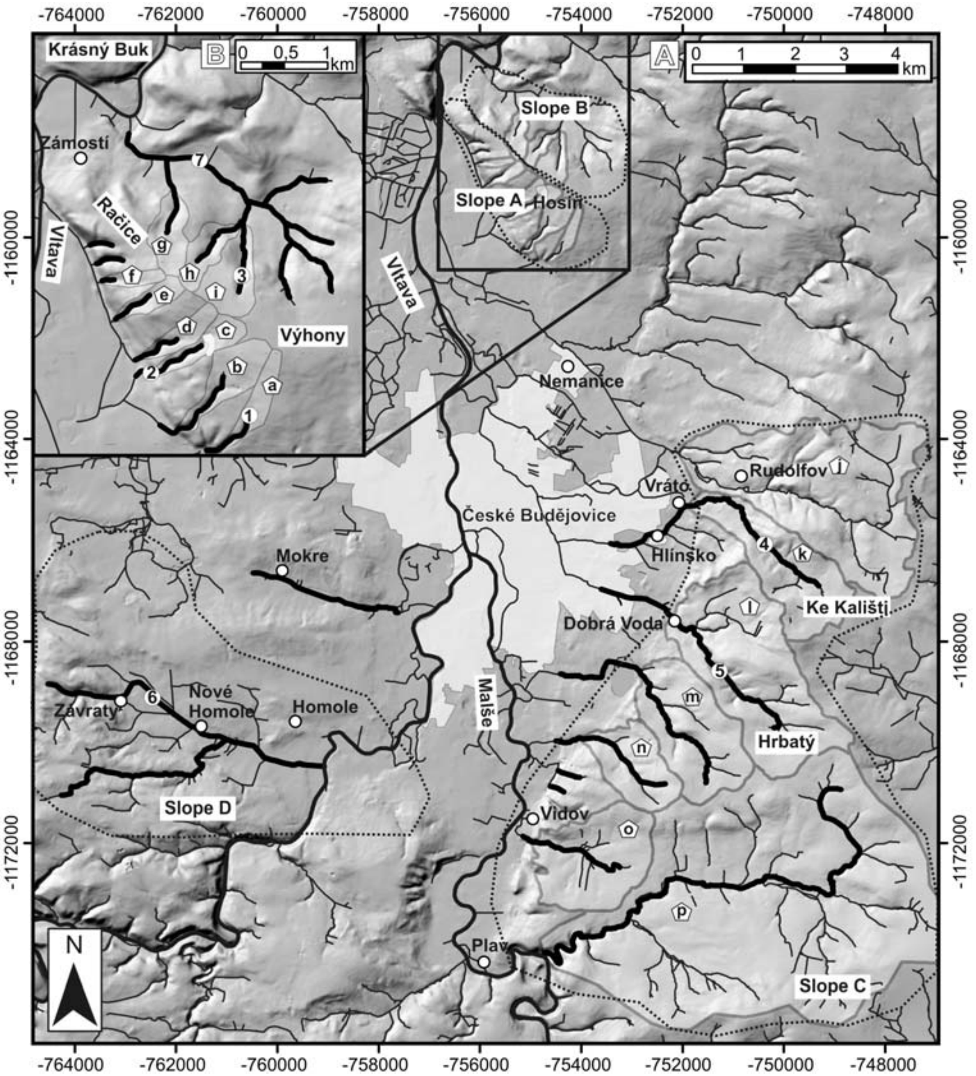


Figure 16. Hillshade view of a DEM of the study area showing the extent of the town České Budějovice as well as the main rivers Vltava and Malše. Smaller villages are marked as dots, and for thalweg sections important hills are marked with white rectangles. Also shown are locations of the seven thalweg-sections plotted in Figure 8A. Thick lines mark the investigated creeks. Highlighted are the subbasin outlets, a-DBA_08; b-DBA_09; c-DBA_10; d-DBA_11; e-DBA_12; f-DBA_13; g-DBB_14; h-DBB_15; i-DBB16; j-DBC_01; k-DBC_02; l-DBC_03; m-DBC_04; n-DBC_05; o-DBC_06 and p-DBC_07. Thin dashed black lines mark slopes A, B, C and D, which are investigated in this study.

The SW slope of the Račice mountain (508 m a.s.l. altitude) named Slope A is facing towards the floodplain of the Vltava river. It forms a prominent morphological scarp following one of the fault branches of the Hluboká fault zone, which is located within the crystalline basement units. The main fault, which delimits the crystalline basement in the footwall from the sedimentary successions of the Budějovice basin in the hangingwall, is located 50 to 150 m in front of the segmented mountain front. The scarp therefore does not coincide with the lithological boundary between crystalline basement rocks and Cretaceous sediments.

Slope B at the Račice mountain faces to the North. The upper part of the slope is located in crystalline basement, while the toe of the slope is located in unlithified Miocene sediments. The lithological contact is not visible from morphology and does not follow the mountain front. Creeks drain into a small tributary of the Vltava river.

The W-facing Slope C is situated further to the south, marking the E border of the Budějovice basin. The hill land reaches up to about 570 m elevation asl. The mapped lithological contact between Cretaceous sediments of the basin fill and crystalline basement rocks along the Rudolfov fault follows the mountain front almost exactly but is hardly visible in field. It can partly be recognized in a high resolution DEM (see Fig. 4). The creeks of subbasins DBC_01 to DBC_03 crossing the northern part of slope C drain directly into the Vltava river while the subbasins further south drain into the Malše river. The southernmost subbasin DBC_07 differs from all the other drainage basins by its size of nearly 30 km² and its general morphological characteristics (Fig. 5). The outlet of the drainage basin is entrenched in a deeply incised meandering gorge, which extends 1 km upstream from the mouth of the tributary to the Malše river. Upstream of this gorge the basin widens and the valley floor width increases to 50 - 100 m. The nearly 10 km long creek branches into many tributaries. A large part of the catchment area of DBC_07 is covered by Cretaceous sediments but the mapped outline of these sediments does not parallel the ENE-WSW oriented drainage basin (Fig. 2; 5).

The morphological comparison of the basin margins shows a very straight mountain front in front of Slope A. There, creeks are characterized by linear thalweg-sections with not more than two tributaries and a maximum length of about 1 km. The runoffs erode into bedrock. Some of the creeks show steps along their thalwegs with minor waterfalls up to one meter height (DBA_12, SWA_06, SWA07_a, b in Fig. 6; DBA_08, DBA_10 in Fig. 8A; Fig. 8B Slope A). Most of the valley floors are narrow with less than 10 m width, no terraces along the streams are developed. Valley slopes are symmetrically V-shaped with gradients of about 30 to 55° (DBA_12, SWA_06, SWA07_a, b in Fig. 6). Some slopes display a convex-up shape with slopes steepening towards the valley floor. The creeks form small active fans at the mountain front, which are situated on top of Pleistocene terrace sediments of the Vltava River.

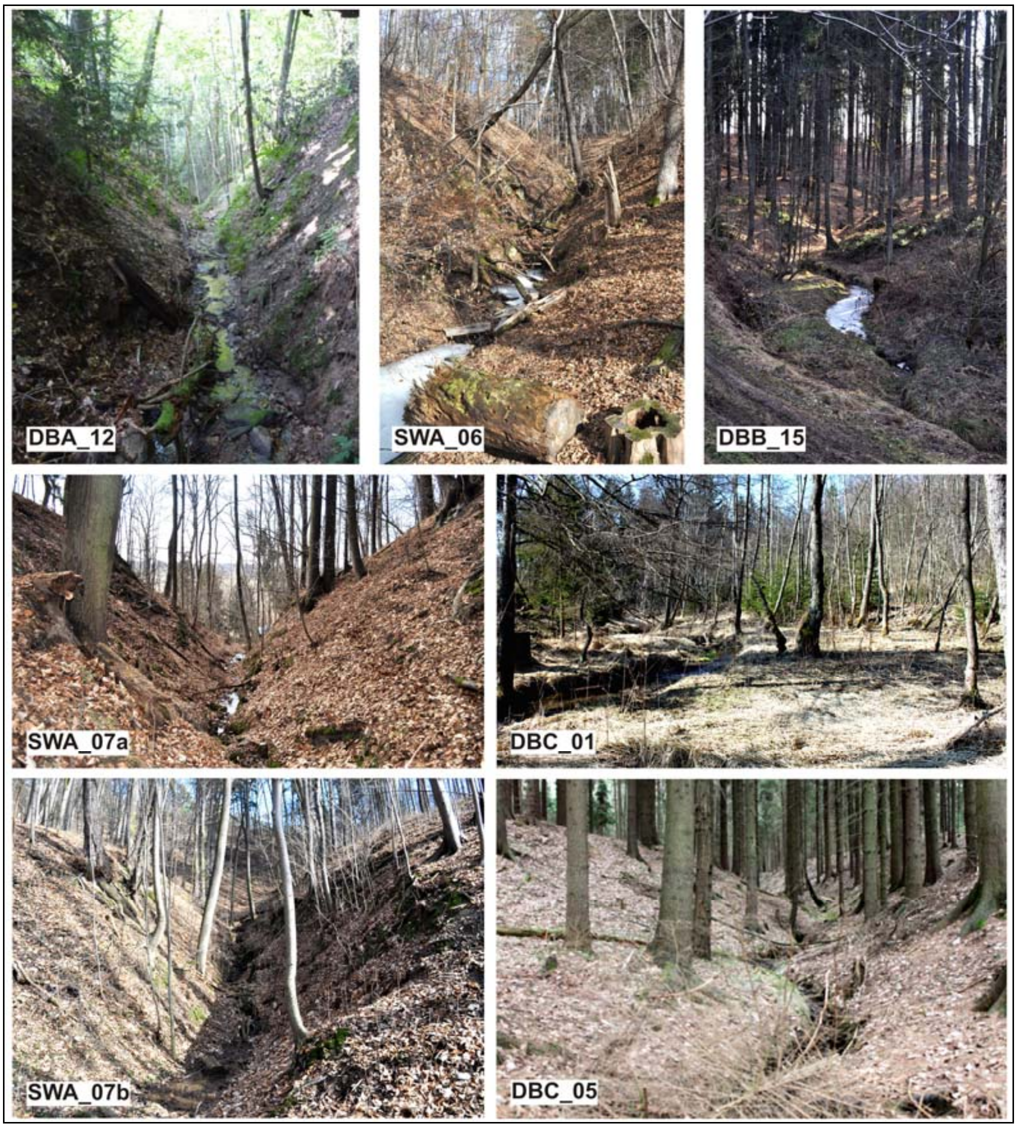


Figure 17. Photographs of the investigated region and their incising creeks. DBA_12**: View from the middle of slope A to top of Račice mountain, a narrow valley floor and steep flanks announce the low Vf-value. The creek is narrow, eroding in bedrock and not meandering.** SWA_06**: View from the morphological scarp (valley entrance) to top of Račice mountain, valley floor is narrow but hillslopes appear less steep than DBA_12 but it developed small bedrock steps.** SWA_07**: View from about 100 m behind mountain front into the basin (SWA_07 a) and to top of Račice mountain (SWA_07 b). Although valley floor is still narrow, the hill slopes are less steep reliant to the decreasing altitude. The Vf values are still very low.** DBB_15**: View from slope B to top of Račice mountain. Valley floor is about 10 m wide, the creek is meandering and develops terraces and erosion banks.** DBC_01 **and** DBC_05 **are photographs of creeks within slope C. Developed are wide alluvial areas, extremely wide valley floors as well as meandering and laterally eroding creeks. Values of Stream Length are influenced by tributaries and there are also anthropogenic influences by dams and fishponds.**

In contrast to Slope A, Slopes B and C show sinuous mountain embayments. Creeks at both slopes are meandering and form slip-off slopes and eroding banks cutting laterally into crystalline bedrock (DBB_15, DBC_05, DBC_01 in Fig. 6). Valley cross-sections are mostly asymmetrical with slope gradients of about 15 to 30°. Additionally, some of the valley flanks include shoulders with smaller slope gradients in their upper parts. Most of the valley floors are covered by thin terrace deposits, which are partly incised by the creeks (DBB_15, DBC_05, DBC_01 in Fig. 6). No bedrock steps or waterfalls occur (DBB_16, DBC_02, DBC_03 in Fig. 8A; Slope B and Slope C in Fig. 8B). The maximum lengths of the creeks reach 2 km at Slope B and up to 8 km at Slope C, respectively. At Slope C, the number of tributaries is higher and catchment areas are larger than those of creeks at Slope A.

The south-western margin of the Budějovice basin has not been surveyed systematically. Cursory morphological mapping revealed meandering creeks with tens to several hundred meters wide flat valley floors covered by thin terrace sediments and with very gentle flanks with slope angles of generally less than 12°. The partly fault-controlled contact between Cretaceous and Miocene sediments and crystalline basement rocks is impossible to recognize from morphology.

4. Morphometric analysis and results

In the current study we use mountain front sinuosity (Smf), stream length gradient (SL), valley floor width-to-height ratio (Vf), drainage basin shape (Rf), the circularity index (C) and the basin elongation ratio (Bs, Re; Tab. 1) to identify those margins of the Budějovice basin, which may be controlled by active vertical displacements. Morphometric analyses are supported by interpretations of knickpoints and thalweg sections. In total, we compared 16 subbasins (six subbasins within slope A; three subbasins within slope B; seven subbasins within slope C; Fig. 5).

Parameter, Formulae	Interpretation	Values, Inferences	References
Stream Length-Gradient (SL) **SL=(ΔH/ΔL)*L**	ΔH/ΔL=channel slope or gradient of the reach; L=total channel length from the midpoint of the reach of interest up-stream to the highest point on the channel.	High SL values - less rock resistance	Hack, 1973
Mountain-Front Sinuosity (Smf) **Smf=Lmf/Ls**	Lmf=length of the mountain front along the foot of the mountain; Ls=length of a straight line along the mountain front.	Smf<1.4 – active tectonics Smf>3 – inactive tectonics	Bull & McFadden, 1977
Ratio of valley floor width-to-height (Vf) **Vf=2*Vfw/[(Eld-Esc)+(Erd-Esc)]**	Vfw=width of the valley floor; Esc=elevation of the valley floor; Eld&Erd=elevation of the left and right valley divides	Low values (<0.5 after Burbank and Anderson, 2001) deep valleys with active incision	Bull & McFadden, 1977
Drainage Elongation Ratio (Re) **Re=(2*√A/√π)/L**	A=basin area; L=basin length	Re<0.5 active tectonics Re>0.75 inactive tectonics	Schumm, 1956
Elongation Ratio (Bs) **Bs=Bl/Bw**	Bl=length of the basin from its mouth to the most distal point; Bw=basin width	High values – high tectonic activity	Ramirez-Herrera, 1998
Circularity Index (C) **C=Ab/Ac**	Ab=basinarea; Ac=area of a circle with the same length of perimeter as the basin.	Low values – more elongated basin	Bell, 2004
Basin shape (Rf) **Rf=Ab/Bl²**	Ab=basin area; Bl=basin length from its mouth to the most distal point	Low values – high tectonic activity	Talling, 1997

Table 6. Table of morphometric parameters and their interpretations used in the present work.

4.1. Stream length gradient (SL)

The stream length gradient is sensitive to changes in channel slope highlighting those parts of a channel, which are out of an equilibrium state (Hack, 1973; Burbank and Anderson, 2001; Densmore et al., 2004; Cowie et al., 2006; Bull, 2007). The parameter correlates with the stream power and is influenced by both, rock type and differential vertical movements. It is used as an indicator of recent tectonic uplift by identifying anomalously high index values on a particular rock type (Harkins et al., 2005; Troiani and Della Seta, 2008). However, the index also increases significantly where the river crosses from resistive hard rock into relatively soft rocks (Keller and Pinter, 2002; Tab. 1).

The SL values are supplemented by thalweg sections constructed for 26 creeks. The sections are used to distinguish equilibrated graded rivers from creeks with knickpoints or convex-up profiles. Knickpoints are a result of disequilibrium steepening due to a relative base level drop (Gardner, 1983), which may be related to variations in bedrock erodibility, localised uplift or a combination of these.

We calculated SL for 26 rivers using contour lines of topographic maps in order to average out vertical noise included in the available DEM data. SL values range from 5 to 200 (Tab. 2). The highest SL values occur at creeks crossing the Hluboká fault (e.g., SL=200, subbasin DBA_12, SWA_06 in Fig. 7A) at positions close to branch faults behind the mountain front within the crystalline basement. This indicates that SL values are not governed by changes in bedrock erodibilty. This interpretation is corroborated by the SL data obtained from Slope B where creeks pass from crystalline rocks into Miocene shale. This lithological contact has no apparent influence on the SL values (Fig. 7A). Higher values obtained for the upper reaches of some creeks are apparently due to anthropogenic overprint and railway construction (e.g., NB_05, DBB_14; Fig. 7A). Remarkably high SL values associated with a knickpoint occurs shortly upstream of the mouth of NB_05 (Luční p., Fig. 7A, 8A).

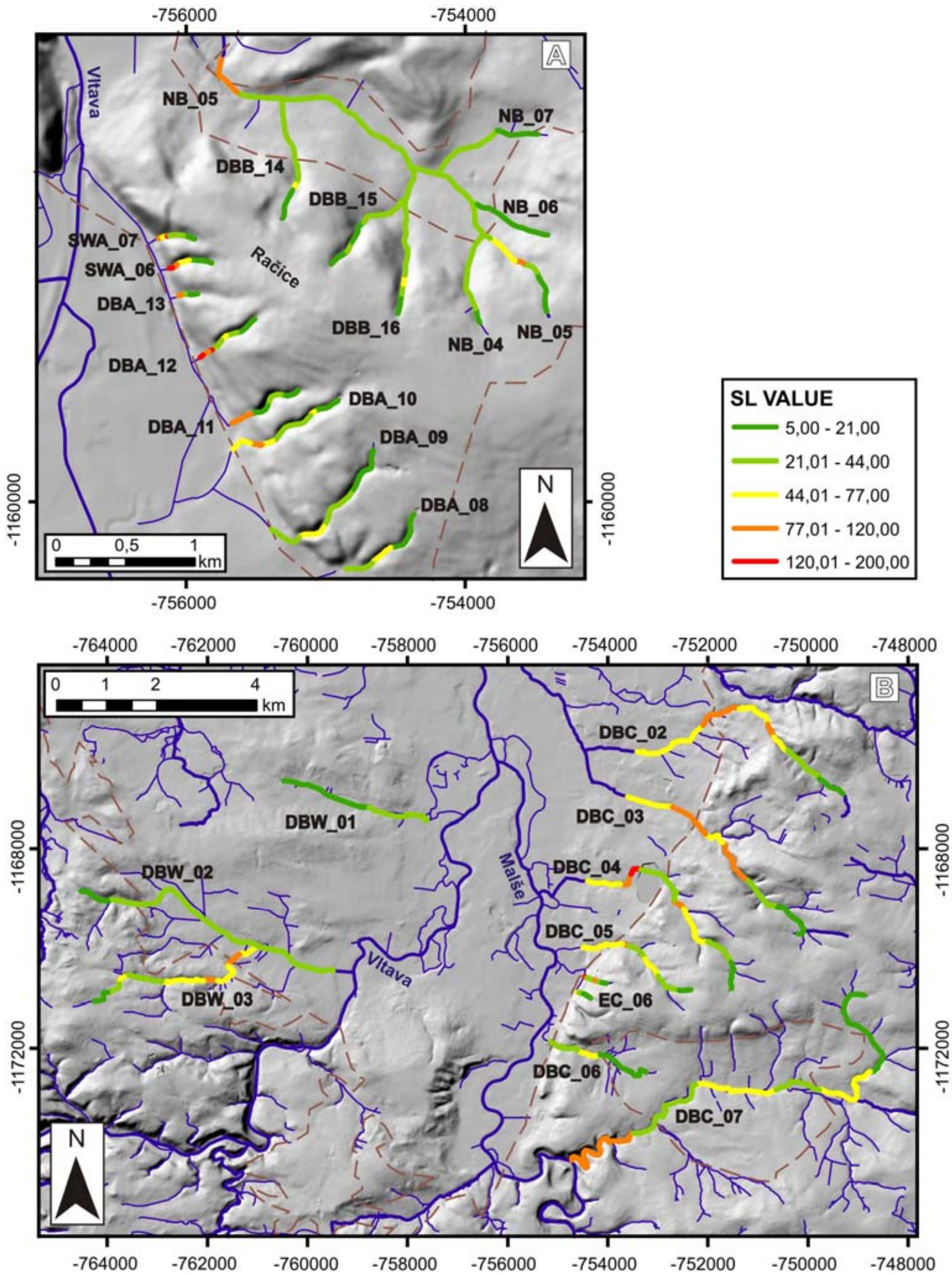


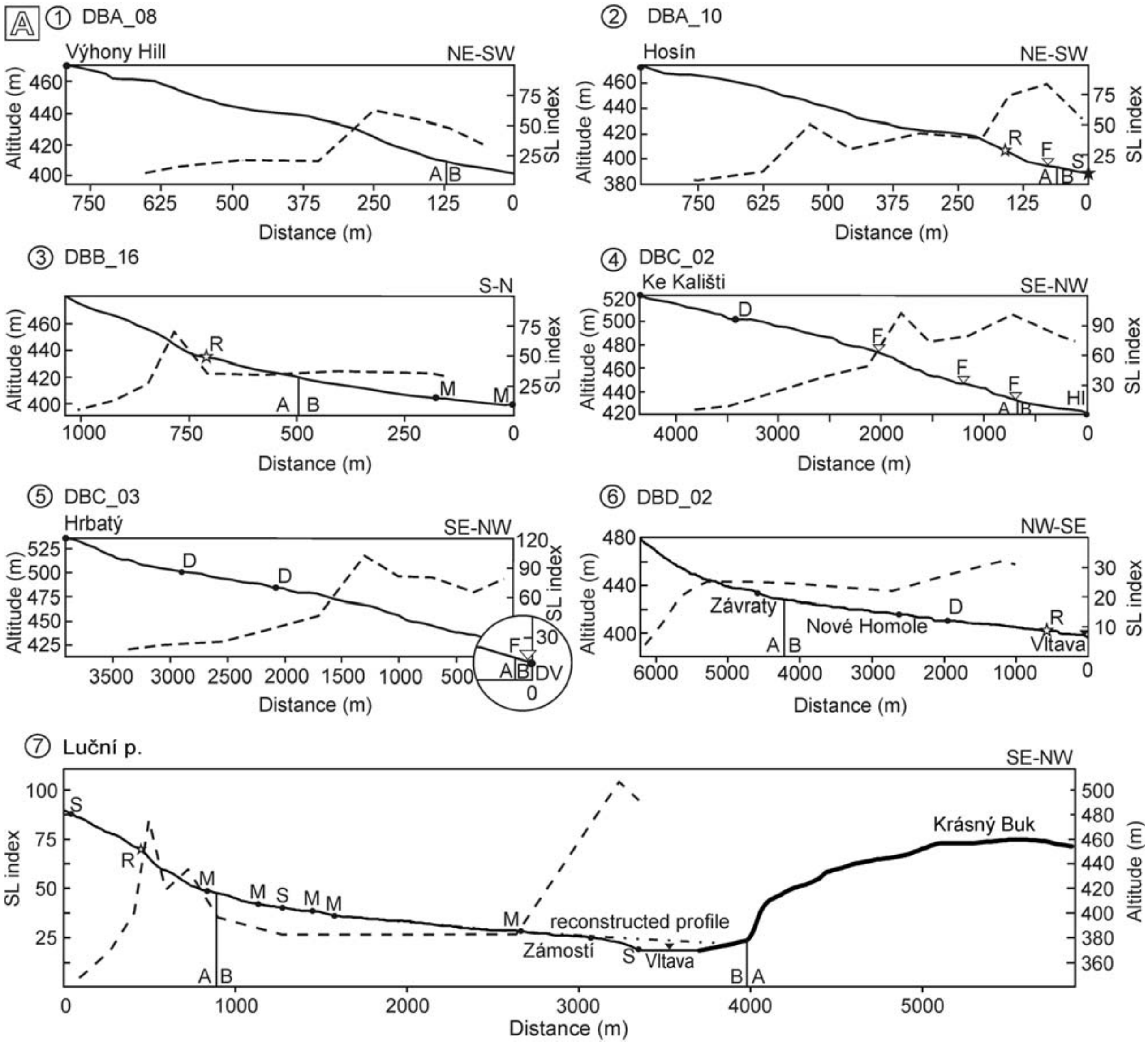
Figure 18. A) Stream Length (SL) values of creeks in the drainage network of Račice mountain NE of Budějovice basin, DBA_08 to SWA_07 (part of Slope A) and DBB_14 to NB_07 (part of Slope B); B) Stream Length (SL) values of creeks in the drainage network of the south-eastern part of the Budějovice basin, DBC_02 to DBC_07 (part of Slope C) and along the western part of the Budějovice basin, DBW_01 to DBW_03 (part of Slope D). Dashed light line marks the contact between crystalline basement rocks and Cretaceous and Miocene sediments, outlines of Slopes A-D are plotted in Figure 5, all SL-values (mean/max/min) are plotted in Table 2.

Creeks at Slope C show moderate to high values SL (~50-100) over a broad area close to the mountain front. The hightest recorded values derive from stream channelling, damming and railway construction (e.g., DBC_04, EC_06, Fig. 7B). At the SW margin of the Budějovice basin only few creeks drain into the Vltava river. These streams are characterized by low to moderate SL values with the relatively highest values occurring at the lithological contacts between crystalline basement and the sedimentary basin fill (Fig. 7B).

	Basin/Creek	SL-value (Mean/Max/Min)
Slope A	DBA_08	34/63/14
	DBA_09	40/75/8
	DBA_10	42/83/5
	DBA_11	46/92/5
	DBA_12	78/200/5
	DBA_13	45/120/5
	SWA_06	60/155/5
	SWA_07	60/128/6
Slope B	DBB_14	34/59/6
	DBB_15	23/44/5
	DBB_16	31/36/6
	NB_04	29/37/16
	NB_05	43/106/6
	NB_06	15/19/5
	NB_07	15/22/7
Slope C	DBC_02	63/104/12
	DBC_03	59/110/9
	DBC_04	57/137/8
	DBC_05	42/104/6
	EC_06	57/134/11
	DBC_06	28/48/8
	DBC_07	45/117/9
Slope D	WD_01	16/23/11
	WD_02	21/25/5
	WD_03	57/111/16

Table 7. Calculated average of Stream length gradients (SL) as well as Minimum and Maximum obtained from each single creek draining basins at the NE, SE and W margin of the Budějovice basin. Grey hatches denote the subbasins located at the Hluboká fault scarp. The highest values of each slope are highlighted. For location of the creeks see Figure 7, for calculation formulae see Table 1.

Marked differences between the creeks at the different slopes are further evident from thalweg sections. The streams crossing the Hluboká fault at Slope A show complex disequilibrium stream profiles marked by single large convex-up knickpoints close to or shortly upstream of the fault (Fig. 8B). The knickpoints close to the fault coincide with high SL values (Fig. 8A). These profiles are distinct from Slope B, which show concave stream profiles passing into convex profiles upstream of the mountain front. A marked knickpoint occurring shortly upstream of the mouth of NB_05 further indicates that the profiles are not fully equilibrated (Luční p., Fig. 8A). The streams crossing the mountain front along the Rudoflov fault show broad convex and concave-convex thalweg sections without single large knickpoints indicative for disequilibrium creeks. Sections from all three slopes are markedly different from the smooth concave thalweg sections obtained from Slope D (Fig. 8B).


A
① DBA_08
Výhony Hill
NE-SW
Altitude (m)
SL index
Distance (m)
② DBA_10
Hosín
NE-SW
③ DBB_16
S-N
④ DBC_02
Ke Kališti
SE-NW
⑤ DBC_03
Hrbatý
SE-NW
⑥ DBD_02
NW-SE
Závraty
Nové Homole
Vltava
⑦ Luční p.
SE-NW
reconstructed profile
Zámostí
Vltava
Krásný Buk

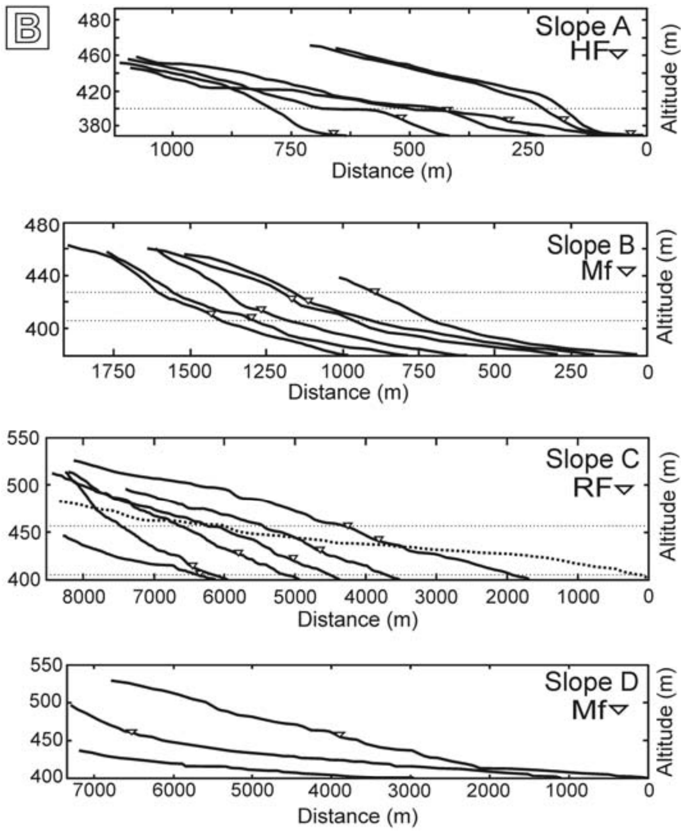


Figure 19. A) Thalweg sections for seven selected creeks in the study area. For location of the creeks see Figure 4. A: Mountain front, B: Basin, F: Hluboká fault. Rudolfov fault, DV: Dobrá Voda, Hl: Hlínsko, R: Railway, S: Street, M: Mouth of a tributary, D: Damming lake. Thin dashed lines are the fitted SL-values, thick line at profile 7 is the surface section. It gives an impression of the connection of SL-Index and Knickpoints within the slopes. Note the different scales in Distance.; B) Longitudinal profiles of the slopes A (stream identification numbers SWA_06, DBA_11, 9, 10, 12, 13, listed as shown from left to the right), B (DBB_14, 15, 16; NB_05, 04, 06), C (DBC_06, 05, 04, 03, 02, 01 and 07 (thick dashed line)) and D (WD_01, 02, 03), HF: Hluboká fault, RF: Rudolfov fault, Mf: Mountain front. Thin dashed lines bring out the band of the appearance of the mountain front and the Faults respectively. It gives an imagination of the Difference between the slope angle in front of the Hluboká fault and the slope aside the fault. Note the variable distinction of the Knickpoints within slope A and the broad correlation with the Hluboká fault. For location of the slopes, the creeks and the fault system see Figure 5. Profiles have different horizontal scales and are vertically exaggerated.

4.2. Mountain front sinuosity (Smf)

The mountain front sinuosity reflects the balance between the erosional and tectonic processes acting on a mountain front. Erosion tends to cut embayments into a mountain front whereas mountain uplift at an active range-bounding fault tends to produce a straight mountain front (Bull and McFadden, 1977; Keller, 1986). Accordingly, mountain fronts associated with active uplift are characterized by low Smf values. At reduced or ceased vertical displacements erosional processes carve a more irregular mountain front with increasing sinuosity and higher Smf values (Tab. 1).

Smf values were calculated for 21 profiles along the slopes A, B, C and D (Fig. 9A, B). Values derive from DEM data along eight 600 m long profiles at Račice mountain and seven 1200 m long profiles at the south-eastern margin as well as six 1000 m long profiles at the south-western margin of the Budějovice basin. The profiles at slopes A and C follow the Hluboká and Rudolfov fault respectively, while slope B and D are not located at a fault. In all cases, crystalline rocks crop out in the ranges behind the front.

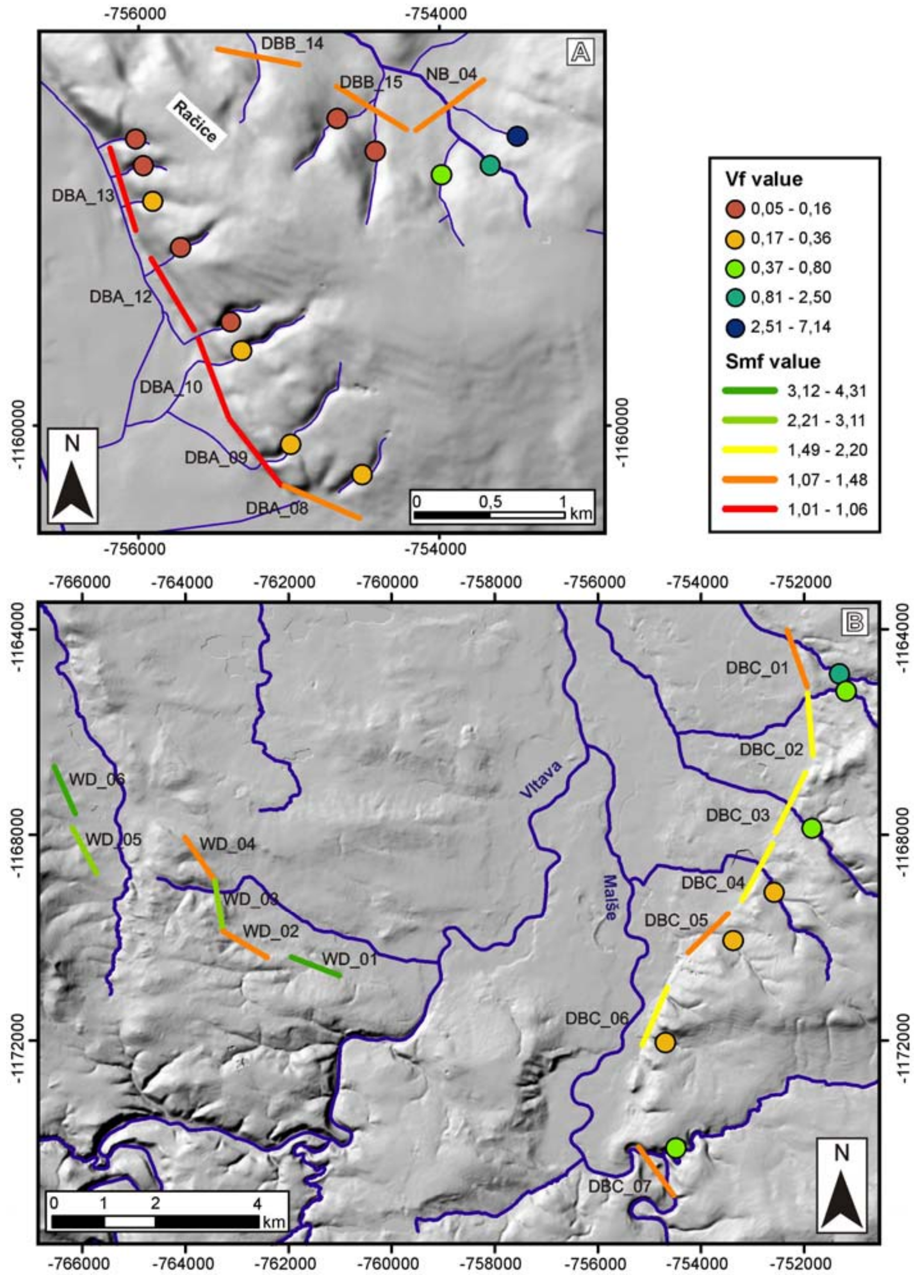


Figure 20. A) Smf- and Vf-Values along the Mountain front of Račice mountain NE of the Budějovice basin, DBA_08 to DBA_13 at Slope A and DBB_14 to NB_04 at Slope B. The Vf-Values are measured with cross-sections 200 m behind the Mountain front; B) Smf- and Vf-Values along the Mountain front at the south-eastern margin of the Budějovice basin (DBC_02 to DBC_07 part of Slope C) and along the Mountain front of the west-part of the Budějovice basin (WD_01 to WD_03 part of Slope D). The Vf-Values are measured with cross-sections 500 m behind the Mountain front. Slopes are plotted in Fig. 5.

The Smf-values at slope A are extremely low ranging between 1.01 and 1.06, characterizing a very straight mountain-piedmont junction in the vicinity of the Hluboká fault (Tab. 3). The relatively highest value of 1.2 is recorded at DBA_08, where the mountain front is located behind the fault. Mountain sinuosities at slope B and C are significantly higher with values between 1.17 to 1.37 at slope B and 1.17 to 2.20 at slope C, respectively (Tab. 3). The highest sinuosity values up to 4.31 are obtained from Slope D.

	Creek	Bs[a]	Re[b]	C[c]	Rf[d]	Vf[e]	Smf[f]	Profile-Location
Slope A	**DBA_08**	5.00	0.44	0.39	0.15	0.26	1.20	in front of DBA_08
	DBA_09	3.94	0.51	0.49	0.21	0.21	1.06	in front of DBA_09
	DBA_10	7.38	0.47	0.42	0.17	0.26	1.02	in front of DBA_10/11
	DBA_11	4.17	0.49	0.48	0.19	0.16		
	DBA_12	4.17	0.51	0.48	0.20	0.05	1.01	in front of DBA_12
	DBA_13	4.56	0.47	0.47	0.17	0.26	1.01	in front of DBA_13/SWA_06
	SWA_06					0.10		
	SWA_07					0.08		
Slope B	**DBB_14**	2.63	0.62	0.65	0.30		1.17	in front of DBB_14
	DBB_15	2.47	0.61	0.56	0.29	0.13	1.33	in front of DBB_15/16
	DBB_16	2.02	0.70	0.65	0.39	0.14		
	NB_04					0.79	1.37	in front of NB_04/05
	NB_05					1.67		
	NB_06					7.14		
Slope C	**DBC_01**	2.24	0.68	0.47	0.36	2.50	1.89	in front of DBC_01
	DBC_02	3.57	0.56	0.46	0.25	0.74	1.17	in front of DBC_02
	DBC_03	2.50	0.70	0.55	0.39	0.80	2.20	in front of DBC_03
	DBC_04	2.13	0.75	0.70	0.44	0.30	1.86	in front of DBC_04
	DBC_05	1.67	0.71	0.69	0.40	0.29	1.36	in front of DBC_05
	DBC_06	1.29	0.89	0.65	0.62	0.36	1.96	in front of DBC_06
	DBC_07	1.78	0.71	0.63	0.40	0.69	1.20	in front of DBC_07
Slope D	**WD_01**						4.16	near Nove Homole
	WD_02						1.32	near Závraty
	WD_03						2.84	near Závraty
	WD_04						1.48	subsequent to WD_03
	WD_05						3.11	subsequent to WD_04
	WD_06						4.31	subsequent to WD_05

Table 8. Quantitative geomorphological indices (Bs, Re, C, Rf, Vf and Smf) obtained from subbasins at the NE and E margin of the Budějovice basin. Grey hatches denote the subbasins located at the Hluboká fault scarp. The hightest and lowest values respectively of each slope are highlighted. For location of subbasins see Figure 10A, B and 11A, B, for calculation formulae see Table 1.

4.3. Ratio of valley floor-width to height (Vf)

This ratio differentiates between broad-floored U-shaped valleys with relatively high Vf-values and V-shaped valleys with relatively low values (Bull and McFadden, 1977; Bull, 2007) and is especially sensitive to tectonic base-level falls (Zuchiewicz et al., 2009). Combinations of Smf and Vf have particularly been used to compare the rate of tectonic activity for different mountain fronts (Silva et al., 2003; García-Tortosa et al., 2008). High Vf values and flat-floored valleys are characteristic for slowly incising rivers with predominant lateral erosion responding to constant base levels (Keller and Pinter, 2002). Low values reflect deep valleys with streams that are actively incising, commonly associated with uplift (Mayer, 1986; Burbank and Anderson, 2001; Azor et al., 2002). Vf is usually investigated at a given distance upstream from the mountain front (Silva et al., 2003).

We calculated this parameter using topographic maps together with DEM and additional field observations. With respect to the height of the surrounding mountains we set cross-valley sections at a distance of 200 m behind the mountain front at slope A and B, and 500 m at slope C, respectively (Fig. 9A, B). All sections are located in crystalline basement rocks. The mountain slope A at the Hluboká fault shows deep and narrow V-shaped valleys with steep valley flanks and straight, mostly unbranched streams that are actively incising into bedrock. The mean Vf value obtained from the seven creeks is 0.19 (0.05 to 0.26; Tab. 3). Slopes B and C show spread valleys, which frequently show plane and wide valley floors with meandering and branched streams. Valley flanks are generally less steep than at slope A but sometimes reach slope angles comparable to A. The mean Vf value calculated for Slope B is 1.97 (5 creeks, 0.13 to 7.14; Tab. 3) and 0.81 for Slope C (seven values between 0.29 and 2.50; Tab. 3).

4.4. Drainage basin shape parameters (Bs, C, Re and Rf)

Parameters describing the shape of drainage basins are commonly used as indicators of recent tectonic activity. The typical basin of a young tectonically active mountain range is elongate and basin shapes become progressively more circular (Bell, 2004) with time after the end of mountain uplift (Ramírez-Herrera, 1998). Drainage basin widths are much narrower near the mountain front on the tectonically active side because streams use most of their energies for downcutting. Active normal faults have short, steep drainages adjacent to the fault, while dendritic basins need more time to develop and therefore represent more mature areas (Bull and McFadden, 1977; Bull, 2009).

To compare the shapes of drainage basins adjacent to the Budějovice basin we computed the four following parameters, which all discriminate between elongate and circular basin: elongation ratio (Bs and Re), circularity index (C) and basin shape (Rf; Tab. 1). Elongate basins indicative of uplift are characterized by low values of Re (after Schumm, 1956), C (Bell, 2004) and Rf (Talling, 1997). High values of these parameters describe more circular basins indicative for low to absent tectonic activity. The elongation ratio (Bs) describes the percentage of basin length and basin width (Ramírez-Herrera, 1998). In contrast to the other indices high Bs values characterize more elongate basins indicative for uplift.

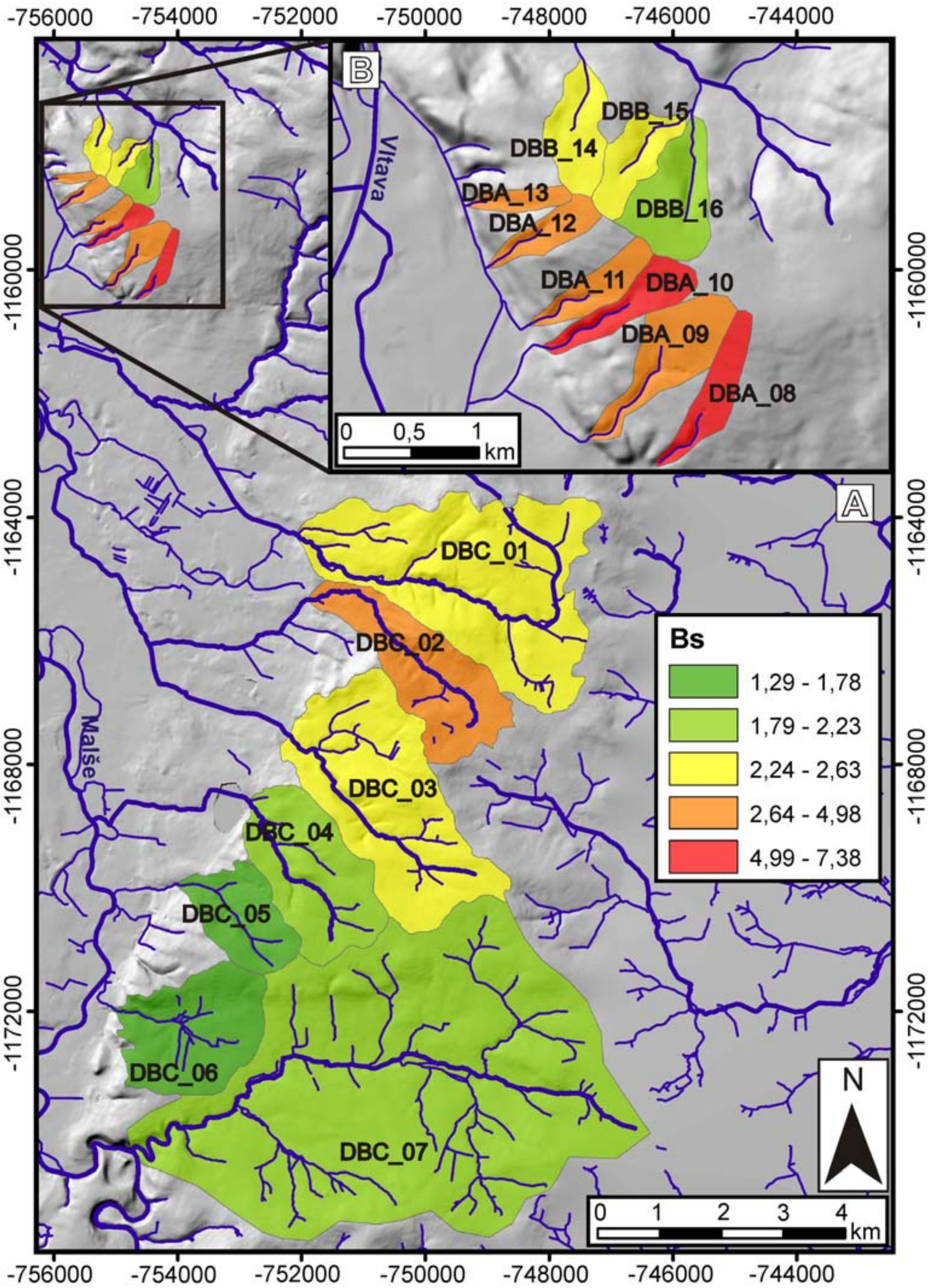


Figure 21. A) Basin elongation (Bs) values for drainage basins at the eastern margin of the Budějovice basin (Slope C) and B) at the morphological scarp of the Hluboká fault (Slope A) as well as for drainage basins north of Račice mountain (Slope B). The highest values appear at the slope next to the Hluboká fault and illustrate this slope as the most tectonic active Mountain front within the study area. For calculation formulae see Table 1; results are plotted in Table 3.

Basin shape indices were calculated for 16 subbasins of the Budějovice basin using DEM data (Fig. 10A, B; Fig. 11A, B). Six basins are located at the Hluboká fault scarp, three at slope B and seven at slope C crossing the Rudolfov fault. The computed values are summarized in Tab. 3. Values show that the most elongated subbasins occur consistently at slope A (Fig. 10A, Fig. 11A) while the basins at slope B and C appear more circular and therefore more mature.

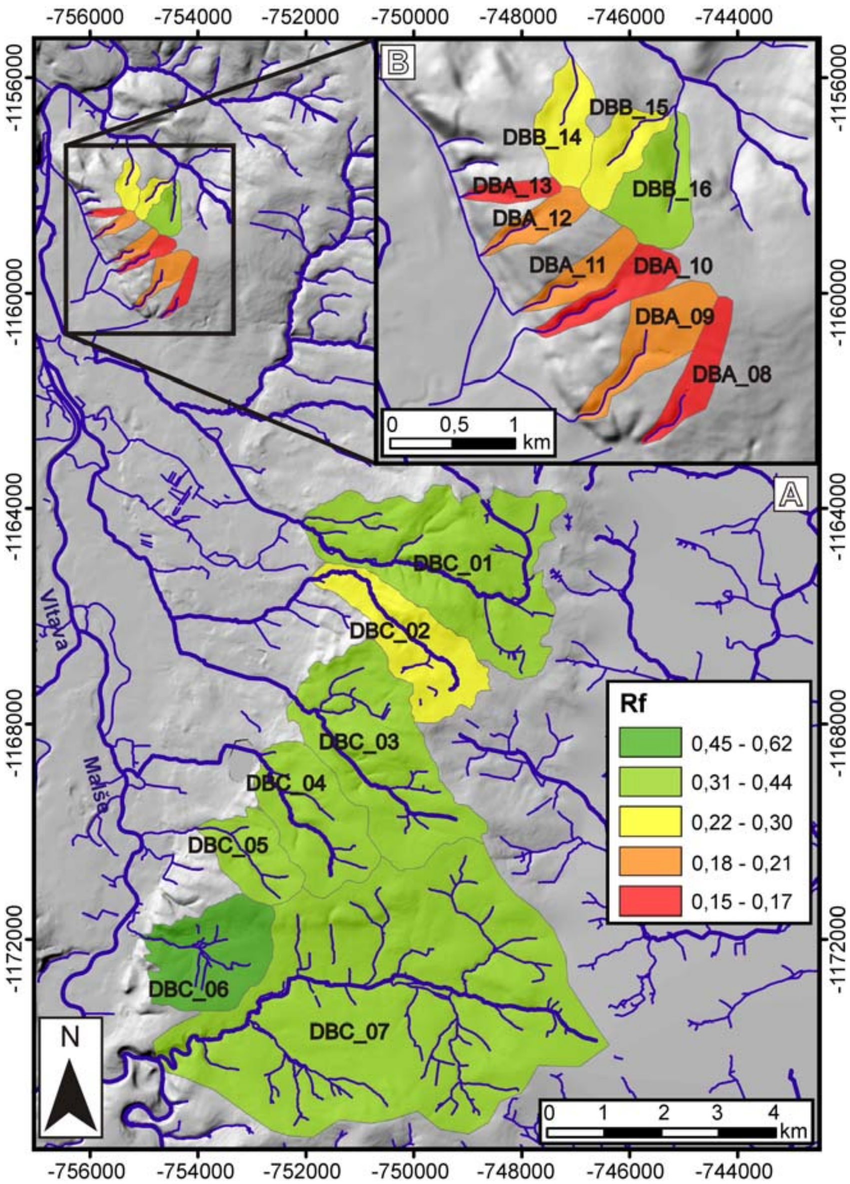


Figure 22. A) Basin shape (Rf) values for drainage basins at the south-eastern margin of the Budějovice basin (Slope C) and B) at the morphological scarp of the Hluboká fault (Slope A) as well as for drainage basins north of Račice mountain (Slope B). The lowest values appear at the slope next to the Hluboká fault and illustrate this slope as the most tectonic active Mountain front within the study area. For calculation formulae see Table 1; results are plotted in Table 3.

All values calculated for Slope A are remarkably different from those of Slopes B and C. Both show similar or overlapping values for all indices (Tab. 3). This similarity between Slopes B and C has already been indicated by the general morphological appearance of both slopes, e.g., the dendritic nature of the streams. Among the calculated parameters Bs discriminates most clearly between the slopes while the circularity index (C) reveals more ambiguous results. The range of the Bs, Re and Rf values measured for all three slopes as well as the computed mean values show a clear difference between Slope A at the Hluboká fault and the Slopes B and C (Tab. 4).

	Bs[a]	**Re**[b]	**C**[c]	**Rf**[d]	**Vf**[e]	**Smf**[f]
Slope A	4.87	0.48	0.46	0.18	0.17	1.06
Slope B	2.37	0.64	0.62	0.33	1.97	1.29
Slope C	2.17	0.71	0.59	0.41	0.81	1.66

Table 9. Mean of Basin parameter (Bs, Re, C, Rf) and average of Valley-floor-width (Vf) and Mountain Front Sinuosity (Smf) for investigated subbasins within slope A, B and C (For location of the slopes see Figure 5). Note the significant difference between slope A at the Hluboká fault scarp and the other two slopes. Furthermore slope C appears as the marginal less active slope in comparison with slope B. Grey hatches denote the slope located at the Hluboká fault scarp.

5. Geodetic Data

Geodetic data prove substantial vertical movements between the Budějovice basin and the crystalline basement units NE and E of it. Vyskočil (1973) provides a detailed isoline map of vertical crustal movements in the surrounding of the Budějovice basin, which is based on levelling campaigns carried out 1940-1947 and 1963-1968 (Fig. 12A). The main features shown by the data are the uplift of the crystalline basement NE of the Hluboká fault and the Lišov horst between the sedimentary basins of Budějovice and Třebon. In contrast to these areas, data indicate that no apparent vertical displacement occurs at the SW margin of the Budějovice basin.

Vertical displacement rates between the mountain ranges at the NE margin of the Budějovice basin and the basin itself reach up to about 1 mm/yr. This is further illustrated by geodetic profiles starting from České Budějovice, which is taken as the reference benchmark. The profiles indicate an uplift of Račice mountain in the footwall of the Hluboká fault with >10 mm in the 20 years observation period (Fig. 12B). Vertical movements across the Hluboká fault are supported by a data obtained from a local geodetic network, which revealed relative vertical displacements between benchmarks close to the fault in its hangingwall and footwall of about 0.2 mm/yr (Vyskočil, 1973). Uplift of the Lišov horst with up to 15 mm in 20 years occurs over a broad area extending over about 15 km between the sedimentary basins of Budějovice and Třebon (Fig. 12C).

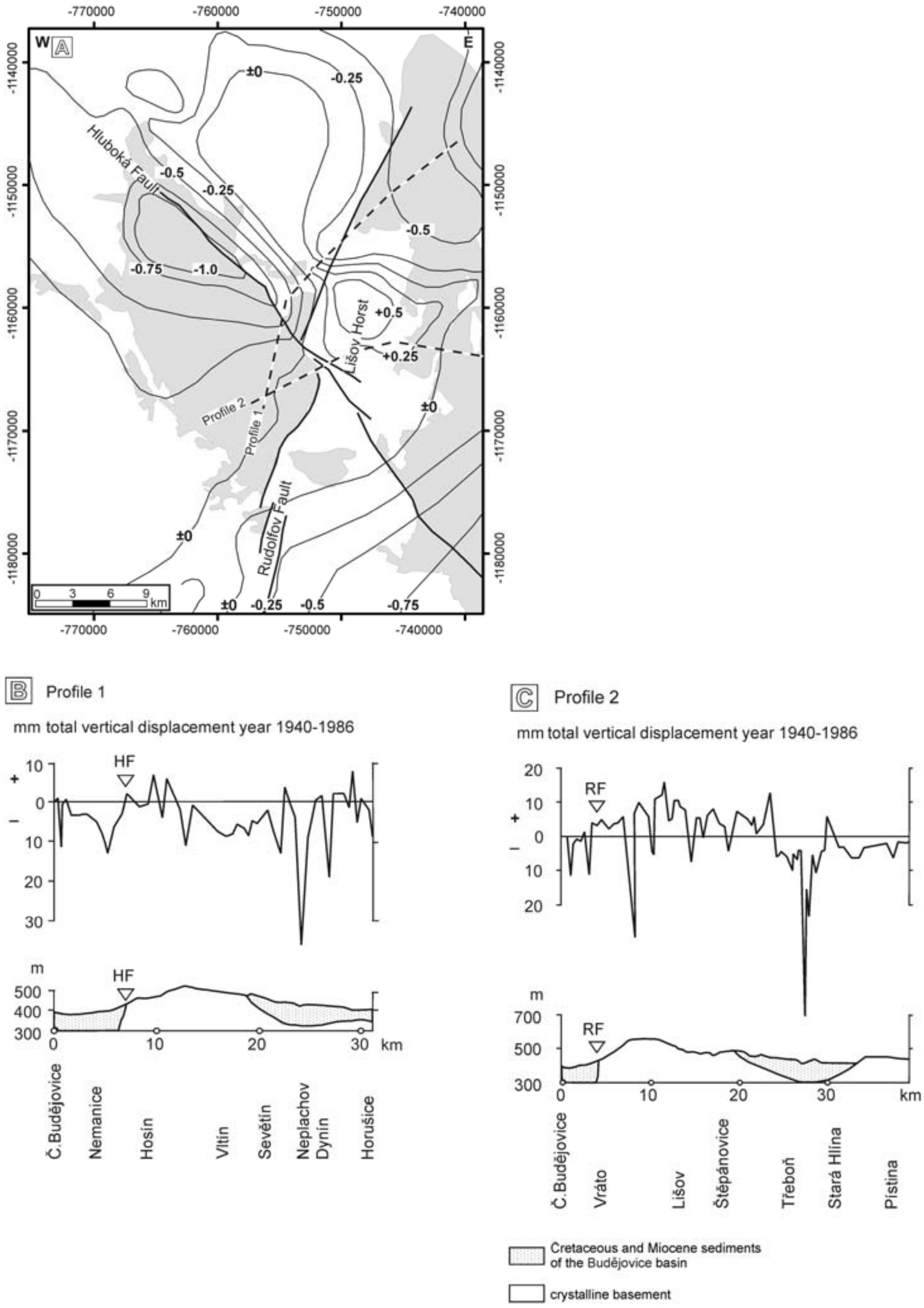


Figure 23. A) Map of vertical crustal movements within the Budějovice basin area. Thick lines are Hluboká and Rudolfov faults. Dashed thick lines are profiles mapped in Figure 12 B and C. The extents of the Budějovice basin (W part of the map) and the Třeboň basin (E part of the map) are highlighted with light grey. The highest amount of uplift appears near Hluboká fault; B) Profile 1 from Budějovice basin to Horušice. Diagram shows the trend of vertical movement, correlated with a geological Profile. HF: Hluboká fault; C) Profile 2 from Budějovice basin to Pístina. Diagram shows the trend of vertical movement, correlated with a geological Profile. RF: Rudolfov fault. Map and profiles are modified after Vyskočil, 1979.

The data are corroborated by regional studies of the Bohemian Massif derived from repeated levelling between the end of the 19th century and about 1980 indicative for uplift of the NE basin margin relative to the Budějovice basin of about 0.6 mm/yr (Vyskočil, 1975; 1996).

6. Discussion

The comparison of the geomorphic indices obtained for the margins of the Budějovice basin highlight the Hluboká fault scarp at the SW slope of Račice mountain as a unique morphological feature. Very low Vf values (0.05 to 0.26) characteristic for deeply incised V-shaped valleys, high SL values (up to 200) close to the Hluboká fault, and elongate drainage basin shapes (best described by Bs, Re and Rf; Tab. 3) strongly suggest that the creeks are actively down-cutting to compensate uplift of the footwall of the Hluboká fault. The fault is further characterized by an almost linear mountain front with extremely low Smf (down to 1.01). Such values are commonly associated with active faulting at a range front. Tectonic uplift controlling the drainage is also evident from the linear thalweg sections and marked knickpoints of the creeks close to the fault, which coincide with the highest SL values.

At Slope B north of Račice mountain, which is not associated with a fault at the mountain front, the values of Vf (0.13 to 1.67) and the basin shape parameters are indicative for less immature basins than those at Slope A. Meandring creeks with thin local terrace deposits show that the drainage system is not exclusively down-cutting as observed at Slope A but that lateral erosion occurs as well. Thalweg sections devoid of large single knickpoints and significantly lower SL values clearly distinguish the creeks from Slope A.

The observed morphological features lead us to the conclusion that uplift of the Račice mountain in the footwall of the Hluboká fault relative to the Budějovice basin and the Vltava river causes a base level fall, which has a direct impact on drainage systems of the Hluboká fault scarp where creeks cross the fault. As the creeks of Slope B also drain into the Vltava River, they are subjected to that base level drop as well. The impact of the base level fall on the upper reaches of the analyzed creeks, however, appears moderate. The creeks feed into a right-hand tributary of the Vltava river. This tributary shows a generally concave stream profile and a marked knickpoint about 300 m upstream of its mouth, which apparently results from the general uplift of the footwall of the Hluboká fault and continuous incision of the Vltava river into the uplifting block. As the mouth of the tributary is located at the eroding bank of a Vltava meander (no. 7 in Fig. 5), it might alternatively be argued that the knickpoint results from the lateral erosion of the Vltava. However, the stream profile (no. 7 in Fig. 8A) clearly shows that lateral erosion cannot explain the elevation difference between the actual thalweg and the reconstructed equilibrium profile. The amount of lateral erosion required for the observed elevation difference exceeds the width of the Vltava river valley by far. We therefore conclude that drainage at the north-facing slope of Račice mountain also responds to tectonic uplift. The fact that the upper reaches of the drainage system appear less immature than those crossing the Hluboká fault scarp and that the knickpoint has not yet migrated upstream along NB_05 may be indicative for a relatively young rapid base level drop (Gardner, 1983; Whipple and Tucker, 1999). The morphological indications for tectonic uplift of the footwall NE of the Hluboká fault are corroborated by the geodetic data shown in Fig. 12, which indicate several tens of millimetres of relative vertical displacements between the Budějovice basin and the Račice mountain.

The mountain front along the Rudolfov fault east of the Budějovice Basin (Slope C) shows morphological characteristics, which are broadly comparable to the northern slope of Račice mountain. Meandring creeks with Vf values higher than those obtained from Slope A, Smf values of a moderately sinuous mountain front, and basin shape parameters characteristic for drainage basins, which are more circular and more mature than those at Slope A, clearly distinguish the range front from the Hluboká fault scarp. Comparing the obtained absolute morphometric values to commonly used classifications of range front activity, however, supports classifying Slope C as a “moderately active” range front (Tab. 1 and references therein). This interpretation is corroborated by moderately high Sl values obtained for a broad area around the Rudolfov fault (Fig. 7) and convex or convex-concave thalweg sections (Fig. 8A, B). Such a section is particularly well illustrated by DBC_07 with an upper reach showing a graded creek profile and a convex profile next to its mouth into the Malše river. We relate these stream profiles to a lowering of the base level due to mountain uplift and incision of Malše river similar to the situation observed for creek NB_05 north of the uplifting Račice mountain. Uplift of the fault block ESE of the Rudolfov fault (Lišov horst) has been proved by geodetic data indicative for up to 0.5 mm of vertical displacement per year (Vyskočil, 1973; Fig. 12).

Mountain sinuosity and SL values obtained from the southwestern margin of the Budějovice basin (Slope D) are significantly different from the mountain fronts discussed above. A sinuous mountain front with inselbergs of crystalline basement and Smf values up to

4.3, generally low SL values and graded concave stream sections are not indicative for significant vertical displacements. Geodetic data further appear to disproof vertical movements across that part of the basin margin (Fig. 12).

The morphologic parameters obtained from those parts of the margin of the Budějovice basin, which are interpreted as active mountain fronts, compare well with recent results from other areas characterized by low to very low deformation rates in intra-plate Europe. Badura et al. (2007) investigated the Sudetic Marginal Fault at the north-eastern margin of the Bohemian Massif. The setting of the proved active fault is comparable to the Budějovice basin with respect to its geological, morphological and climatic setting forming the contact between crystalline basement and a Neogene sedimentary basin (Štěpančíková et al., 2010). Morphometric values obtained from that fault (Vf = 0.8; Smf = 1.05; Re = 0.6; Rf = 0.3; average values) are almost identical to those from the fault-controlled margins of the Budějovice basin (except for higher Smf values computed for the Slope C along the Rudolfov fault; compare Tab. 4). Paleoseismological data from the Sudetic Marginal Fault suggest vertical displacements of about 0.03 mm/y at this mountain front during the Late Pleistocene-Holocene (Štěpančíková et al., 2010).

The Vf and Smf values obtained from the basin margins along the Hluboká and Rudlofov faults are further in the same range as values from active mountain fronts in the Betic Cordillera (Vf ~ 0.05-1.4; Smf = 1.01-1.9; García-Tortosa et al., 2008; Pedrera et al., 2009; Giaconia et al., 2012). Vertical displacements in the Betic Cordillera in SE Spain have been estimated with 0.07-0.1 mm/y during the Early Pliocene-Holocene (Braga et al., 2003).

7. Conclusion

Geomorphological analysis of the Budějovice basin in the southern Bohemian Massif reveals conclusive evidence of active vertical displacements between the flat-floored morphological basin and the mountain ranges NE and SE of it. Vertical displacements apparently occur at the Hluboká and Rudolfov fault, which delimit the basin and its Cretaceous, Miocene and Quaternary sedimentary fill from the surrounding crystalline basement complex. Both faults originated from ductile and brittle-ductile Variscan shear zones and showed a protracted history of tectonic reactivation through Cretaceous and Miocene times. Evidence for uplift of the range fronts along both faults comes from an integrated analysis of geomorphic features and morphometric parameters characterizing linear mountain fronts, disequilibrium creeks crossing the basin margin, and elongated drainage basins.

Geomorphic data particularly highlight the basin margin along a part of the Hluboká fault delimiting the basin to the NE. There, deeply incised linear V-shaped valleys eroding into bedrock, stream profiles with marked single knickpoints, very high stream-length gradients near the fault, elongated drainage basins and a very linear mountain front indicate a young base level fall related to the vertical displacement between the Budějovice basin in the hangingwall of the Hluboká fault, and its footwall (Račice mountain). Uplift of the crystalline basement units SE of the Rudolfov fault is indicated by convex-up stream profiles of the creeks crossing the fault, moderate to high stream-length gradients, and low sinuosity of the range front. The calculated morphometric parameters suggest that uplift at this mountain front is less pronounced than the uplift of the footwall of the Hluboká fault. The morphometric data obtained from both fault-controlled basin margins differ significantly from data obtained from the SW margin of the Budějovice basin, which is apparently not subjected to differential vertical movements. The geomorphological indices obtained from the active range fronts delimiting the Budějovice basin are quantitatively comparable to morphometric parameters obtained from other areas of slow intra-plate deformation.

The morphometric evidence for uplift of the fault blocks in the footwall of the Hluboká and Rudofov fault are corroborated by geodetic data obtained from repeated precise levelling (Vyskočil, 1973; 1975; 1996). For the Hluboká fault these data suggest relative vertical displacement rates of several tenths of a millimetre per year between the Budějovice basin in the hangingwall and the Račice mountain in the footwall of the fault, respectively. Similar velocities are obtained for the uplift of the Lišov Horst in the footwall of the Rudolfov fault relative to the Budějovice basin (Fig. 12).

The results obtained from the study area in the Bohemian Variscan basement clearly show that the applied technique is well capable to identify slow relative vertical movements within an area of general regional uplift. The reliability of the results increases by using a combination of different and independent geomorphic parameters to characterize mountain front morphology, creeks and drainage basin shapes. The approach can at least partly eliminate the limitations arising from non-tectonic factors such as different bedrock lithology and anthropogenic overprint on the landscape under investigation.

In our study we found that mountain front sinuosity and basin shape parameters are most meaningful to identify the location of active faults, while the stream length parameter may be strongly influenced by human activity. In any case fieldwork is inevitable to classify the obtained values and support the interpretation.

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Appendix C

Homolová, D., Lomax, J., Špaček, P. and Decker, K., 2012. Pleistocene terraces of the Vltava River in the Budějovice basin (Southern Bohemian Massif): new insights into sedimentary history constrained by luminescence data. Geomorphology, 161-162, 58-72.

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Pleistocene terraces of the Vltava River in the Budějovice basin (Southern Bohemian Massif): New insights into sedimentary history constrained by luminescence data

Dana Homolová [a,*], Johanna Lomax [b,c], Petr Špaček [d], Kurt Decker [a]

[a] Department of Geodynamics and Sedimentology, University of Vienna, Althanstrasse 14, 1090 Wien, Austria
[b] Institute of Applied Geology, University of Natural Resources and Life Sciences, Peter-Jordan-Strasse 70, 1190 Wien, Austria
[c] Department of Geography, Justus-Liebig-University Giessen, Senckenbergstrasse 1, 35390 Giessen, Germany
[d] Institute of Physics of the Earth, Masaryk University, Tvrdého 258/12, Brno, Czech Republic

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ABSTRACT

We studied Quaternary sediments from the Budějovice basin in southern Bohemia, now being able to reconstruct the landscape formation of this area during the late Pleistocene. The main objective of this study was to map fluvial terraces of the rivers Vltava and Malše in the basin and to constrain their ages by luminescence dating. Topographic data from a high-resolution DEM in combination with lithological profiles of more than 1000 boreholes allowed identifying five terrace levels (BB 1 to BB 5) with bases ranging from 7 m below to 26 m above the recent mean water level of the Vltava River. For the lowermost terrace level BB 1, a consistent stratigraphy with ages ranging between 84.5 ± 9.0 ka and 7.9 ± 0.8 ka was constrained. Additionally, we obtained luminescence ages of alluvial fan and colluvial deposits, which allow us to better constrain the late Pleistocene sedimentation history of the study area. Based on the spatial distribution of derived ages, the terrace level BB 1 represents a complex sediment body incorporating more distinct packages of river aggradation. The presence of stacked fluvial deposits of Pleistocene age underneath the recent floodplain points to an ongoing subsidence or relative tectonic stability of the Budějovice basin during the late Pleistocene.

1. Introduction

Alluvial deposits act as valuable archives of environmental changes and play an important role in defining Quaternary stratigraphies. Terrace sequences reflect periods of fluvial accumulation and erosion resulting from an interaction of climatically controlled and neotectonic processes in the late Cenozoic (Balatka and Kalvoda, 2008; Gibbard and Lewin, 2009; Westaway et al., 2009).

The Vltava River, with a length of ca. 377 km and a catchment area occupying more than 27,000 km^2 on the Czech territory, forms the biggest fluvial system in the Czech Republic (Linhartová and Zbořil, 2006). Based on stream length and differences in morphological development, the terrace system of the Vltava River can be longitudinally subdivided into two sections: the upper reach from the source to the confluence with the river Sázava, and the lower reach down to the confluence with the river Labe (Tyráček et al., 2004). This study deals with upper reaches of the Vltava River terraces in the Mesozoic Budějovice basin that (according to Tyráček, 2001) do not fit into the standard schemes of other rivers in the Czech Republic.

Extensive Cenozoic fluvial deposition in the Bohemian Massif took place at least since the lower Miocene and most probably farther in the past, but the best preserved occurrences are those of Pleistocene age (Tyráček, 2001). Since the Pliocene, the originally flat topography of the Budějovice basin has been reshaped by fluvial erosion and minor amounts of aggradation that, in combination with the regional uplift of the Bohemian Massif, has lead to the development of a terrace staircase (Chábera, 1965; Tyráček et al., 2004).

Mapping the horizontal and vertical extent of the preserved terrace remnants turned out to be challenging owing to their relatively small thickness compared to the lower reach of the Vltava River or to other major European rivers such as Danube or Rhine. Because the headwaters of the Vltava River were never extensively glaciated (Nývlt et al., 2011), the sediment supply as well as the transport energy of the river was much lower than in glaciated regions. Periodic downcutting of the river in course of the Pleistocene has lead to erosion of older fluvial deposits and, their redeposition in lower areas. Preserved are therefore only relatively thin portions of former gravel bodies with a reduced extent.

According to the classic scheme to subdivide terrace sequences in central Europe, the Vltava River terraces were assigned by most scientists (e.g., Puffer, 1918; Engelmann, 1938; Chábera, 1965) to the main alpine glacial periods Donau, Günz, Mindel, Riss, and Würm according to Penck and Brückner (1909). However, this association is not straightforward as the terraces are not connected to moraine bodies like in the Alps (e.g., van Husen, 2000).

In more recent studies dealing with the Vltava River terraces at its lower course, authors tried to correlate the development of the terrace

* Corresponding author. Tel.: +43 1 4277 53 442; fax: +43 1 4277 9534.
E-mail addresses: dana.homolova@univie.ac.at (D. Homolová), johanna.lomax@geogr.uni-giessen.de (J. Lomax), spacek@ipe.muni.cz (P. Špaček).

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staircase with the regional uplift of the Bohemian Massif as well as with the global climatic cyclicity (Balatka and Kalvoda, 2008) in accordance with the studies of Bridgland and Westaway (2008), Gibbard and Lewin (2009) or Westaway et al. (2009). The most recent attempt to put the terrace system of the downstream part of the Vltava River into a stratigraphic framework has been published by Tyráček et al. (2004). In such studies, the staircase of terrace bodies is matched to the global marine isotope stages (MIS), using beside their altitude and stratigraphic build up, also mammalian and/or mollusk and/or pollen biostratigraphical correlation to biozones dated elsewhere, analyses of overlying loess/paleosol sequences to infer minimum ages, and geomorphological correlations with other river terrace systems across Europe. However, absolute age data were not reported for any of these studies. Without absolute ages of fluvial sediments of the Bohemian Massif, any correlation with European stratigraphic schemes remains an unconstrained theory (Tyráček, 2001).

The goal of the present study is to provide absolute ages of Pleistocene fluvial deposits of the Vltava River using luminescence dating, and to improve the stratigraphic framework with this new data. So far, luminescence dating of sediments in the Czech Republic has been done only on loess sediments of archeological sites (Musson and Wintle, 1994; Zander et al., 2000; Richter et al., 2009) and peat bog deposits in the Krkonoše Mountains (Engel et al., 2010). This work therefore provides first luminescence ages of fluvial sediments on the Czech territory. Additionally, because the Quaternary deposits of the Bohemian Massif are mostly unfossiliferous (Tyráček, 2001), luminescence dating remains the key method in building a Pleistocene stratigraphy for this region.

To identify Quaternary landforms in the study area, a detailed analysis of a digital elevation model (DEM) in combination with the analysis of borehole data and field survey was performed. These techniques were combined with data from literature and geological maps of the study area.

2. Regional setting

The study area is situated in southern Bohemia (Czech Republic) and includes the southeastern part of the Budějovice basin, crossed by the river Vltava and its right-hand tributary Malše (Fig. 1).

The Budějovice basin is a fault-bounded sedimentary basin with a complex subsidence history overlying the Moldanubian crystalline complex of the Bohemian Massif. Its elongated shape is determined by a system of faults striking predominantly NW–SE and NNE–SSW such as the NW–SE-striking Hluboká Fault at the NE margin of the basin (Fig. 2B). Permian, Cretaceous, and Miocene sediments record repeated reactivations of faults at or close to the basin margin, which may have continued into the Quaternary (Svoboda, 1966).

The crystalline basement consists of Precambrian to Paleozoic metamorphic rocks of the Moldanubian of Šumava and southern Bohemia (Tyráček and Růžička, 1994), including highly metamorphosed mica schists, gneisses, and migmatites as well as igneous rocks of the central Bohemian and Moldanubian Plutons (Slánská, 1976). The oldest unmetamorphosed sediments in the study area are represented by the upper Carboniferous and lower Permian coal-bearing claystones and sandstones of the Blanice Graben east of the Hluboká Fault (Suk et al., 1989).

The most abundant stratigraphic unit of the Budějovice basin is the upper Cretaceous Klikov Formation, reaching a thickness of 340 m. These poorly sorted gray and red sandstones and mudstones lie directly on the weathered crystalline basement (Svoboda, 1966; Slánská, 1976).

Fluvio-lacustrine sediments of the Zliv and Mydlovary Formations are deposited either directly on the crystalline basement or on the Cretaceous sediment fill. Diatoms found in these sediments refer to their Miocene age (Řeháková, 1963). Reaching a maximal thickness of 15 m, the Zliv Formation consists of grayish-green sandy clays at the base, coarsening upward into sandstones and conglomerates, which in the upper part are often strongly silicified. The up to 60-m-thick Mydlovary Formation consists of grayish-green clayey sands and sandstones to olive-green clays with layers of dark gray coaly clays, xylites, and greenish diatomaceous clays (Svoboda, 1966).

Quaternary deposits in the study area form only a relatively thin sediment cover, being mostly a result of fluvial accumulation and periglacial processes such as congelifraction, geli- and solifluction, and cryoturbation. The most widespread sediments are fluvial sandy gravels and pebbly sands of the rivers Vltava and Malše, reaching a thickness of up to 8 m. These coarse-grained facies reflect periods of high sediment supply resulting from congelifraction during glacial periods, when climatic conditions characteristic for periglacial regions prevailed in the study area (Soergel, 1921; Záruba et al., 1977). According to Tyráček (2001), all aggradations of fluvial gravel and sand in the Bohemian Massif originated in a cold climate under braided river conditions, whereas only thin layers of the gravel were redeposited by laterally migrating meandering channels during warmer periods.

The lithology of the fluvial sediments reflects the bedrock properties of the drainage area. Beside subangular to subrounded clasts of Moldanubian crystalline rocks, well-rounded quartz pebbles from reworked Cretaceous and Miocene deposits are included. Fine-grained fractions of terrace deposits show similar lithological composition. In general it can be stated, that the younger the terrace, the larger the portion of fresh bedrock-eroded gravel and the smaller the portion of redeposited quartz pebbles from older deposits.

Terrace levels in the study area do not appear as a morphological terrace staircase with pronounced horizontal terrace surfaces and separating risers, but as slopes gently tilted toward the Vltava River. This is apparently the result of periglacial processes such as gelifluction and/or cryoturbation. These processes have lead to redeposition of the terrace material downslope and to a smoothing of the former terrace staircase morphology.

Beside periglacial gelifluction, the originally flat topography of the terraces was also modified by up to 15-m-thick alluvial fans, deposited by small right-hand tributaries of the Vltava River and best developed along the morphological scarp parallel to the Hluboká Fault (Fig. 3). Sandy overbank deposits are found in recent floodplains of the two main rivers as well as along their tributaries (Domácí et al., 1989; Suk et al., 1989; Vrána et al., 1990).

As mentioned above, the elongated form of the Budějovice basin is a result of regional tectonics. A prominent morphological scarp parallel to the NW–SE-striking Hluboká Fault can be followed along the NE limit of the basin (Fig. 2B). Near the village Hosín, the vertical distance between the old peneplain on top of the crystalline (500 m asl) and the Vltava floodplain (375 m asl) reaches 125 m on a horizontal distance of only 1.5 km (Balatka and Přibyl, 1997). To the SE, the fault scarp gets less pronounced. In the southernmost part of the basin, the NNE–SSW-trending scarp of the Rudolfov Fault near the village of Vidov morphologically terminates the basin.

3. Materials and methods

3.1. Geomorphologic analysis

A geomorphologic analysis based on topographic data from a high-resolution DEM was used to identify Quaternary landforms in the study area. These include surfaces and risers of fluvial terraces and alluvial fans.

For this purpose, a DEM with a grid resolution of 10 m was created from digital contour lines with a 2-m contour interval (ZABAGED, 2009) and from geodetic points as well as from lines representing river banks and lakes digitized from the analog topographic map 1:10,000 (Základní mapa České Republiky 1:10 000, 2008). In places where the resolution of the DEM appeared insufficient, morphological features had to be mapped in the field.

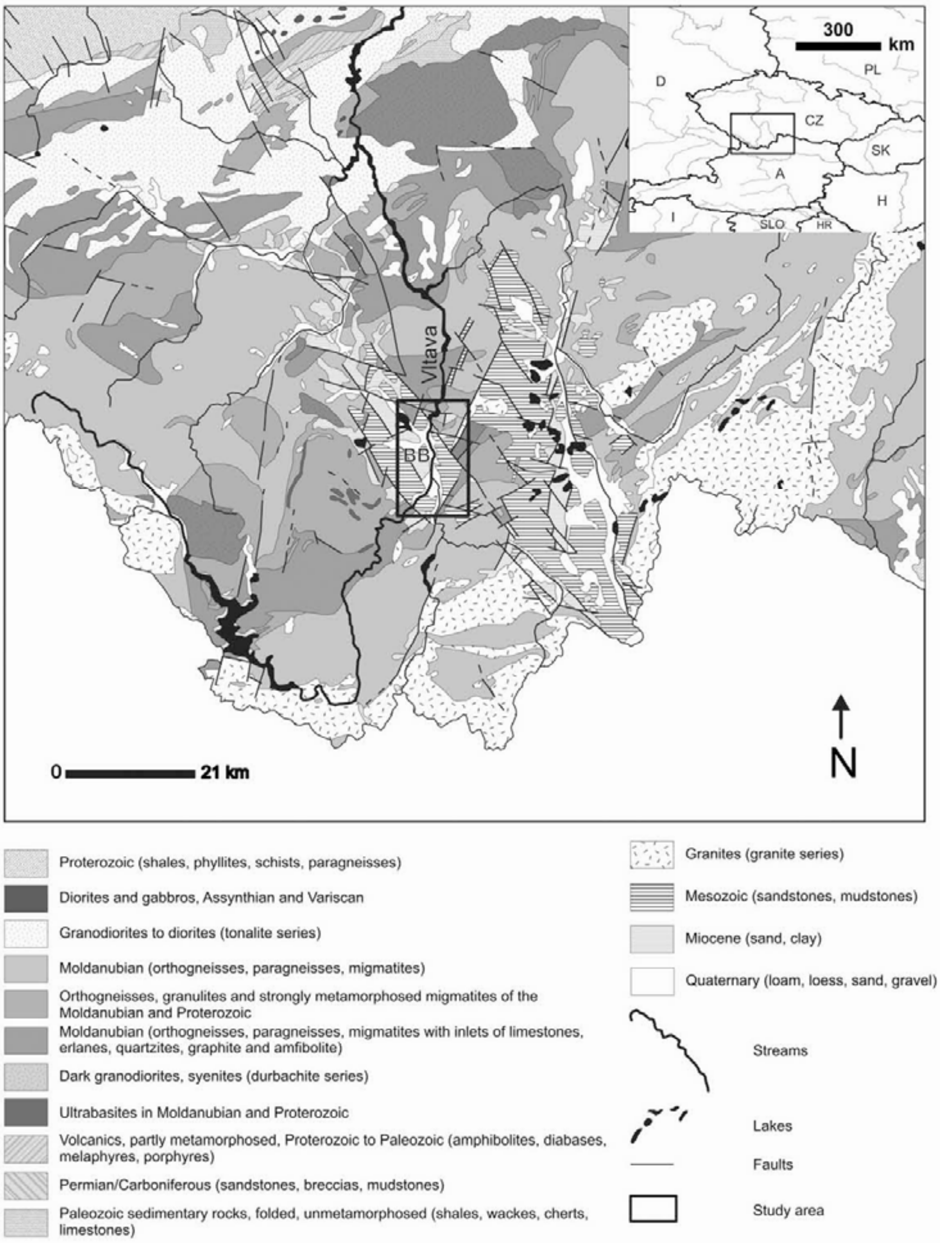

Fig. 1. Geological map of southern Bohemia (Cháb et al., 2007, modified) and location of the study area (black rectangle); BB — Budějovice basin.

Additionally, georeferenced historic map sheets of the Austrian Second Military Survey were used to obtain information about the geomorphologic situation in the study area of the years 1836–1842, primarily about the course of the rivers Vltava and Malše. These map sheets provide a very exact base map (Timár et al., 2006) as the georeferencing accuracy is below 10 m.

3.2. Interpretation of borehole data

To determine the characteristics and thickness of Quaternary sediments and to collect samples for sedimentologic analyses as well as for luminescence dating, eight core drillings and two outcrops (see also Špaček et al., 2011) were studied in detail and sampled (Fig. 2A; Table 1).

In a GIS-project, data from the DEM were combined with data from boreholes collected from the archive of the Czech Geological Survey (Geofond), from drillings conducted during this study, and from outcrop observations. In total, 1111 data points (Fig. 2B) were used to model the horizontal and vertical extent of fluvial terraces in the study area (Fig. 3).

By analyzing lithological profiles from drilling data (Fig. 4; Figs. 5–6), fluvial sandy gravel was identified as the marker lithology characteristic

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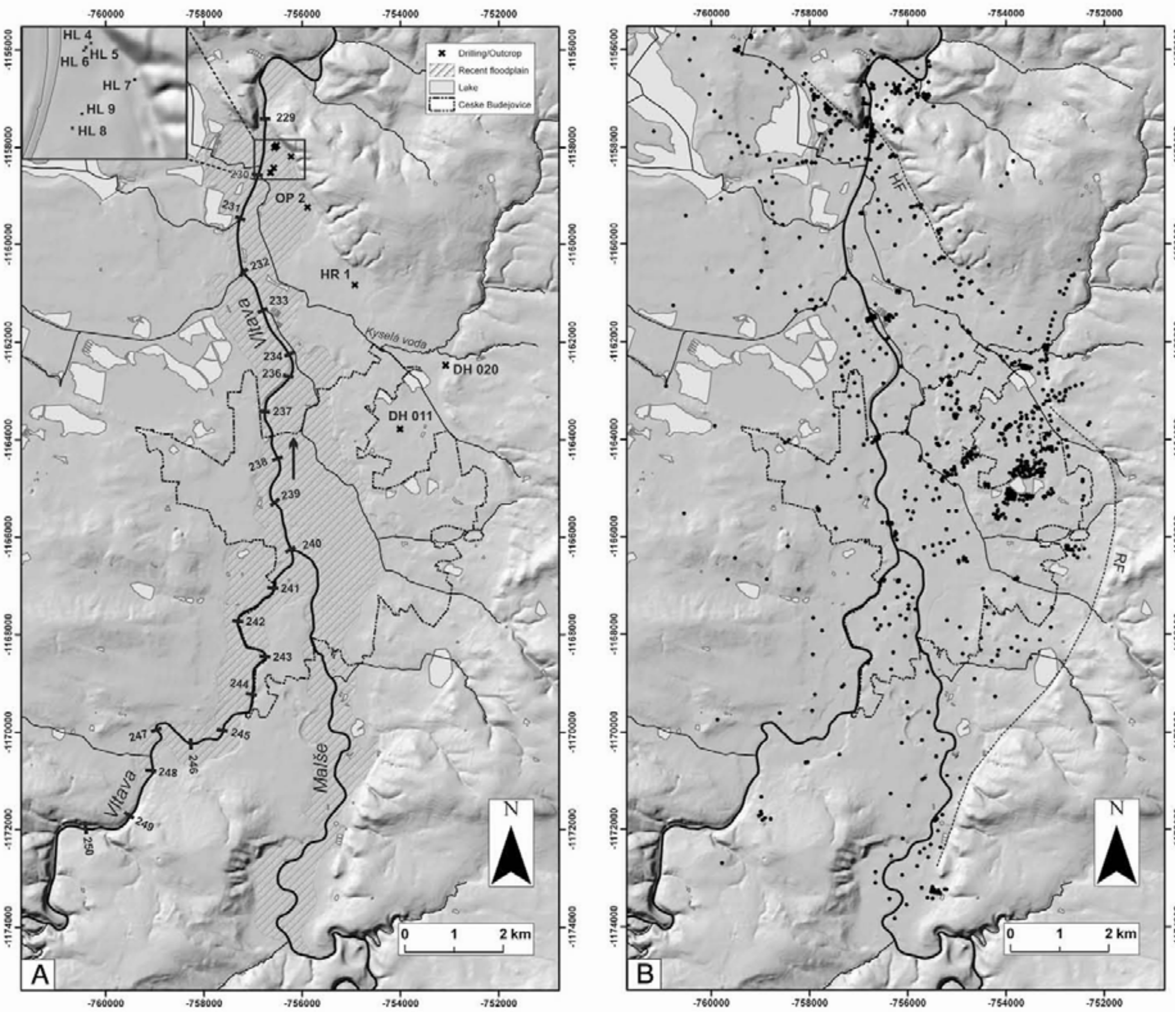

Fig. 2. Hillshade view of a digital elevation model (DEM) of the study area. (A) Location of sampling sites (drillings/outcrops). Numbers mark the stream-km of the Vltava River. (B) Distribution of boreholes used for mapping the terrace extent (black dots). Dashed line approximately shows the surface traces of the Hluboká and Rudolfov Faults (HF/RF) forming morphological scarps along the basin margin.

for fluvial terraces, as coarse gravel is the only sediment type that can unequivocally be assigned to the Vltava and Malše Rivers. Fine-grained fluvial sediments may be confused with Neogene or Cretaceous deposits. A similar approach was used by Chábera (1965) in the Budějovice basin as well as by Chábera and Vojtěch (1972) by mapping the Lužnice River terraces in the adjacent Třeboň basin.

The base of fluvial gravel was mapped as the base of a fluvial terrace in a particular area. The definition of the relative elevation of the gravel base with respect to the recent Vltava water level is crucial for the identification of terrace levels in the study area. Intensive stream straightening and the high number of dams make the definition of the natural water level of the Vltava River challenging, which in this study was solved with smoothing of the longitudinal profile derived from data about the water level from 1973. From this data, a surface having the same elevation gradient as the Vltava River was modeled. The relative elevation of the gravel base was then calculated by subtracting the elevation of the water level from the elevation of the gravel base.

3.3. OSL/IRSL dating

In total, 16 samples from fluvial terraces and cover sediments were dated using optically and/or infrared stimulated luminescence (OSL and IRSL). Eleven samples were dated at the luminescence laboratory of the University of Natural Resources and Life Sciences (BOKU) in Vienna (Austria) and five samples at the Sheffield Centre for International Drylands Research (SCIDR) luminescence laboratory (Sheffield, UK). A summary of relevant data from luminescence dating is given in Table 2.

All samples were taken from drilling cores except of DH 011/2, DH 020/1 and DH 020/2, which were taken from outcrops. Even though our major effort was to collect fine-grained, preferably sandy samples, we could not omit taking samples containing or surrounded by larger clasts. This was the case by samples taken from coarse-grained terrace gravels (HL-4D, HL 8/2, HL 8/3, HL 8/4, HL 7/4.1 and partly HL-5B as well as DH 011/2).

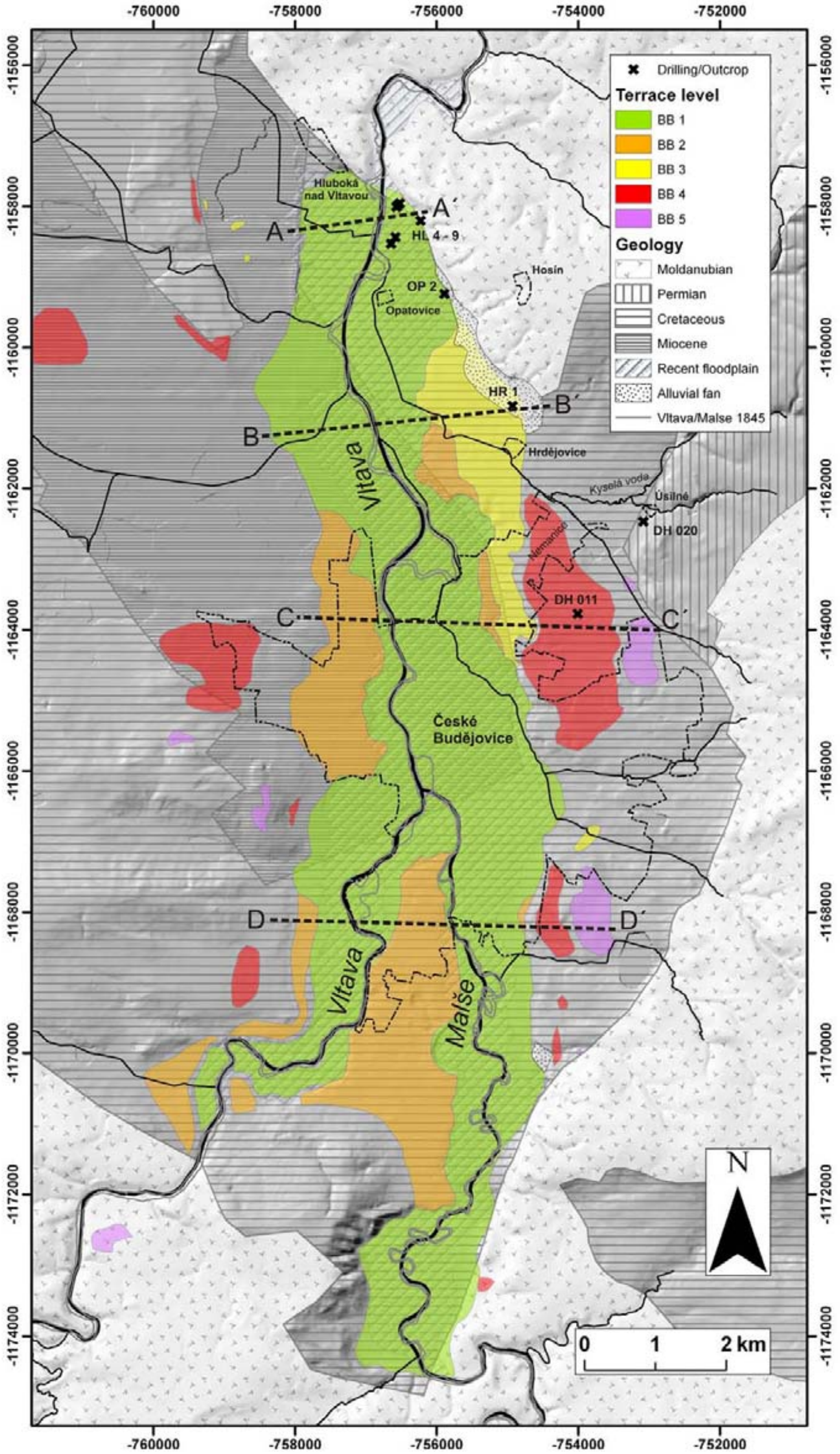

Fig. 3. Terrace levels BB 1 to BB 5 derived from morphological and borehole data projected on a simplified geological map of the study area. Lines show the location of cross sections in Fig. 4.

Table 1
Sample sites location data.

Site name	Location	X[a]	Y[a]	Lat (N)	Long (E)	Elevation (m asl)
HL 4	Hluboká n. Vltavou	−756,523.8	−1,157,955.1	49.046771°	14.449790°	373.2
HL 5	Hluboká n. Vltavou	−756,556.0	−1,157,984.8	49.046504°	14.449382°	373.4
HL 6	Hluboká n. Vltavou	−756,571.1	−1,158,006.7	49.046279°	14.449189°	373.2
HL 7	Hluboká n. Vltavou	−756,230.3	−1,158,202.5	49.044943°	14.454253°	373.0
HL 8	Hluboká n. Vltavou	−756,647.5	−1,158,528.6	49.041455°	14.449039°	373.6
HL 9	Hluboká n. Vltavou	−756,583.6	−1,158,431.9	49.042664°	14.450111°	373.0
HR 1	Hrdějovice	−754,931.5	−1,160,825.8	49.023138°	14.476880°	387.3
OP 2	Opatovice	−755,893.8	−1,159,235.2	49.036141°	14.460572°	374.2
DH 011	Nemanice	−754,011.4	−1,163,773.7	48.997941°	14.494497°	399.0
DH 020	Úsilné	−753,082.8	−1,162,468.4	49.010740°	14.504764°	402.0

[a] X–Y (m) stand for Jednotná trigonometrická sít' katastrální (JTSK) system used in the Czech Republic.

Radionuclide concentrations of the surrounding material for dose rate calculation were determined using laboratory gamma spectrometry (Vienna) and by inductively coupled plasma mass spectrometry (Sheffield).

Dose rates in all samples were comparably high, ranging from 3.0 to 7.1 Gy/ka (for the feldspar fraction) and averaging 4.0 Gy/ka. The reason is most likely that sediments are derived from crystalline rocks of the Bohemian Massif (see Section 2.), which usually have high contents of uranium, thorium, and potassium.

Slightly higher dose rates of samples HL-6A and HL 8/1 (feldspar fraction) are probably a result of pedogenic processes in sampled layers. The value of 7.1 Gy/ka (sample HL 9/1) was an outlying value which greatly exceeded the other values clustering around 3 and 5 Gy/ka. To ensure the reliability of the gamma-spectrometry measurement, we measured this sample twice, with the same result. The variability certainly does not reflect an instrumental error of the gamma-spectrometer, which has a very high reproducibility of 0.3, 0.5, and 0.6% for K, Th and U respectively, for a common sedimentary sample (loess).

The high dose rates pose a problem concerning the upper age limit in the study area. Common quartz saturation doses lie at around 200 Gy (e.g., Lomax et al., 2011); and for feldspar from the Budějovice basin, a saturation dose of ~530 Gy was determined. Divided by an average dose rate of 4.0 Gy/ka, the typical upper age limit for quartz lies at around 50 ka and for feldspar at around 130 ka.

Because of the higher saturation dose of feldspar compared to quartz, the majority of the samples were dated using a single-aliquot regenerative-dose (SAR) infrared stimulated luminescence (IRSL) or post-IR IRSL (pIRIR) protocol (Wallinga et al., 2000; Blair et al., 2005; Thomsen et al., 2008; Buylaert et al., 2009) of the potassium-rich, coarse grain feldspar fraction. Most of the younger samples were dated using the OSL signal of coarse grain quartz, following the SAR protocol of Murray and Wintle (2000). Three samples were dated using both the SAR IRSL and pIRIR protocol (HL 8/1, HL 8/2 and HL 8/3), whereas for sample HL 8/1, the OSL method was used too. Further details are listed in Table 2.

4. Results

4.1. Terrace staircase

Based on the relative elevation of the gravel base derived from borehole data and on topographic data from the DEM, five terrace levels in the Budějovice basin (BB 1 to BB 5) were identified (Figs. 3 and 4). Gravel occurrences at positions higher than 26 m above the recent Vltava water level were not included in this study, as they are well documented in Chábera (1965).

4.1.1. Terrace level BB 1

The horizontal extent and the top of the terrace level BB 1 are roughly coincident with the recent floodplains of the rivers Vltava and Malše and can be followed along the whole course of both rivers in the basin (Fig. 3). It is the largest terrace body in the study area, covering an area of more than 30 km^2. The relative elevation of the gravel base derived from the majority of the drillings located within this terrace level ranges from 4.1 to 0.5 m below the recent Vltava water level. In some places, the gravel base was reached even deeper, down to 7 m under the water level. The top surface coincides with the recent floodplain, situated about 2 m above the recent water level.

The terrace material consists of sub- to well-rounded polymict gravel covered either by fine-grained loamy and sandy flood sediments or by the recent soil. The relative portion of quartz pebbles in the coarse gravel reaches 50%. The thickness of the gravel layer ranges between 1.5 and 4.5 m, reaching up to 8 m in places where the terrace base is lower.

4.1.2. Terrace levels BB 2 and BB 3

The terrace level BB 2 is observed on both sides of the rivers Vltava and Malše and in the southern part of the study area between the rivers (Fig. 3). On the right river bank, a terrace riser of erosional origin can be followed along the whole river course through the basin, delimiting the recent floodplain against the higher terrace level.

The relative elevation of the gravel base ranges from 0 to ~4 m above the recent Vltava water level. The terrace body consists of an up to 5-m-thick layer of sub- to well-rounded polymict coarse gravel with clasts of up to 20 cm diameter and a top layer of fine-grained sediment mostly of colluvial origin. The relative portion of quartz pebbles is higher than in sediments of the terrace level BB 1, reaching up to 70%.

The terrace level BB 3 is identified from a terrace base at elevations between 4 and 10 m above the Vltava water level; its extent is only recognizable by the relative elevation of the gravel base. The surface of the terrace on the right bank of the Vltava River is not shown as a distinct morphological step but appears transitional to the top of BB 2. The composition and thickness of the terrace material is the same as BB 2. This terrace level covers a larger area on the right river bank and can be found only as remnants on the left river bank near the village of Hluboká nad Vltavou. As this is also the case by all terrace levels above the recent floodplain, the surface as well as the base of the terrace gently slope toward the river and does not appear as a horizontal plane.

4.1.3. Terrace levels BB 4 and BB 5

Sediments of terrace levels BB 4 and BB 5 could be reached by drillings only on the right banks of the two rivers. The occurrences of these terrace levels on the left bank of the Vltava River marked on the map are taken from the literature (Chábera, 1965).

The base of fluvial gravel of the terrace level BB 4 ranges from 12 to 18 m above the Vltava water level; the thickness of the gravel-bearing layer reaches up to 4 m. The terrace material consists of sub- to well-rounded polymict sandy gravel of up to 20 cm diameter with relative portions of quartz pebbles reaching up to 80%. Up to 5-m-thick layers of clayey and loamy sands of fluvial and colluvial origin cover the sandy gravels of this terrace.

The terrace level BB 5 has its base between 20 and 26 m above the recent Vltava water level and is made of an up to 3-m-thick layer of

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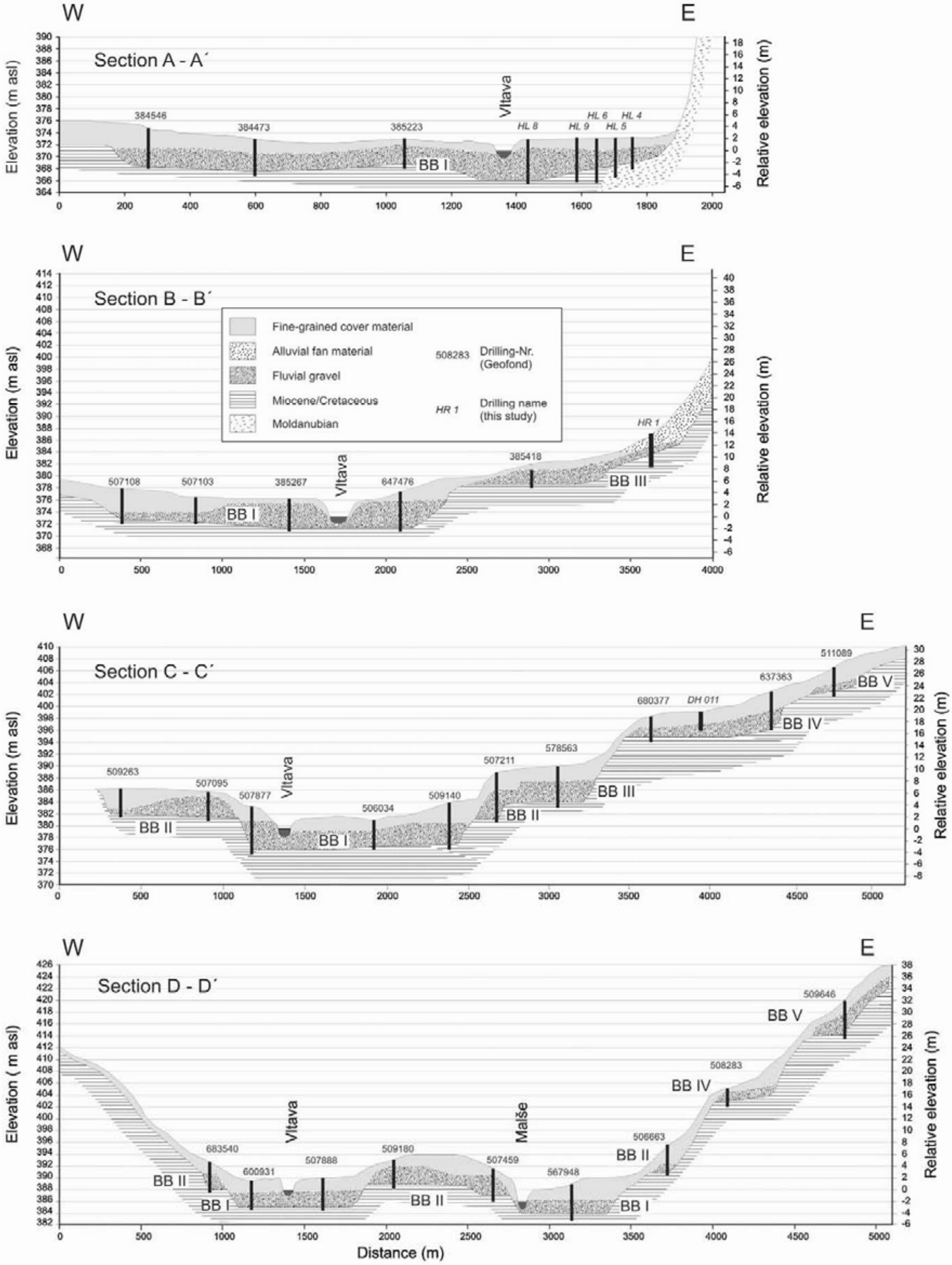

Fig. 4. Cross sections through the Budějovice basin (location see Fig. 3) showing the horizontal and vertical extent of the terrace bodies as well as the location of some boreholes used for mapping them. On these profiles, the characteristic morphology with the former terrace staircase being smoothed from gelifluction can be observed (see text in Section 2).

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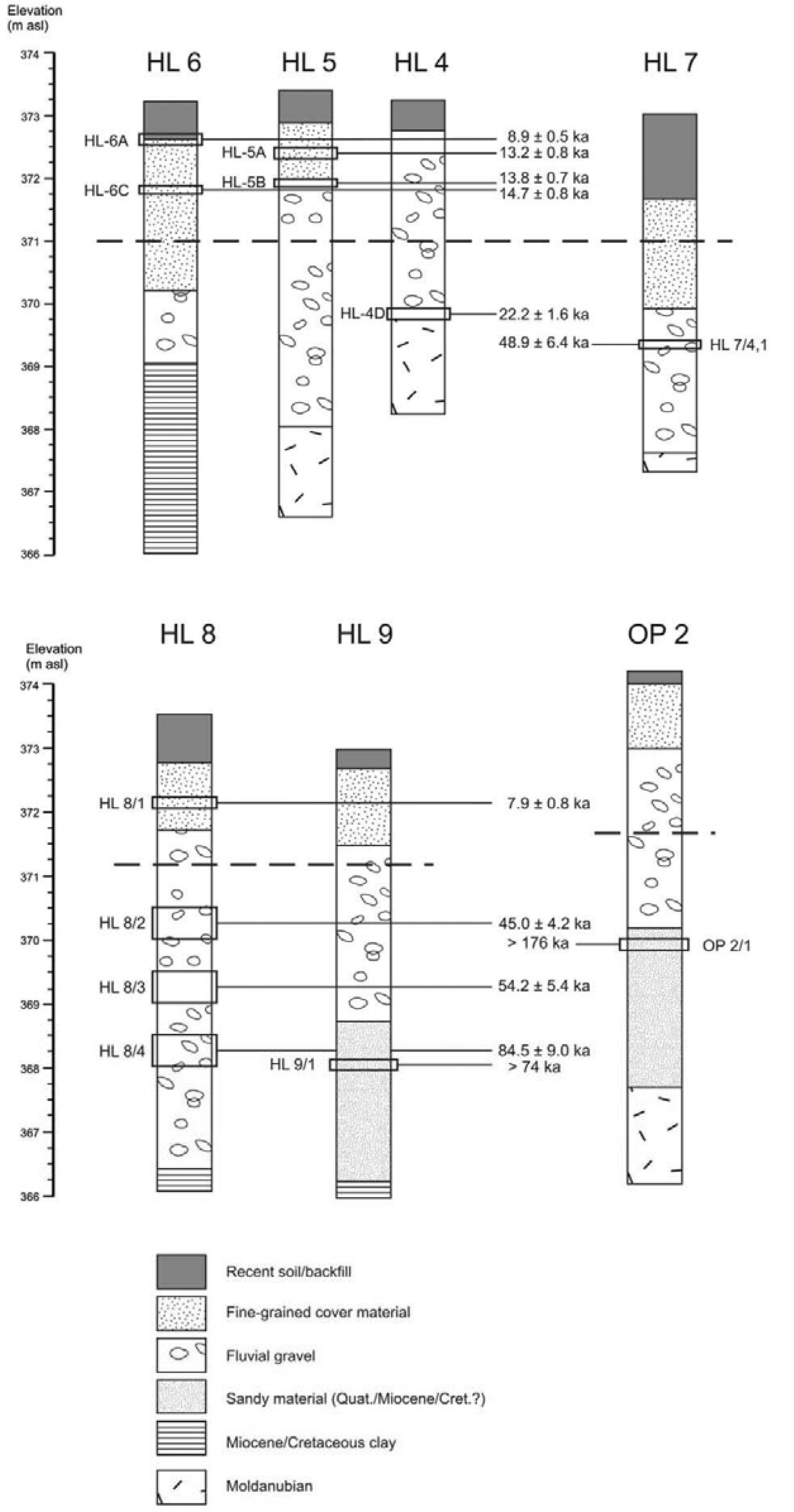

Fig. 5. Lithological profiles of boreholes HL 4 to HL 9, and OP 2 with the position of luminescence samples and their ages. The dashed line represents the mean Vltava water level.

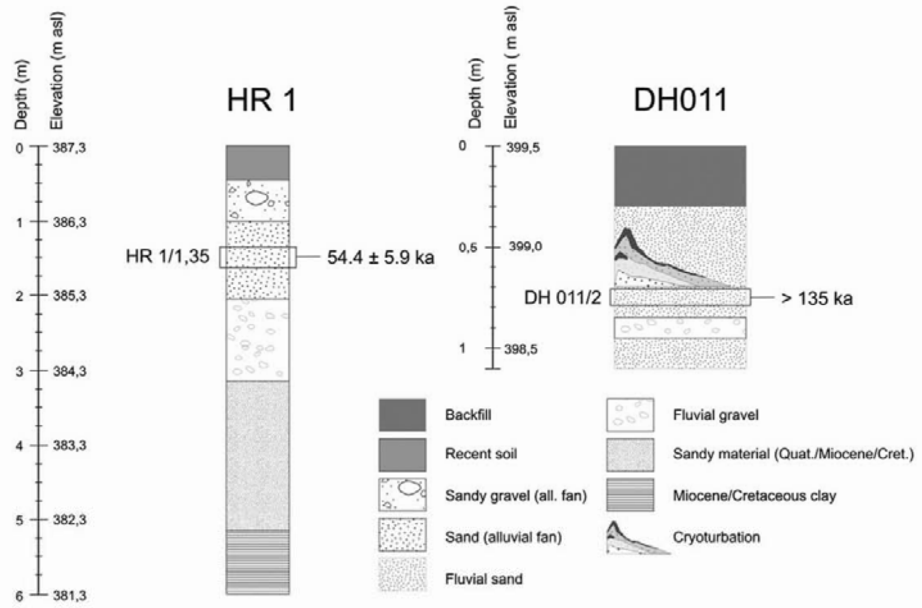

Fig. 6. Lithological profiles of the drilled HR 1 and outcrop DH 011 with the position of luminescence samples and their ages.

coarse sandy gravel, predominantly consisting of quartz. Covered by up to 6-m-thick layers of colluvial clayey and loamy sand, this old terrace has completely lost its original flat morphology and is recognizable only in cross-sections based on drillings and partly by the presence of rounded pebbles on the top.

4.2. Sedimentological characteristics and luminescence ages

All results from luminescence dating are summarized in Table 2 and illustrated in Figs. 5 and 6. More detailed lithologic profiles of all boreholes conducted during the research are described in Špaček et al. (2011).

Table 2
Summary of results from luminescence dating.

Sample name	Depth below surface (m)	Stratigraphic unit	Protocol (mineral)	Feldspar/quartz dose rate (Gy/ka)	n[a]	RSD (%)[b]	De (Gy)[c]	Age (ka)
HL-6A[d]	0.6	BB 1 cover	OSL (Q)	4.88 ± 0.24	24	9	43.4 ± 0.78	8.9 ± 0.5
HL-6C[d]	1.4	BB 1 cover	OSL (Q)	3.75 ± 0.20	24	11	55.3 ± 1.20	14.7 ± 0.8
HL-5A[d]	1.0	BB 1 cover	OSL (Q)	3.95 ± 0.21	22	12	52.2 ± 1.32	13.2 ± 0.8
HL-5B[d]	1.5	BB 1 top	OSL (Q)	3.59 ± 0.18	19	8	49.4 ± 0.95	13.8 ± 0.7
HL 4D[d]	3.5	BB 1 base	OSL (Q)	3.81 ± 0.23	23	27	84.6 ± 3.43	22.2 ± 1.6
HL 8/1[e]	1.4	BB 1 cover	IRSL (FS)	4.93 ± 0.43	8	9	38.9 ± 1.6	7.9 ± 0.8
			post-IR IR (FS)	4.93 ± 0.43	6	24	77.3 ± 7.3	15.7 ± 2.0
			OSL (Q)	3.99 ± 0.34	11	22	34.0 ± 2.4	8.5 ± 0.9
HL 8/2[e]	3.3	BB 1 middle	IRSL (FS)	4.11 ± 0.36	9	7	185.0 ± 6.7	45.0 ± 4.2
			post-IR IR (FS)	4.11 ± 0.36	6	7	167.3 ± 6.7	40.7 ± 3.9
HL 8/3[e]	4.3	BB 1 middle	IRSL (FS)	4.21 ± 0.37	6	10	228.4 ± 10.7	54.2 ± 5.4
			post-IR IR (FS)	4.21 ± 0.37	6	11	212.0 ± 10.8	50.3 ± 5.1
HL 8/4[e]	5.3	BB 1 base	IRSL (FS)	3.74 ± 0.33	14	21	316.5 ± 18.8	84.5 ± 9.0
HL 7/4.1[e]	4.1	BB 1 middle	IRSL (FS)	3.94 ± 0.29	13	36	192.6 ± 20.8	48.9 ± 6.4
HR 1/1.35[e]	1.3	BB 3 cover	IRSL (FS)	4.35 ± 0.41	8	13	236.8 ± 12.5	54.4 ± 5.9
DH 011/2[e]	1.0	BB 4	IRSL (FS)	3.90 ± 0.35	–	–	In saturation	> 135
HL 9/1[e]	4.9	M/C[f]	IRSL (FS)	7.13 ± 0.65	–	–	In saturation	> 74
OP 2/1[e]	4.2	M/C[f]	IRSL (FS)	3.00 ± 0.29	–	–	In saturation	> 176
DH 020/2[e]	1	Solifluction loam	IRSL (FS)	3.75 ± 0.34	7	10	71.1 ± 3.3	18.7 ± 1.9
DH 020/1[e]	2.3	Solifluction loam	IRSL (FS)	3.97 ± 0.36	7	10	90.3 ± 4.3	22.7 ± 2.3

Errors on paleodoses are a combination of the standard error from the Central Age Model (Galbraith et al., 1999) and a 3.5% error accounting for uncertainties in calibrating the beta source. Errors on individual De-estimates of measured subsamples are based on counting statistics and an instrumental error of 1.5% (Galbraith et al., 2005).

[a] n – number of accepted aliquots.

[b] RSD – relative standard deviation.

[c] De – Paleodose.

[d] Sample dated by SCIDR (quartz fraction 90–250 μm, 9.6 mm Ø aliquots SAR protocol (Murray and Wintle, 2000), preheat temperature 240 °C for 10 s, detection with Hoya U340 filter).

[e] Sample dated by BOKU (quartz or K-rich feldspar fraction 100–200 μm, 1 and 2 mm Ø aliquots). Quartz: SAR protocol (Murray and Wintle, 2000), preheat temperature 260 °C for 10 s, detection with Hoya U340 filter. Feldspar: SAR protocol (Wallinga et al., 2000; Blair et al., 2005), preheat temperature 270 °C for 10 s. Post-IR IR protocol (Buylaert et al., 2009), preheat temperature 250 °C for 60 s, second IR stimulation at 225 °C, detection with LOT-Oriel interference filter (~410 nm).

[f] M/C – Miocene/Cretaceous.

4.2.1. Sediments of terrace level BB 1

In the course of the field survey, seven drillings were conducted in the lowermost terrace level near the town of Hluboká nad Vltavou (Fig. 2B). Drillings HL 4 to HL 9 and OP 2 in the vicinity of Hluboká nad Vltavou and Opatovice, respectively, revealed an up to 4-m-thick layer of polymict coarse gravel with sub- to well-rounded pebbles of up to 10 cm diameter in a sandy matrix. This layer is covered either directly by the recent soil (HL 4) or by fine-grained flood sediments and the soil on the top (HL 5 to HL 9). The fine-grained cover material, and partly the recent soil as well, show gleyic marbling. In HL 8, an over 5-m-thick layer of coarse gravel was revealed, probably representing a deeply incised channel. Absolute ages of the sediments sampled from this terrace level are shown in Fig. 5.

4.2.2. Sediments of terrace levels BB 3 and BB 4

Sediments of terrace level BB 3 were reached by drilling HR 1 (Fig. 6). The ~1-m-thick layer of fluvial sandy gravel with subrounded clasts of up to 10 cm diameter is interpreted as a terrace deposit of the Vltava River. The base of fluvial gravel was reached at ~384 m asl (10 m above the Vltava water level).

Exposures of fluvial sediments of the terrace level BB 4 in a construction pit (outcrop DH 011) showed terrace material with coarse sand and gravel made up of clasts with up to 5 cm diameter reworked by cryoturbation (Fig. 6). The terrace base could not be reached. A sample from underneath the cryoturbation layer at 398.7 m asl (20 m above the Vltava water level) provided a minimum luminescence age of 135 ka.

4.2.3. Valley edge overburden

The material overlying the fluvial deposits of the terrace level BB 3 was recovered by the drilling HR 1 (Fig. 6). It probably originates from one of the small right-hand tributaries of the Vltava River crosscutting the morphological scarp of the Hluboká Fault forming an alluvial fan deposited on top of the former terrace surface (Fig. 3). This is also indicated by the topography. A sample from the cover layer shows a luminescence age of 54.4 ± 5.9 ka constraining the minimum age of the fluvial gravel underneath.

The deposition of the fan material on top of the terrace took place mainly after, but probably also during the deposition of the fluvial gravel. The intercalation of fluvial gravel and alluvial fan material in one of the fans along the Hluboká Fault scarp described by Balatka and Přibyl (1997) supports this assumption.

During construction work in the vicinity of Úsilné, unsorted, fine-grained deposits with a high content of angular fine gravel were found at the contact to Permian claystones. Sediments of both units were strongly reworked by freeze-and-thaw processes showing cryoturbation patterns such as structures formed from injection of sediments into polygonal cracks or irregular folds (Lowe and Walker, 1997). Sand wedges of more than 2 m depth in the Permian claystones also can be found (Fig. 7).

Two samples from this section were dated, showing ages of 18.7 ± 1.9 ka (DH 020/2) and 22.7 ± 2.3 ka (DH 020/1). These results are in accordance with the geological map (Suk et al., 1989), where slope deposits in this area were assigned to the Würm glacial. The cryoturbation processes must have taken place after their deposition meaning that even after the LGM, climatic conditions favorable for cryoturbation prevailed here.

4.3. Luminescence dating: determination of equivalent doses

In our study, we dated Quaternary clastic sediments from different sedimentary environments: fluvial sandy gravels of the river Vltava, alluvial fan material and colluvial deposits. By luminescence dating of the investigated samples, three potential problems need to be considered. First, the waterlain and colluvial character of sediments might have resulted in incomplete signal bleaching during transport and deposition. Second, as mainly the IRSL signal of K-feldspars was analyzed, anomalous fading during geological storage times might have resulted in signal shortfall and age underestimation. And third, due to high dose rates, some of the feldspar samples approached signal saturation and only minimum ages could be determined.

Incomplete bleaching is detectable through analysis of equivalent dose (De) distributions, if small aliquots (ideally single grains) are used (e.g. Olley et al., 1998; Bailey and Arnold, 2006). Those samples

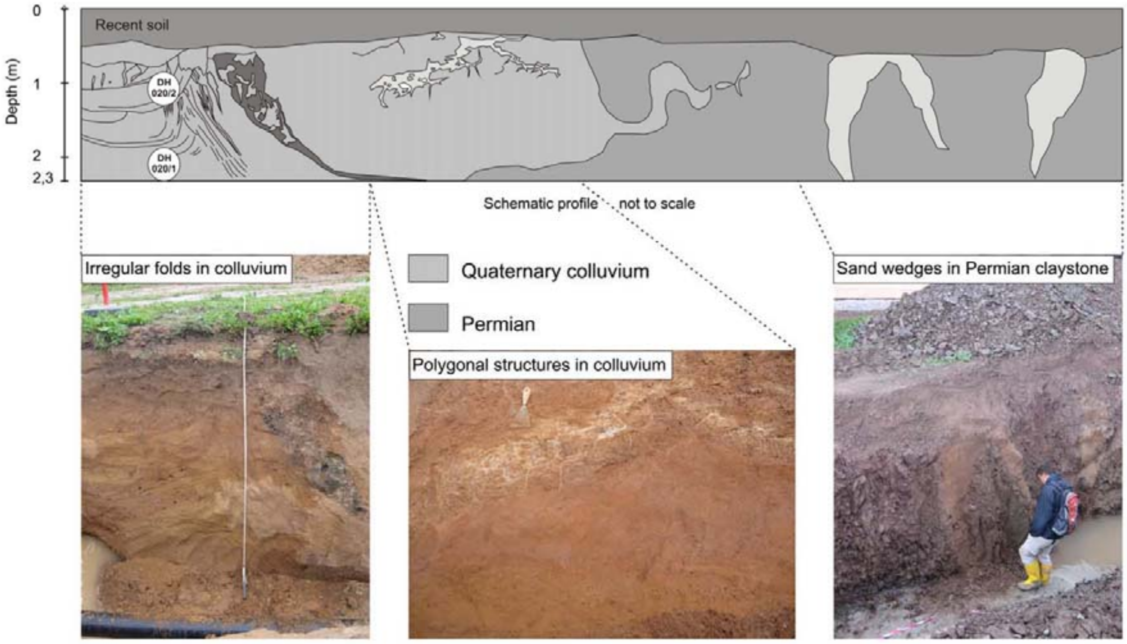

Fig. 7. Simplified sketch of outcrop DH 020 showing cryoturbation structures and the location of samples for luminescence dating.

which were measured with small aliquots (1 mm and 2 mm Ø) showed low relative standard deviations of <13%, and Gaussian-shaped distributions for the majority of samples (see Fig. 8). The samples HL 7/4.1 and HL 8/4 show a higher degree of scatter, which might be ascribed to the presence of larger clasts in the surrounding material and to the signal approaching saturation, respectively. We thus consider bleaching a minor problem for most of the analyzed samples.

Four of the five samples measured with 9.6 mm Ø aliquots also showed normally distributed De-values with a low level of scatter. The sample HL-4D showed a scattered multimodal De-distribution, which was probably caused by incomplete bleaching and the resulting age was subsequently extracted by finite mixture modeling. All remaining De-values were calculated using the central age model (Galbraith et al., 1999).

In order to assess the potential degree of fading, three feldspar samples were measured with the so called pIRIR protocol (Thomsen et al., 2008; Buylaert et al., 2009). This protocol determines a De using IR stimulation at 225 °C which follows an IR stimulation at 50 °C. The first, low temperature stimulation is suggested to empty more unstable traps, while the high temperature stimulation should produce a more stable signal.

For samples HL 8/2 and HL 8/3, the conventional IRSL ages and the pIRIR ages are in good agreement within errors although the pIRIR signal has been shown to often produce an unbleachable residual under natural conditions, which can cause age overestimation of several ka (e.g. Buylaert et al., 2009). In sample HL 8/1, the pIRIR age overestimates the conventional IR age. The pIRIR age is considered unreliable, because of a large overdispersion of 22%, and in view of this scatter, a too low number of measured aliquots. For the same sample, a quartz OSL age was determined additionally, which agrees with the conventional feldspar age.

A fading test using a modified approach of Auclair et al. (2003) was carried out on sample HL 8/1. The modification of the protocol was to measure the 'prompt' signal after a certain delay time of 4000 s (66 min). The logic behind this procedure is that all measurements were carried out in a non-'run one at a time' mode. This means that during standard measurements a significant delay between irradiation and signal measurement occurs, when many of aliquots are measured in one measurement. With the 'delayed prompt' signal we try to mimic this effect to a certain degree, although delay times during standard measurements were slightly longer.

The resulting fading rate (expressed through the g-value) is small (g = 0.5%) (Fig. 9). Fading rates as low as these (and also larger ones) are sometimes argued to be a laboratory artifact, at least in pIRIR studies (Buylaert et al., 2011; Thiel et al., 2011). We therefore did not correct our ages for this small fading rate. Furthermore, fading correction is only considered reliable in the linear part of the growth curve (Huntley and Lamothe, 2001), and most of our Pleistocene samples are already in the exponential part of the growth curve.

A further indication of negligible fading in nature is the fact that the natural signal of three samples is in saturation (Thiel et al., 2011). The saturation levels of these samples lay at around 530 Gy, and the natural signals greatly exceeded this level (Fig. 10). The

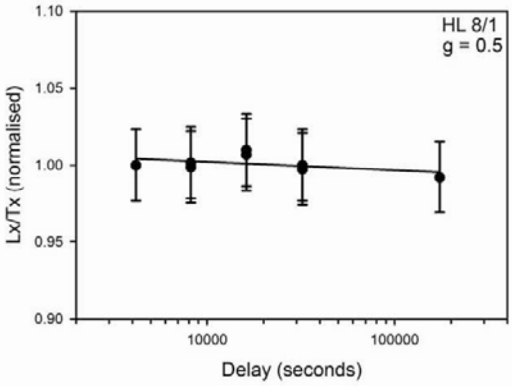

Fig. 9. Fading test of feldspar samples HL8-1, following a modified protocol of Auclair et al. (2003). The fading test was carried out on one large aliquot (6 mm).

minimum ages in Table 2 are derived from dividing the saturation level of 530 Gy by the individual dose rates of the respective samples.

It should be noted that the fading test was only carried out on one (large) aliquot, and only on one sample, thus may not be representative for other aliquots or samples. However, together with the further evidence, i.e. feldspar doses in saturation, consistent quartz and feldspar ages and consistent IRSL and pIRIR ages, we think that fading of the feldspar signals is of minor importance for the samples of this study.

5. Discussion

5.1. Terrace morphology

The presence of a terrace staircase in the Budějovice basin serves as a clear evidence for a regional uplift in the study area in the past, whereby at least since the late Pleistocene, the basin was inactive or slowly subsiding. This is proved by the fact, that the thalweg of the modern river sits on a stacked sequence of fluvial sediments deposited since the last ~100 ka. Similar morphological build up of the river valley with a terrace staircase situated above the recent water level and the modern river thalweg sitting on the youngest gravel body can be observed along reaches crossing the Bohemian Cretaceous Basin as well as the basins adjacent to the Carpathian foredeep in Moravia (Tyráček and Havlíček, 2009).

In most regions with ongoing regional uplift such as the Rhine valley (Kock et al., 2009) or along the rivers Loire and Arroux (Straffin et al., 1999) fluvial deposits of the MIS 2 are situated above the recent

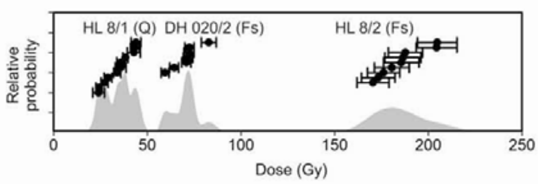

Fig. 8. De-distributions of samples HL 8/1 (Quartz, OSL, n = 11), HL 8/2 (Feldspar, IRSL, n = 9) and DH 020/2 (Feldspar, IRSL, n = 7). De-values were obtained on small (1 mm) aliquots.

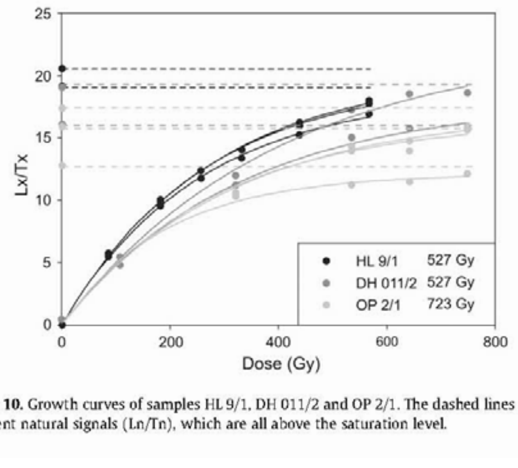

Fig. 10. Growth curves of samples HL 9/1, DH 011/2 and OP 2/1. The dashed lines represent natural signals (Ln/Tn), which are all above the saturation level.

floodplain, which is in contrast to the situation observed in the Budějovice basin and other areas within the Bohemian Massif. Along the river Danube, a similar situation to that on the Vltava River prevailed until ~6000 y BP (van Husen, 2000), but here, the reason was the high sediment load after the retreat of the glaciers that hindered the river in cutting into its MIS 2-terrace. In case of the Vltava River, this scenario can be completely ruled out because its headwaters were not extensively glaciated.

Comparing the results of this study with older studies about fluvial terraces in the Budějovice basin remains problematic, since it is not clear which water level was used for calculating the relative elevations of the terraces in these studies (Table 3). Chábera (1965) mapped five terrace levels of Vltava and Malše in the Budějovice basin as well, but with terrace bases ranging between 3 m below to 41 m above the Vltava water level. His terrace level V relatively well coincides with the terrace level BB 1 described in this study, but there is almost no accordance concerning relative elevations of higher terrace levels.

Concerning the vertical differences between the five terrace levels, some accordance with a morphostratigraphic interpretation of terraces in the Bohemian Massif discussed in Tyráček (2001) can be observed. This interpretation uses a major subdivision of terraces into three groups: *high-, middle- and low-terrace groups* corresponding to the Lower Pleistocene, Middle Pleistocene and Upper Pleistocene. According to this scheme, the lower terrace levels BB 1, BB 2 and BB 3, showing relatively small vertical differences between each other, can be assigned to the low-terrace group. Higher terrace levels BB 4 and BB 5 with a slightly bigger vertical difference with respect to the lower terrace BB 3 can be assigned to the middle-terrace group. Occurrences of depleted quartz pebbles at higher elevations which are not object of this study could subsequently be assigned to the high-terrace group.

By plotting the borehole data on a longitudinal profile of the Vltava River (Fig. 11), a relatively high scatter in the relative elevation of the gravel base within individual terrace levels can be observed. The terrace bases do not appear as horizontal planes, but show an undulating erosional surface with depressions representing former main channel thalweg segments (see Fig. 4). We consider such topography of a terrace base as a result of a strong lateral shift of the river's main channel(s), easily eroding in the soft sandy and clayey sediments of the Miocene and Cretaceous. Within the terrace level BB 1, the vertical scatter of the gravel base reaches up to 6 m, being almost as high as the mean thickness of the whole gravel layer.

In the whole study area, the preserved terrace remnants get thinner with increasing age and vertical distance from the modern river, which is apparently a result of an ongoing decay of the (originally probably much thicker) terrace bodies by erosion, soli- and gelifluction, cryoturbation, and alluvial fan tributary erosion. Cryoturbated colluvial sediments from Úsilné described in this study (outcrop DH 020) serve as a clear evidence for such processes, constrained by luminescence dating to the last glacial maximum. We dated the deposition of alluvial fan material on top of the terrace BB 3 to ~50 ka (MIS 3), but it cannot be ruled out that similar processes took place during all other cold and wet phases of the last 100 ka.

5.2. Sedimentary history and regional comparison

According to the luminescence ages obtained from the drillings in the vicinity of Hluboká nad Vltavou, the patchy preservation of fluvial gravel in the lowermost terrace level BB 1 goes back to at least the MIS 5 (Fig. 12). Here, three age clusters can be recognized: one around the last glacial maximum (ca. 20 ka), one between 40 and 60 ka and one around 80 ka. Due to the fact that the error range of luminescence dates by samples older than ca. 20 ka exceeds the duration of the cold/warm phases of the last 100 ka, correlations between fluvial deposition and the paleoclimate are restricted to the last 20 ka. Based on the spatial distribution of the luminescence ages, the terrace BB 1 probably represents a complex sediment body incorporating more distinct packages of river aggradation that are separated by one or more disconformities.

The youngest group of samples taken from the recent floodplain is represented by fine-grained, mostly sandy overbank sediments covering the fluvial gravels, deposited in a low-energy environment typical to preserve from youngest warm phases: Two Holocene samples dated to about 9 ka (Boreal) and 3 samples from the Bølling/Allerød Interstadial (according to Nádor et al., 2007) dated to 13 to 15 ka.

In general, the sandy gravel of the lowermost terrace level BB 1 can be assigned to the last glacial period (Würm), which is in accordance with former studies dealing with fluvial terraces in this area (Chábera, 1965; Novák, 1990). In the Geological map of the Czech Republic (Vrána et al., 1990), fluvial gravels in this area are partly assigned to the Riss glacial, which according to our results is very unlikely, but cannot be completely ruled out because no basal fluvial gravel ages were obtained.

Fluvial gravel of the terrace level BB 2 must be older than 90 ka when we assume that its deposition took place before the deposition of the oldest sediments of BB 1. For the terrace level BB 4, only a minimum age of 135 ka was obtained, which allows us only to state that the terrace is Rissian or older. The same can be done in case of terrace level BB 3, where the age of the alluvial fan material constrains the terrace deposits underneath as older than ~50 ka.

At the lower reach of the Vltava River, the Maniny terrace (VII) near Prague can be correlated with the lowermost terrace BB 1 in Budějovice basin. Cryoturbated loess loams covering large areas of the Maniny terrace were dated using mollusk based biostratigraphy as of Würm Pleniglacial age (Záruba et al., 1977). Consequently, the accumulation of this terrace was completed during the MIS 2. Correlation of higher terrace levels along the Vltava River course without absolute ages of their sediments would remain speculative and is therefore omitted here.

One of the very few examples to compare the situation in the Budějovice basin to is the terrace system in the Dyje–Svratka basin situated in southern Moravia (Tyráček and Havlíček, 2009). Authors of this study describe twelve terrace levels preserved as patches

Table 3
Comparison of data from this study with older studies by Puffer (1918), Engelmann (1938), and Chábera (1965).

Glacial period	L. Puffer (1918) confluence Vltava–Malše		R. Engelmann (1938) Budějovice basin		S. Chábera (1965) confluence Vltava–Malše		This study Budějovice basin	
Günz	"Old glacial" Oberterrasse	T[a]: 15	O-Terrasse	T: 26-15	II. terrace	T: 41 B[b]: 33		
Mindel					III. terrace	T: 20 B: 15	BB 5 BB 4	B: 20–26 B: 12–18
Riss	Hochterrasse	T: 8	U-Terrasse	T: 6-5	IV. terrace	T: 6 B: 2	BB 3 BB 2	B: 4–10 B: 0–4
Würm	Niederterrasse	T: 1.5–1			V. terrace	T: 2 B: −3	BB 1	B: −0.5 to −4 (−7)

[a] T stands for maximal relative elevation of the terrace top in meters above Vltava.
[b] B stands for minimal relative elevation of the terrace base in meters above Vltava.

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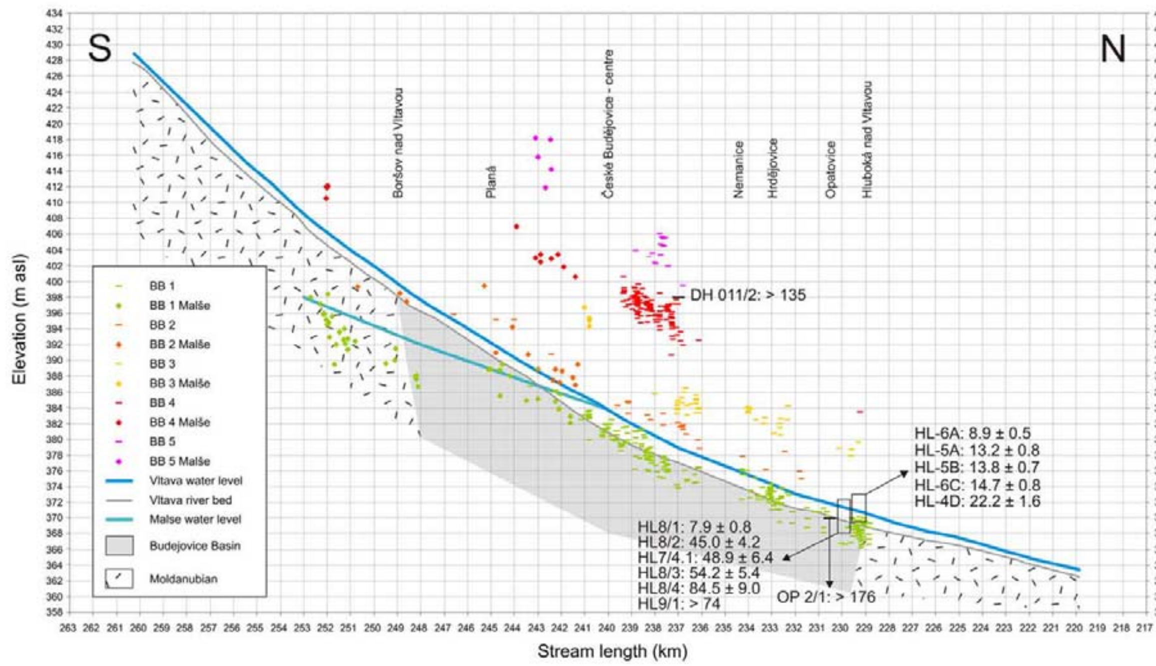

Fig. 11. Longitudinal profile of the rivers Vltava and Malše with data points representing the elevation of the gravel base derived from all drillings and luminescence ages of fluvial sediments (in ka).

along the rivers Dyje, Jevišovka, Jihlava and Svitava–Svratka: six levels of Tertiary age and six levels formed during the Quaternary. Fluvial sandy gravels of the lowermost terrace level (Terrace I) are hereby filling the valley bottoms and the thalweg of the modern river sits on the top, similar to the terrace level BB 1 in the Budějovice basin. There are no absolute ages of sediments from the Dyje–Svratka basin presented in the study, but the authors propose a Pleistocene age of the Terrace I constrained by loess with the pedocomplex (PK) II paleosol and colluvia overlying the floodplain gravel in the Jevišovka valley.

In general, we consider the presence of stacked fluvial deposits of Pleistocene age underneath the recent floodplain in the Budějovice basin as well as in other areas within the Czech Republic mentioned above as an evidence for their ongoing subsidence or relative tectonic stability during the late Pleistocene.

6. Conclusions

Within the Budějovice basin, five terrace levels of the rivers Vltava and Malše (BB 1 to BB 5) were identified by integrating morphological data from a high-resolution DEM, field survey, and subsurface data from boreholes. The use of borehole data turned out to be crucial for mapping fluvial terraces in this area because, morphologically, these do not appear as a terrace staircase with characteristic horizontal surfaces and separating risers but as gentle slopes tilted to the river valley. This appearance is attributed to periglacial gelifluction, which took place during the last glacial maximum and similar cold phases before. The originally flat topography of the terraces was also overprinted by alluvial fans of small right-hand tributaries of the Vltava River, which were formed mainly after but probably also during the deposition of

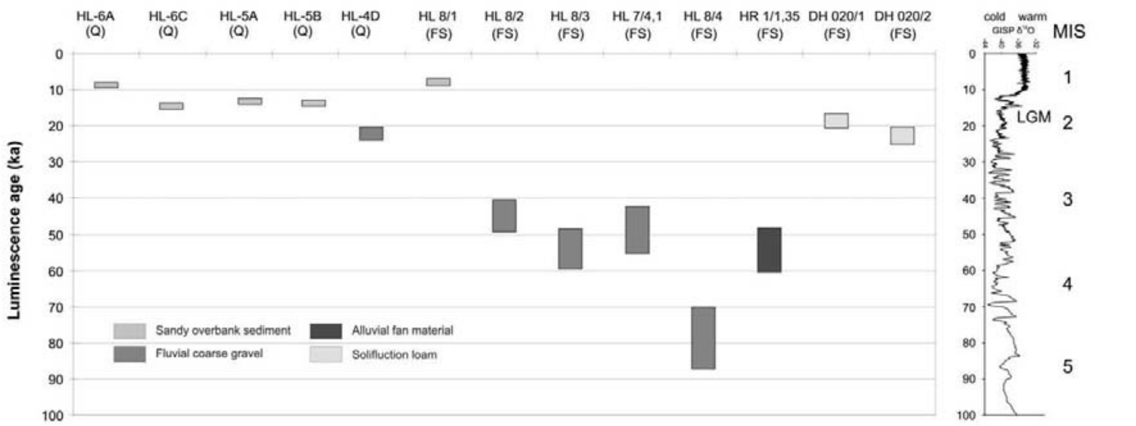

Fig. 12. Luminescence data plot of all samples from this study with associated depositional environments; Q — quartz signal, FS — feldspar signal, LGM — Last Glacial Maximum, boundaries of marine isotope stages (MIS) derived from Preusser and Fiebig (2009), $\delta^{18}O$ — data by Grootes and Stuiver (1997).

the underlying terrace. The deposition of fluvial coarse gravel of the lowermost terrace BB1 took place at least since the MIS 5 and allows us to assign this terrace to the Würm glacial. Sandy overbank sediments covering this terrace were deposited during the Bølling/Allerød-Interstadial and the Holocene. Fluvial sediments of higher terrace levels were beyond the dating range of the luminescence method, which to some extent is a result of the relatively high dose rates of sediments in this area.

Further mapping and dating of fluvial sediments, especially in the southern parts of the study area, is necessary to round up the story about Pleistocene alluvial deposition in the study area.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.geomorph.2012.04.001. These data include Google map of the most important areas described in this article.

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Appendix D

Homolová, D., Lomax, J. and Decker, K. (in preparation for submission to "Quaternary Research"). Vltava River terraces in the vicinity of Hluboká nad Vltavou - Zámostí (Southern Bohemia).

Vltava River terraces in the vicinity of Hluboká nad Vltavou - Zámostí (Southern Bohemia)

Dana Homolová[a*], Johanna Lomax[b,c] and Kurt Decker[d]

[a] Department of Geodynamics and Sedimentology, University of Vienna, Althanstrasse 14, 1090 Wien, Austria

[b] Institute of Applied Geology, University of Natural Resources and Life Sciences, Peter-Jordan-Strasse 70, 1190 Wien, Austria

c Department of Geography, Justus-Liebig-University Giessen, Senckenbergstrasse 1, 35390 Giessen, Germany

Abstract

This study brings new results from mapping and dating of fluvial terraces of the river Vltava in the vicinity of Hluboká nad Vltavou - Zámostí (Southern Bohemia). With a combination of spatial data analysis, geomorphological mapping and analysis of drilling profiles, five terrace levels CB1 to CB 5 with bases ranging from 5 meters below to 45 meters above the Vltava water level were mapped. Fluvial sediments from the lowermost terrace level CB 1, morphologically corresponding to the recent floodplain, show luminescence ages ranging from ~ 60 ka to ~ 1 ka. This terrace level represents a complex sediment body incorporating more packages of river aggradation. Terraces CB 2 - CB 5 situated above the recent floodplain do not appear as morphological terraces because the original topography was smoothed by periglacial processes. Because of limitations of the luminescence method, the dating of sediments from the higher terraces was not possible. The lowermost terrace levels BB 1 and CB 1 along the Vltava River on both sides of the Hluboká fault show no change in the thickness and relative elevation of base below the water level but there is a mismatch of relative elevations of terraces situated above the recent floodplain on both sides of the fault. The occurrence of ~ 37 ka and ~ 14 ka old fluvial sediments several meters above the recent floodplain north of the Hluboká fault causes some problems to reconstruct the late Pleistocene valley development in this area as well. The mismatch of higher terrace levels and the occurrence of fluvial sediments of similar age at different position may be explained by

Quaternary active tectonics. These may have lead to the vertical displacement of the fluvial sediments on both sides of the Hluboká fault.

1. Introduction

The main focus of this study is on mapping and dating of fluvial terraces of the Vltava River near Hluboká nad Vltavou-Zámostí with the aim to reconstruct processes that have lead to the recent form of the Vltava valley around the Budějovice basin in Southern Bohemia.

The morphological build up and sedimentological content of fluvial sequences provide us valuable information about the landscape development in a particular area. Quaternary climatic fluctuations have lead to an alternation of fluvial aggradation and erosion that in combination with different rates regional uplift forced the formation of either terrace staircases or stacked fluvial sequences (Bridgland and Westaway, 2008; Starkel, 2003).

An important factor influencing the terrace morphology of river valleys is also the active surface deformation in form of folding, faulting and tilting (Schumm et al., 2002). These processes can lead to horizontal or vertical displacement of terrace bodies of the same age, which afterwards occur at different morphological positions.

This approach was used by reconstructing the neotectonic activity of the Hluboká fault, delimiting the sedimentary Budějovice basin from its crystalline basement north of it. Flowing from south to the north, the Vltava River deposited terrace bodies of different horizontal and vertical extent on both sides of the fault since the Pliocene (Tyráček, 2001). By mapping and dating fluvial sediments in the foot wall (crystalline basement) and hanging wall (Budějovice basin) of the fault, it should be possible to follow the activity of the fault during the Quaternary.

For building terrace stratigraphies of the Vltava River in this area, authors of former studies used their relative elevation above the river bed and some petrographic characteristics of fluvial sediments (Ambrož, 1935; Engelmann, 1939; Chábera and Novák, 1976). Based on morphological mapping, terraces were assigned to the five main glacials Donau, Günz, Mindel, Ris and Würm based on the system of Penck and Brückner (1909).

Such a simple assignment of fluvial terraces to the main glacial periods is not straightforward, because the headwaters of the Vltava River were never extensively glaciated (Nývlt et al., 2011). Without absolute age data of fluvial sediments, any stratigraphic assignment of the terraces remains theoretical.

Since the fluvial sediments of the Vltava River occurring in the study area are completely unfossiliferous, luminescence dating was used as the key method to get absolute ages of these sediments. The combination of morphological mapping, interpretation of borehole data and luminescence dating brings new insights into the terrace stratigraphy in the study area.

2. Regional setting

The study area is located in Southern Bohemia near the town Hluboká nad Vltavou north of České Budějovice. It comprises the Vltava River floodplain and surrounding hills northwest of the Hluboká fault, delimiting the Moldanubian crystalline basement to the sedimentary fill of the Budějovice basin in the south (Fig 1).

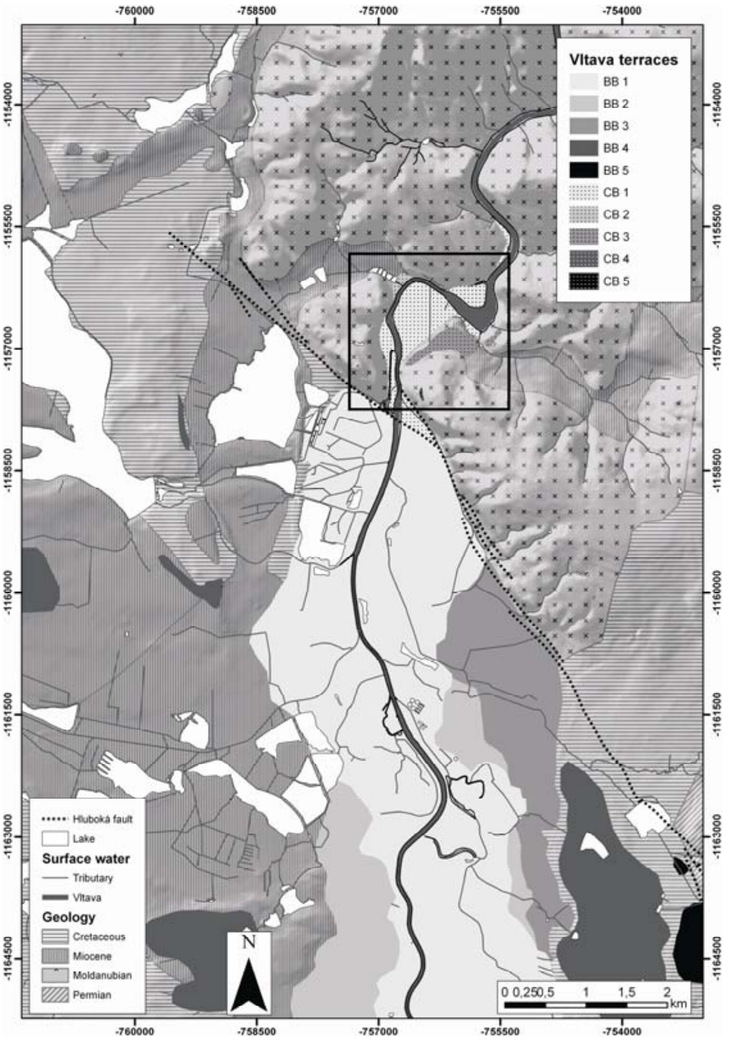

Fig. 21. Overview of the eastern part of the Budějovice basin and the Moldanubian crystalline basement northeast of the Hluboká fault. Displayed are the main geological units and the extent of Quaternary fluvial terraces based on Homolová et al. (2012) (terraces in the Budějovice basin) and results of this study (terraces north of the Hluboká fault). Black rectangle marks the extent and position of the study area.

With a length of ca. 377 km and a catchment area of more than 27 000 km^2 on Czech territory, the Vltava River forms the biggest fluvial system in the Czech Republic (Linhartová and Zbořil, 2006). Longitudinally, the river can be divided into two sections: the upper reach from the source to the confluence with Otava and the lower reach down to the confluence with Labe (Balatka and Sládek, 1962). The focus of this study is on a short section of the river at its upper reach north of the Budějovice basin.

After crossing the basin from south to the north, the Vltava River passes a narrow gauge near Hluboká nad Vltavou and enters the crystalline basement. North of Hluboká nad Vltavou-Zámostí, the river forms two big meanders in a relatively wide valley before entering the canyon-like narrow section further downstream (see Fig. 2).

The Moldanubian crystalline basement is formed by highly metamorphic Precambrian and Paleozoic rocks, mainly leucocratic migmatites and migmatized sillimanite-biotite paragneisses (Vrána et al., 1990).

Miocene sands and clays of the lower Mydlovary formation are deposited directly on weathered crystalline and occur mainly along the wide NW-SE-oriented channel located several meters above the recent Vltava River floodplain (Fig. 1). Based on analyses of macroflora, this formation was assigned to the Middle Miocene (Kvaček and Teodoridis, 2007). Characteristic for this formation is the occurrence of green clays with a variable content of organic, coal and diatomaceous components or pure diatomites and lignites (Slánská, 1963).

The Quaternary is represented mainly by Pleistocene fluvial sediments of the river Vltava and by slope deposits such as solifluction loams and loess loams. In course of the Pleistocene, periglacial cryoturbation in combination with soli- and gelifluction have lead to a downward redeposition of slope material and smoothing of the original valley morphology. Fluvial terraces therefore do not appear as horizontal surfaces, but as more or less tilted slopes. They are identified only by the occurrence of sandy coarse gravels, characteristic for fluvial transport.

The fluvial terraces is the study area were assigned to the glacial periods Donau, Günz and Riss based on their relative elevation above the recent Vltava water level (Vrána et al., 1990) but there are some discrepancies in the morphological approach to the terrace assignment. For example fluvial pebbly sands along the Vltava River and its local tributaries with the relative top ranging between 0 and 26 meters above the water level were assigned to the Riss glacial. Keeping in mind the fact, that the thickness of fluvial deposits in this area rarely exceeds 8 meters, the terrace top range of 26 meters appears strongly unrealistic.

Loess loams and solifluction loams found on slopes surrounding the Vltava River floodplain were assigned to the Würm period. Loamy overbank sediments of the Vltava River and its tributaries, recent creek alluvia and anthropogenic deposits of Holocene age are found as well (Základní Geologická Mapa ČSSR 1:25.000, 1982; Vrána et al., 1990). The stratigraphic assignment of these sediments is not supported by any dating method.

Two major fault systems striking in NW-SE and (N)NE-(S)SW direction, respectively, dominate the fault geometry of the region surrounding the Budějovice basin: the sinistral (N)NE-(S)SW-striking Blanice-Rodl-fault zone and the dextral NW-SE strinking Jáchymov fault system (Malkovský, 1987). This system is interpreted as a conjugate set of ductile wrench faults formed by N-S directed compression during the late stage of the Variscan orogeny (Brandmayr et al., 1995; Wessely, 2006).

The morphologically pronounced Hluboká fault, delimiting the sedimentary fill of the Budějovice basin to its Moldanubian crystalline basement, is part of the NW-SE-striking Jáchymov fault zone. The displacement along the Hluboká fault started in late Variscan times, continued during several reactivation phases in post-Cretaceous and post-Miocene times and continued probably into the Quaternary (Váchal et al., 2009). The fault offsets the top of the crystalline basement underlying the sedimentary fill of the Budějovice basin for up to about 340 m (Porpaczy et al., 2011).

3. Methods

3.1. Field survey

In course of the field survey, fluvial sediments of the Vltava River and other Quaternary deposits were reached by 13 drillings. Except for drillings HLR 1, HL 16, J 3 and J 6, all drillings were located in the recent Vltava River floodplain near Hluboká nad Vltavou-Zámostí (Fig. 2; Table 1). The remaining drillings were situated above the recent floodplain. The main focus was on the wide valley by Hluboká nad Vltavou-Zámostí, where the conditions for forming fluvial terraces, conducting drillings and taking samples were the best.

Site name	X	Y	Elevation (m asl)	Depth (m)	Thick. Quat (m)	Base Quat. (m asl)	Thick. gravel
HL 1	-756741.0	-1156708.0	371.7	10	5.5	366.2	2.5
HL 10	-756690.7	-1156808.2	372.5	4	3.6	368.9	3.1
HL 11	-756752.2	-1156801.5	372.1	5	4.5	367.6	2.8
HL 2	-755809.4	-1156394.9	371.5	16.5	8.2	363.3	4.7
HLR 1	-756690.1	-1156091.0	376.7	1.2	-	not reached	-
HL 16	-756924.6	-1156660.9	373.2	6	5.5	367.7	1.5
J 1	-755940.7	-1156331.1	371.0	9	7.2	363.8	4.5
J 3	-756757.8	-1156117.9	375.3	11	6	369.3	3.4
J 4	-756469.1	-1156347.4	371.0	5.5	5	366.0	4.5
J 5	-756371.8	-1156575.7	371.4	7	5	366.4	4.5
J 6	-756227.1	-1156757.5	378.5	4	2.6	375.9	0.7
J 7	-756356.1	-1156376.7	371.5	4	3.4	368.1	2.9
J 8	-756035.2	-1156287.4	371.0	5.4	4.2	366.8	3.6

Table 10 List of drillings conducted during the field survey in the vicinity of Hluboká nad Vltavou-Zámostí. X-Y (m) stand for Jednotná trigonometrická síť katastrální (JTSK) system used in the Czech Republic

Site name	X	Y	Elevation (m asl)
DH 005	-756934.3	-1156667.9	372.4
DH 007	-756223.0	-1156231.1	390.5
DH 008	-756474.6	-1157565.0	414.0
KR	-755577.1	-1156671.0	382.4
DH 033	-756427.9	-1156106.9	393.9
DH 034	-756238.4	-1156166.1	394.0
DH 036	-756451.5	-1156074.1	390.0
DH 037	-755539.5	-1156448.3	380.0

Table 11 List of outcrops revealing fluvial sediments in the vicinity of Hluboká nad Vltavou. a X-Y (m) stand for Jednotná trigonometrická síť katastrální (JTSK) system used in the Czech Republic

To get more data about terrace deposits located above the recent floodplain, four outcrops revealing fluvial coarse gravel were mapped and sampled: DH 005, DH 007, DH 008 and KR (Table 2). Additionally, occurrences of depleted coarse gravel (DH 033, DH 034, DH 036 and DH 037) and borehole data from the archive of the Czech Geological Survey (Geofond) were used to round up the picture (Fig. 2).

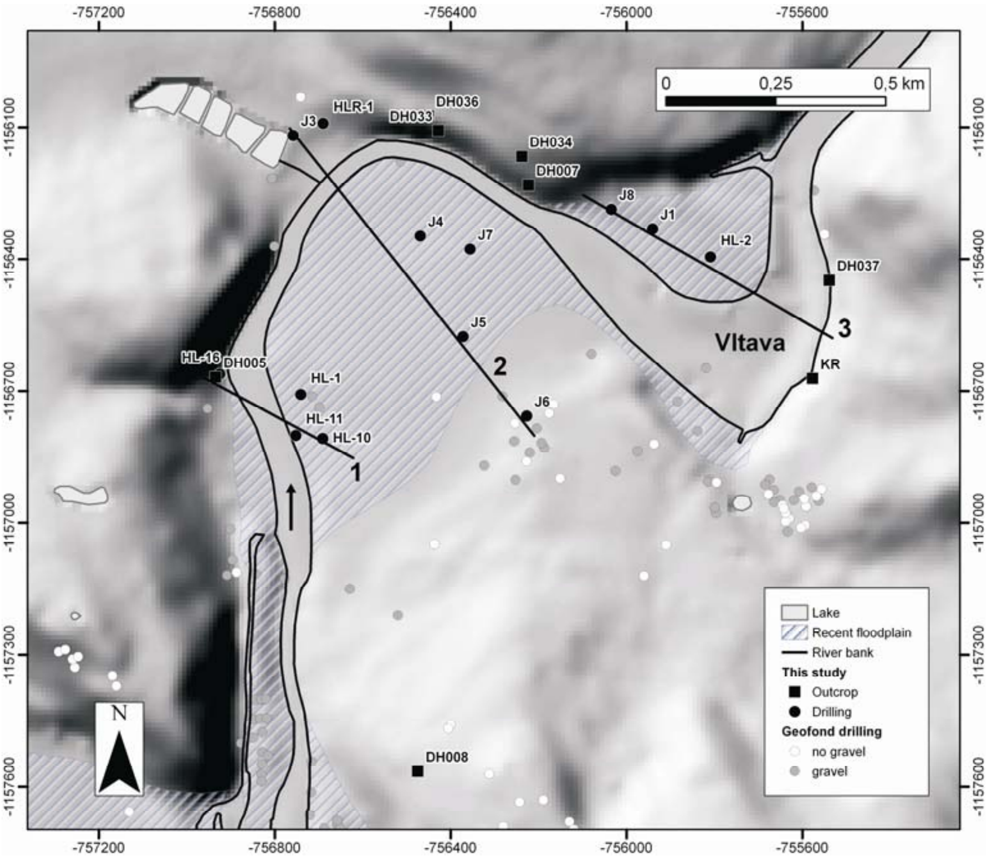

Fig. 22 Location of data points used for mapping Quaternary fluvial terraces in the vicinity of Hluboká nad Vltavou. Black lines numbered 1 -3 show the position of cross-sections through the area.

3.2. Geomorphologic analysis

Based on topographic data from a high-resolution digital elevation model in combination with results from the field survey, a morphological analysis of the study area was done. With the help of the 3D Analyst tool in ArcGis, slope angle from the DEM in degrees was calculated for the whole study area (Fig. 4). The main focus was on recognition of flat or very gently tilted areas, representing terrace surfaces and steep slopes surrounding them. Such an analysis was helpful to reconstruct the processes that have lead to the present form of the landscape.

Because the study area is characterized by a relatively strong anthropogenic overprint in form of agricultural use and stream regulations, historical map sheets of the Austrian Second Military Survey were used to obtain information about the topographic situation in the study area of the years 1836-1842 (Fig. 3) (Timár et al., 2006).

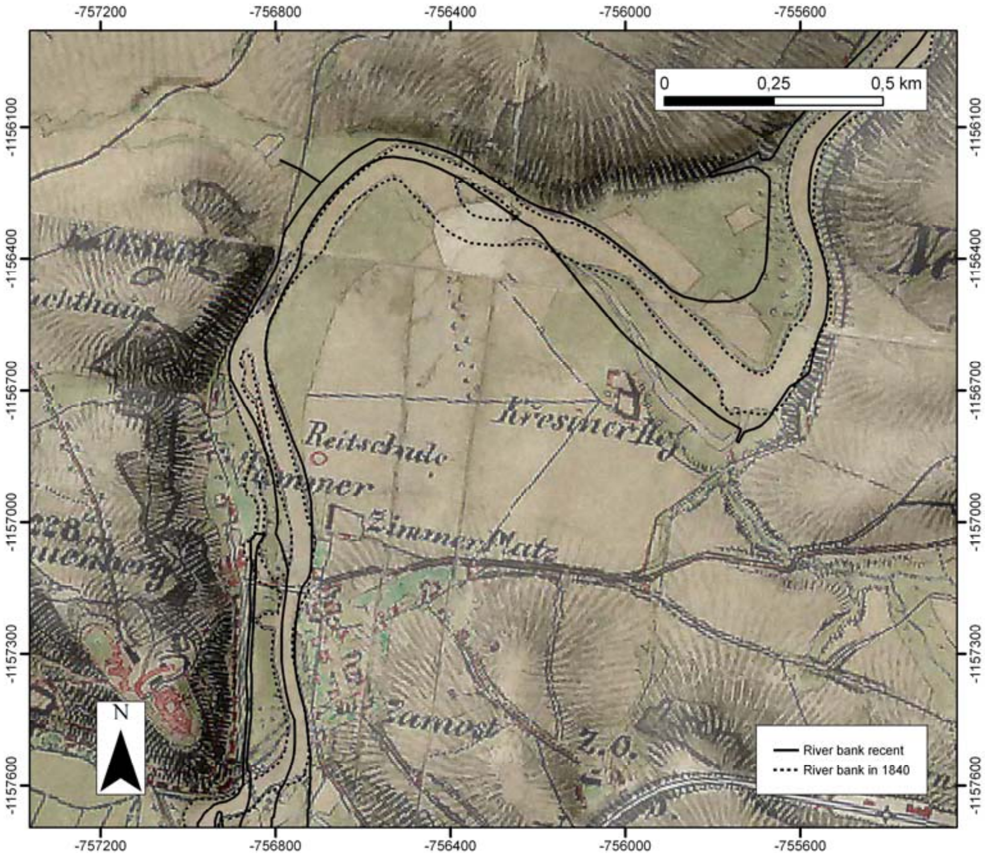

Fig. 23 Historical map of the Austrian 2nd Military Survey showing the Vltava River course around 1840 compared with the recent river course. Note the high accuracy of the historical map (Timár et al., 2006).

3.3. Interpretation of borehole/outcrop data

For mapping the horizontal and vertical distribution of fluvial sediments in the study area, more than 100 lithological profiles of boreholes were analyzed with respect to thickness and basic sedimentological characteristics of Quaternary fluvial deposits. Borehole data was collected predominantly from the archive of the Czech Geological Survey (Geofond). The analysis of drilling profiles was based mainly on the grain size, where sandy gravel or pebbly sand was recognized as characteristic for fluvial deposits. The definition of the terrace base was easy in places, where fluvial deposits lie directly on crystalline, but this task turned out to be relatively tricky, when fluvial sediments are underlain by fine-grained Miocene deposits. In cases, where only archive data was available, the grain size (sandy gravel or pebbly sand) was used for defining the terrace base. A similar approach was used in former studies dealing with Vltava River terraces in the Budějovice basin (Homolová et al., 2012).

After analyzing all core profiles and defining the thickness of fluvial sandy gravel, the base of the particular terrace was calculated by substracting the elevation of the water level from the elevation of the gravel base. For a detailed description of the procedure to calculate the relative elevation of the terrace base see Homolová et al., 2012.

The definition of the terrace base in outcrops situated above the recent floodplain turned out to be event more complicated than in the boreholes. The reason is that in all outcrops except for DH 005 and DH 007, fluvial sediments (mainly coarse gravel) were reworked and redeposited downslope by cryoturbation and/or periglacial solifluction. In these cases, only the minimal relative elevation of fluvial gravel above the recent floodplain could have been defined. The base of fluvial gravel in DH 005 was not reached, so the only site, where the terrace base was clearly recognizable, is the outcrop DH 007.

3.4. Luminescence dating

To obtain numerical ages of Quaternary sediments in the study area, 16 samples were dated using optically and infrared stimulated luminescence. Six samples were dated at the luminescence laboratory of the University of Natural Resources and Life Sciences (BOKU) in Vienna (Austria) and ten samples at the Sheffield Centre for International Drylands Research (SCIDR) luminescence laboratory (Sheffield, UK). Table 3 shows a summary of relevant data from luminescence dating.

Samples DH 005/1, DH 007/1, KR 1, and KR 2 were taken from outcrops by hammering metal tubes into the cleaned outcrops wall and transported in black bags protected from sunlight. The remaining samples were taken from drilling cores in plastic tubes, also protected from sunlight, or as larger sediment blocks. In the latter case, only the inner parts of the blocks, not exposed to sunlight, were used for luminescence analysis.

Radionuclide concentrations of the surrounding material for dose rate calculation were determined using laboratory gamma spectrometry (Vienna) and by inductively coupled plasma mass spectrometry (Sheffield).

4. Results and discussion

4.1. Morphological analysis of the study area

The most prominent morphological feature is the flat Vltava River floodplain, stretching along the river mainly in the inner parts of the meanders. These flat areas are flooded during catastrophic floods and show a strong anthropogenic overprint in the form of stream regulation, dams and intensive agricultural use. In this context, the historical map sheets provided valuable help by finding suitable drilling locations avoiding areas with strong anthropogenic overprint.

To the south - southeast, the flat floodplain gently rises and changes to an elevated subhorizontal area, representing the next terrace level (Fig. 4). This area is interpreted as an originally flat terrace surface, smoothed by periglacial soli- and geliflucion and cryoturbation. This causes problems by reconstructing the original terrace morphology in this area.

The outer parts of the meanders are characterized by very steep slopes, susceptible to mass movements. These slopes are also more or less influenced by periglacial processes, which have lead to redeposition of older terrace deposits downslope (see section XX).

In the northwestern part of the study area, there is a relatively flat estuary of a channel-like valley, leading to the outer part of the bigger Vltava River meander (Fig. 4).

4.2. Interpretation of borehole data

Out of ca. 100 drillings used for mapping the fluvial terraces, ca. 60 % reached fluvial coarse gravel. Fig. 4 shows the relative elevation of the gravel base derived from drilling and outcrop data, which was used for mapping the horizontal and vertical extent of the terraces.

Out of 13 drillings conducted in course of the field survey, nine were located in the recent Vltava River floodplain (Fig. 1), all of them reaching the terrace base. Four drillings were located above the recent floodplain (HL-16, J 3, J 6 and the hand drilling HLR 1). In the drilling HL-16, fluvial gravel of the lowermost terrace covered by a thick layer of backfill was revealed (Fig. 9). The base of fluvial gravel in the drilling J 3 was reached above the recent Vltava Water level and in the drilling J 6, only remnants of a redeposited terrace in form of loose coarse gravel mixed with sand was found. The hand drilling HLR 1 revealed only one meter of silty sand. Simplified lithological profiles of all drillings used for mapping the terraces are shown in cross-sections through the study area (Figs. 10 - 12).

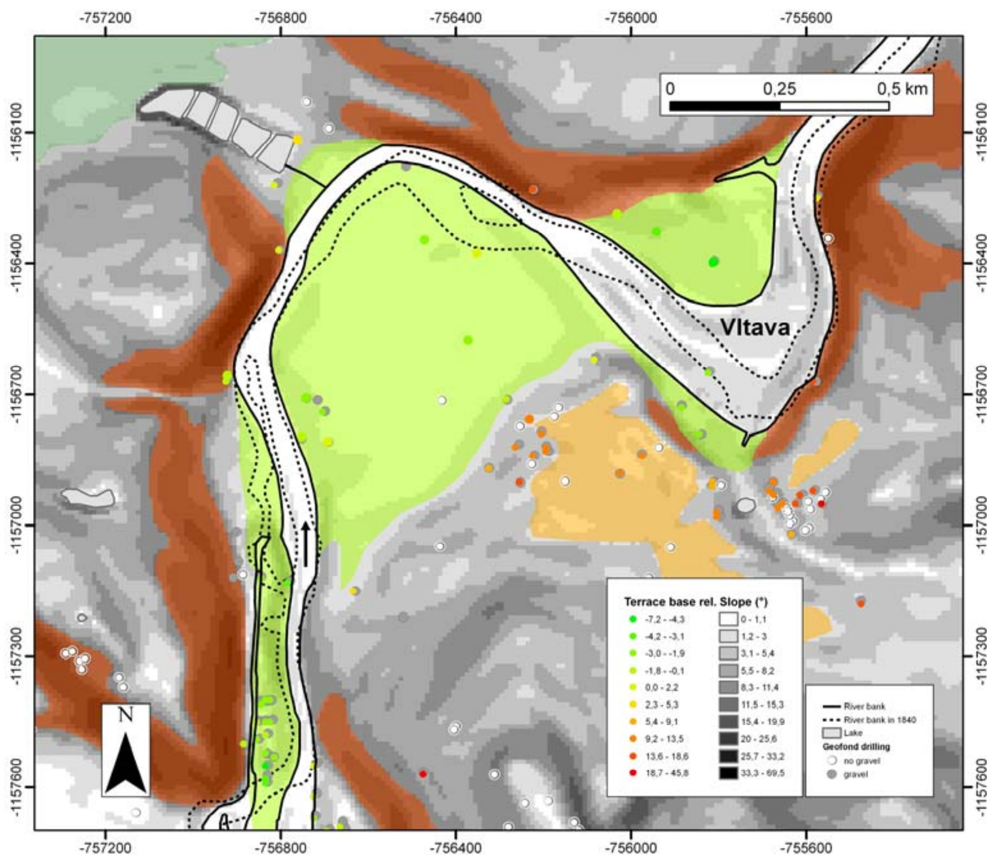

Fig. 24 Map showing the angle of slopes in the study area (in °) calculated from the DEM. Light green areas represent the Vltava River floodplain, orange areas the elevated terrace level, red areas mark steep slopes and the dark green area represents the channel-like vide valley (see text), leading to the recent Vltava River. Also displayed is the relative elevation of terrace base above the Vltava water level in meters.

4.3. Description of outcrops

4.3.1. Outcrop DH 008

The site is situated ca. 45 m above the recent floodplain near an area which in the geological map 1:25.000 (Základní Geologická Mapa ČSSR 1 : 25.000, 1982) is mapped as a fluvial terrace assigned to the Günz glacial period. The walls of a construction pit revealed an up to 3-m-thick layer of colluvial material overlying the crystalline basement rocks. The deposits contain well-rounded pebbles, presumably of fluvial origin, but the original horizontal bedding was subsequently reworked by slope processes. Two sections were mapped in the outcrop: the NW- and the SE-wall. The NW-wall shows matrix-supported colluvia with partly laminated layers of angular gneiss components and well-rounded quartz pebbles (Fig. 5a). The SE-wall is characterized by more distinct horizontal layering (Fig. 5b).

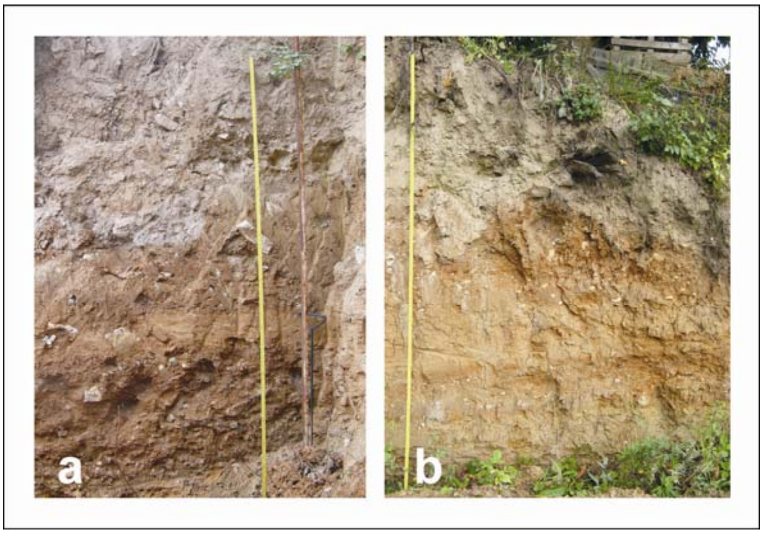

Fig. 25 (a) The NW-wall of the outcrop DH 008, revealing matrix-supported colluvial material containing well-rounded pebbles and (b) the SE-wall showing subhorizontal bedding of matrix-supported pebbly sand with well-rounded quartz pebbles and angular gneiss components. Length of scale is 2 meters.

4.3.2. Outcrop DH 007

The road cut exposes an over 1-m-thick layer of horizontally laminated fluvial sand and gravel on top of a crystalline basement rock, covered by silt and recent soil (Fig. 6). The silty sediments can be described as loess, deposited probably during the last glacial (Würm). The pebbles have a rusty coating and are partially weathered. The base of the fluvial terrace is located at elevation of approximately 389 m, 20 m above the recent floodplain.

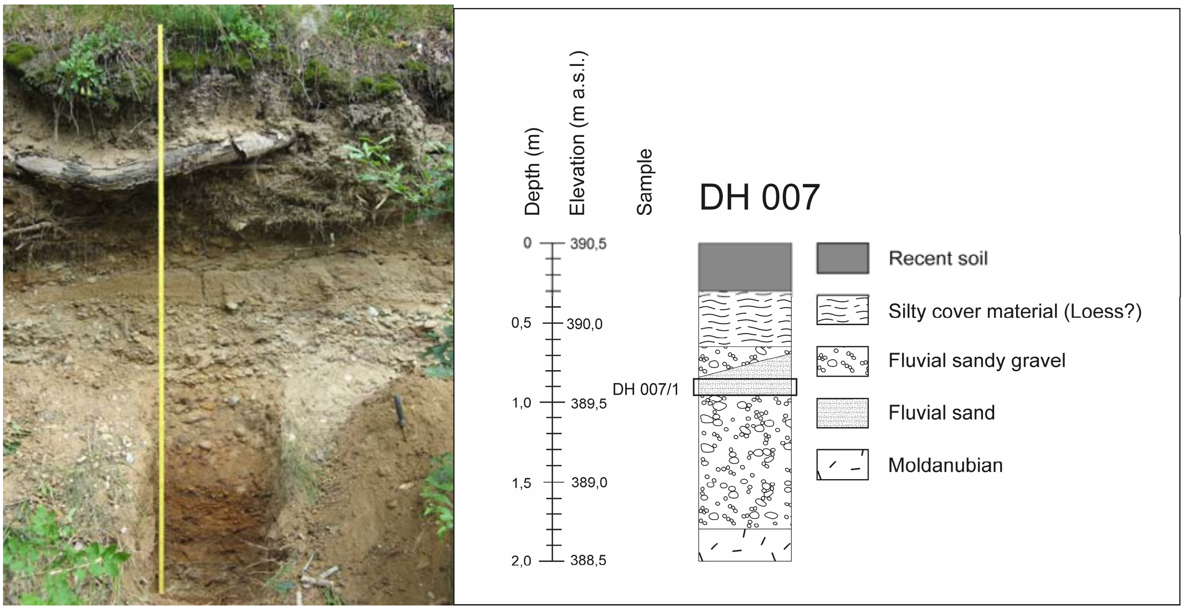

Fig. 26 Picture and lithological profile of the outcrop DH 007 showing horizontally laminated fluvial sand and gravel on weathered Moldanubian crystalline. Outcrop is situated on the left river bank, looking direction is NE.

4.3.3. Remnants of fluvial terraces on the left river bank

On the left river bank, approx. 20 meters above the recent floodplain, several remnants of a fluvial terrace with well-rounded coarse pebbles are found (outcrops DH 033, DH 034 and DH 036). These gravels probably belong to the same terrace level as the sediments found in the outcrop DH 007, because they are found at almost the same elevation.

4.3.4. Remnants of fluvial terraces on the right river bank: DH 037 and KR

On one of the steep slopes on the right river bank in the eastern part of the study area, an approx. 50 cm thick layer of fluvial coarse gravel occurs, apparently displaced by mass movements, reworked and mixed with the underlying crystalline by cryoturbation (outcrop DH 037). The original elevation of the gravel layer was presumably several meters higher.

Situated near the outcrop DH 037 on the right erosion bank of the meander, a landslide uncovered a remnant of redeposited fluvial gravel overlying the crystalline. The strongly weathered and cryoturbated gneiss is covered by a layer of rusty sands, an approximately 30 cm thick layer of coarse fluvial gravel, a second layer of sand and by recent soil on the top (Fig. 7). All layers, including components of weathered gneiss are strongly reworked by cryoturbation. The coarse gravel was probably redeposited by slope movement/gelifluction and does not represent the terrace in its original position.

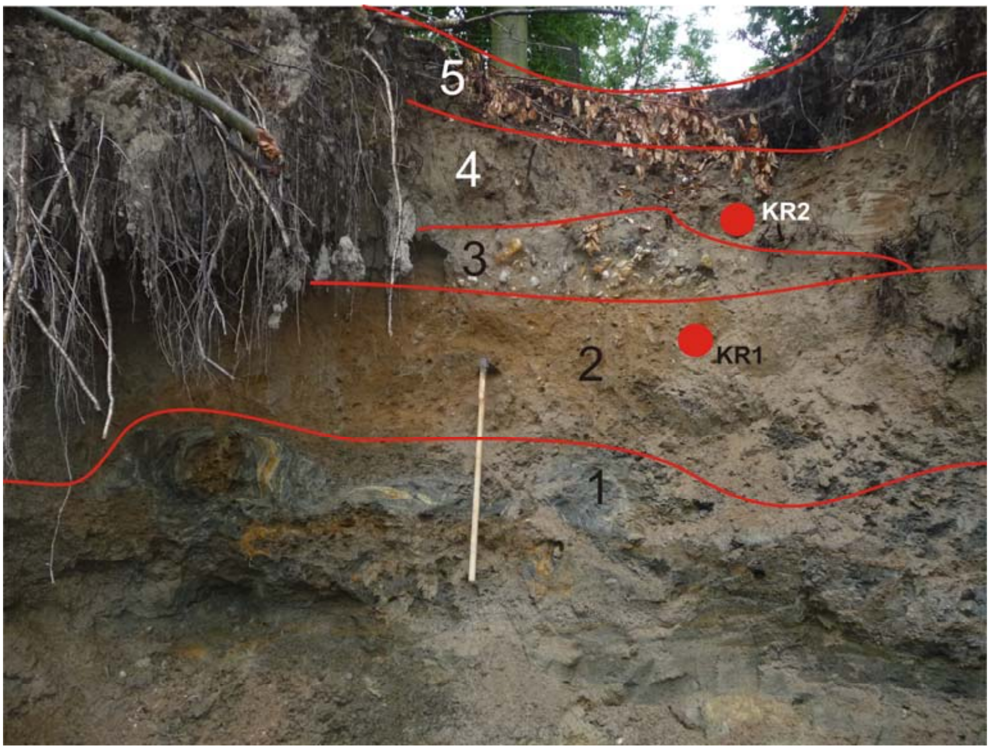

Fig. 27 Outcrop KR; Weathered gneiss, strongly reworked by cryoturbation (1) covered by rusty sand (2) a thin layer of gravel (3), sand (4) and the recent soil (5). Red circles indicate the luminescence sampling points. The looking direction is SSE, length of scale is approx. 1.2 meters.

4.3.5. Outcrop DH 005

In a construction pit located several meters above the Vltava River, fluvial coarse gravel below about 372 m overlain by several meters of sand was revealed. The base of fluvial gravel was not reached. The lower 145 cm of coarse sand and fine gravel were well sorted with planar cross bedding (Fig. 8e-f), most probably of fluvial origin. This layer was overlain by about 50 cm of medium to coarse sand with plane lamination, and about 90 cm of intercalated 2 to 5 cm thick layers of medium and coarse sand, silt and shale (Fig. 8b-d). The latter succession displays plane lamination. The whole succession shows a general fining-up trend and is interpreted as fluvial channel fill overlain by flood plain deposits.

In the upper parts of the profile, the fluvial succession is overlain by alternating layers of fine and medium sand partly containing humus. Showing a dip of 10° to 20° parallel to the actual slope (Fig. 8a), this succession is interpreted as a colluvium.

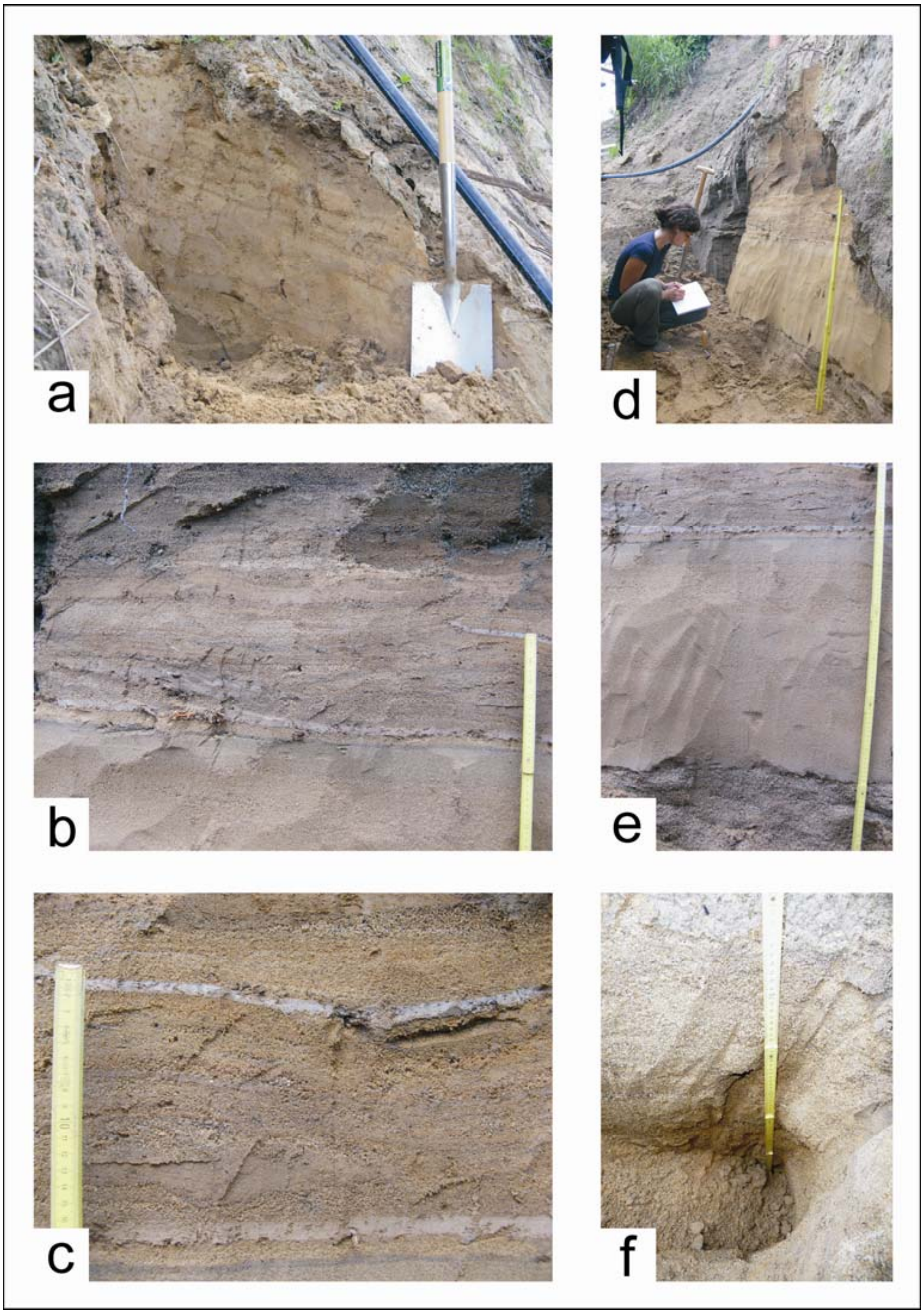

Fig. 28 Outcrop DH 005 (a) Section 3.6 - 4.5 m; colluvial sand with bedding dipping parallel to the slope direction, (b) Section 1.5 - 2.1 m; alternating thin layers with variable grain size, humus and mica content (flood deposits) on top of laminated well sorted fluvial medium sand, (c) Section 1.7 - 1.9 m; intercalated medium to coarse sand and shale interpreted as flood deposits, (d) Section 0.9 - 2.5 m; fining-up succession of coarse to medium sand and laminated sand-clay intercalations, (e) Section 0.9 - 1.8 m; coarse cross-bedded sand overlain by medium to coarse grained massive sand, (f) Section 0 - 0.75 m; coarse sand / fine gravel overlying coarse fluvial gravel at the bottom of the pit. The main outcrop wall (b-e) is facing toward E, wall showing the colluvium (a) is facing towards S.

4.4. Luminescence data

All relevant information concerning luminescence dating including sampling depth, dose rate, number of accepted aliquots, relative standard deviation, paleodose and numerical ages are listed in Table 3. The ages are given years from the present day (2012) presented with one sigma confidence intervals incorporating systematic uncertainties with dosimetry data, paleomoisture content and errors associated with De-determination.

Sample name	**Depth below surface (m)**	**Stratigraphic unit**	**Protocol (mineral)**	**Feldspar/ quartz dose rate (Gy/ka)**	**n[a]**	**RSD (%)[b]**	**De (Gy)[c]**	**Age (ka)**
DH 005/1	-0.3	CB 1 cover	IRSL (FS)	4.03 ± 0.36	25	13	94.3 ± 5.8	**23.6 ± 2.4**
DH 007/1	0.9	CB 4	IRSL (FS)	4.21 ± 0.38	-	-	> 530	**> 125**
HL 11/1	2.5	CB 1 cover	IRSL (FS) OSL (Q)	5.57 ± 0.48 4.88 ± 0.41	17 13	18 20	26.4 ± 1.4 13.5 ± 0.8	**4.74 ± 0.48** 2.76 ± 0.29
HL-11B[d]	1.85	CB 1 backfill	OSL (Q)	3.30 ± 0.18	11	6	111 ± 2	**33.8 ± 2.0**
HL-11C[d]	2.5	CB 1 cover	OSL (Q)	4.26 ± 0,21	13	4	14.58 ± 0.17	**3.42 ± 0.17**
HL-11D[d]	4.5	CB 1	OSL (Q)	2.82 ± 0.16	19	24	15.56 ± 0.71	**5.53 ± 0,41**
HLR 1/2	1	colluvium	IRSL (FS) post-IR IR (FS) OSL (Q)	4.34 ± 0.39 4.34 ± 0.39 3.60 ± 0.30	7 6 10	6 5 18	101.3 ± 4 128.1 ± 4.5 106.8 ± 6.9	23.33 ± 2.29 **29.5 ± 2.8** 29.7 ± 3.2
KR 1	1.5	colluvium	IRSL (FS)	5.41± 0.4	5	16	399 ± 30	**73.7 ± 7.8**
KR 2	1	colluvium	IRSL (FS)	4.17 ± 0.3	11	4	50.8 ± 1.6	**12.2 ± 0.96**
J 1/1[d]	1.2	CB 1 cover	OSL (Q)	5.79 ± 0.27	22	27	7.43 ± 0.33	**1.28 ± 0.08**
J 1/4[d]	2.5	CB 1 cover	OSL (Q)	3.22 ± 0.17	21	8	106.28 ± 2.33	**33.0 ± 1.9**
J 1/12[d]	7.2	CB 1	OSL (Q)	2.50 ± 0.13	16	12	502.1 ± 18.4	**201 ± 13**
J 3/5[d]	3.7	CB 2	OSL (Q)	2.73 ± 0.13	22	20	36.98 ± 1.36	**13.55 ± 0.83**
J 3/7[d]	5.8	CB 2	OSL (Q)	2.29 ± 0.12	20	6	83.91 ± 1.21	**36.7 ± 2.0**
J 5/2[d]	3.5	CB 1	OSL (Q)	1.85 ± 0.10	20	14	54.86 ± 1.98	**29.7 ± 1.9**
J 7/3[d]	3.2	CB 1	OSL (Q)	5.05 ± 0.28	18	5	299.5 ± 3.0	**59.4 ± 3.3**

Table 12 Luminescence dating - data sheet
[a]n - number of accepted aliquots.
[b]RSD – relative standard deviation.
[c]De - Palaeodose.
[d] Sample dated by SCIDR (quartz fraction 90-250 µm, 9.6 mm Ø aliquots SAR protocol (Murray and Wintle, 2000), preheat temperature 240°C for 10 s, detection with Hoya U340 filter).
[e] Sample dated by BOKU (quartz or K-rich feldspar fraction 100-200 µm, 1 and 2 mm Ø aliquots. Quartz: SAR protocol (Murray and Wintle, 2000), preheat temperature 260°C for 10 s, detection with Hoya U340 filter. Feldspar: SAR protocol (Wallinga et al., 2000; Blair et al., 2005), preheat 270°C for 10 s. Post-IR IR protocol (Buylaert et al., 2009), preheat temperature 250°C for 60 s, second IR stimulation at 225°C, detection with LOT-Oriel interference filter (~ 410 nm).
[f]M/C - Miocene/Cretaceous.
Errors on paleodoses are a combination of the standard error from the Central Age Model (Galbraith et al. 1999) and a 3.5% error accounting for uncertainties in calibrating the beta source. Errors on individual De-estimates of measured subsamples are based on counting statistics and an instrumental error of 1.5% (Galbraith et al. 2005).

All but two samples dated by SCIDR appear to be reproducible, being resent prior to burial. For samples J 1/1 and J 3/5, which show appreciable De scatter, this has been assumed due to post-depositional disturbance (J 1/1) and imcomplete bleaching prior to burial (J1/12). Numerical ages of these samples should be taken with caution. It must be noted that sample J 1/4 has a significant non-fast OSL component, sample J 7/3 was at or near saturation and that the De values for sample J 1/12 are high for quartz.

Some results from luminescence dating by BOKU must be also taken with caution. The age of sample DH 005/1 is possibly slightly underestimated due to fading, having potentially the same age as sample HLR 1/2. This sample shows a very low scatter in feldspar analysis, hence completely bleached. A slight age underestimation (by 20 %) of the (low temperature) IRSL age can be assumed. Quartz and IR ages appear more reliable. In case of sample HL 11/1, both, feldspar and quartz fraction show a relatively high scatter of De-values. Thus, some incomplete bleaching may be expected, which possibly affects the feldspar fraction more than the quartz fraction. Both ages may be slightly overestimated. In any case, the Late Holocene age of the deposit is certain. The age of the sample KR 1 is not totally reliable, because of high De approaching saturation and low amount of measured aliquots. However, its early Weichselian age is more or less certain. The sample KR 2 shows a very low scatter, being completely bleached, but the age is possibly underestimated. Other samples in the study area showed, that fading is of minor importance in the study area (Homolová et al., 2012).

4.5. Terrace staircase in the vicinity of Hluboká nad Vltavou-Zámostí

In the vicinity of Hluboká nad Vltavou-Zámostí, 5 terrace levels were recognized, named CB 1 to CB 5 (Table 4). The results from field mapping, drillings and luminescence dating are visualised in form of lithological profiles (Fig. 9) and cross sections through the area (Fig. 10).

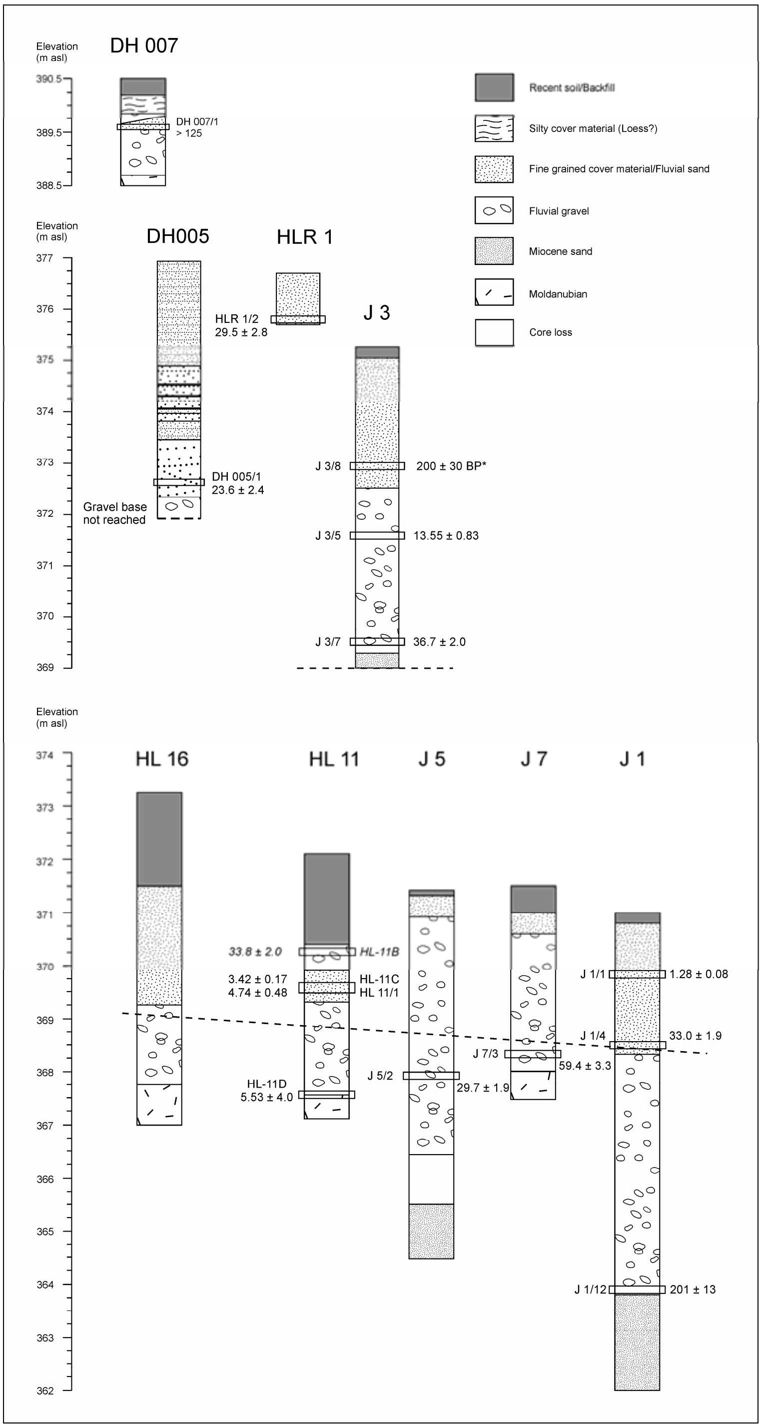

Fig. 29 Lithological profiles of drillings and outcrops in and above the Vltava River floodplain showing the luminescence ages of analysed samples. The dashed line represents the mean Vltava water level.

4.5.1. Terrace level CB 1

The extent and the top of the lowermost terrace level CB 1 almost entirely correspond to the recent floodplain (Fig. 11). Only along the floodplain margins close to the steep slopes of the crystalline massif, terrace sediments are partly covered by sandy colluvia. The base of the fluvial gravel ranges between ca. 5 m and 0.5 m under the recent Vltava water level. The terrace material consists of an up to 5 m thick layer of polymict sub- to well rounded sandy coarse gravel and an up to 3 m thick layer of fine-grained flood sediments on top.

Sediments of this terrace level sampled from drillings HL 11, J 1, J 5 and J 7 show ages ranging from approx. 60 ka to ~ 1 ka (Figs. 11-12). The sample J 1/12 is showing a luminescence age of ca. 200 ka, but this must be taken with caution (see section 4.4.). In outcrop DH 005, coarse sand overlying the fluvial gravel was sampled and dated to ca. 23 ka (sample DH 005/1), which means, that the fluvial gravel underneath must have been deposited before.

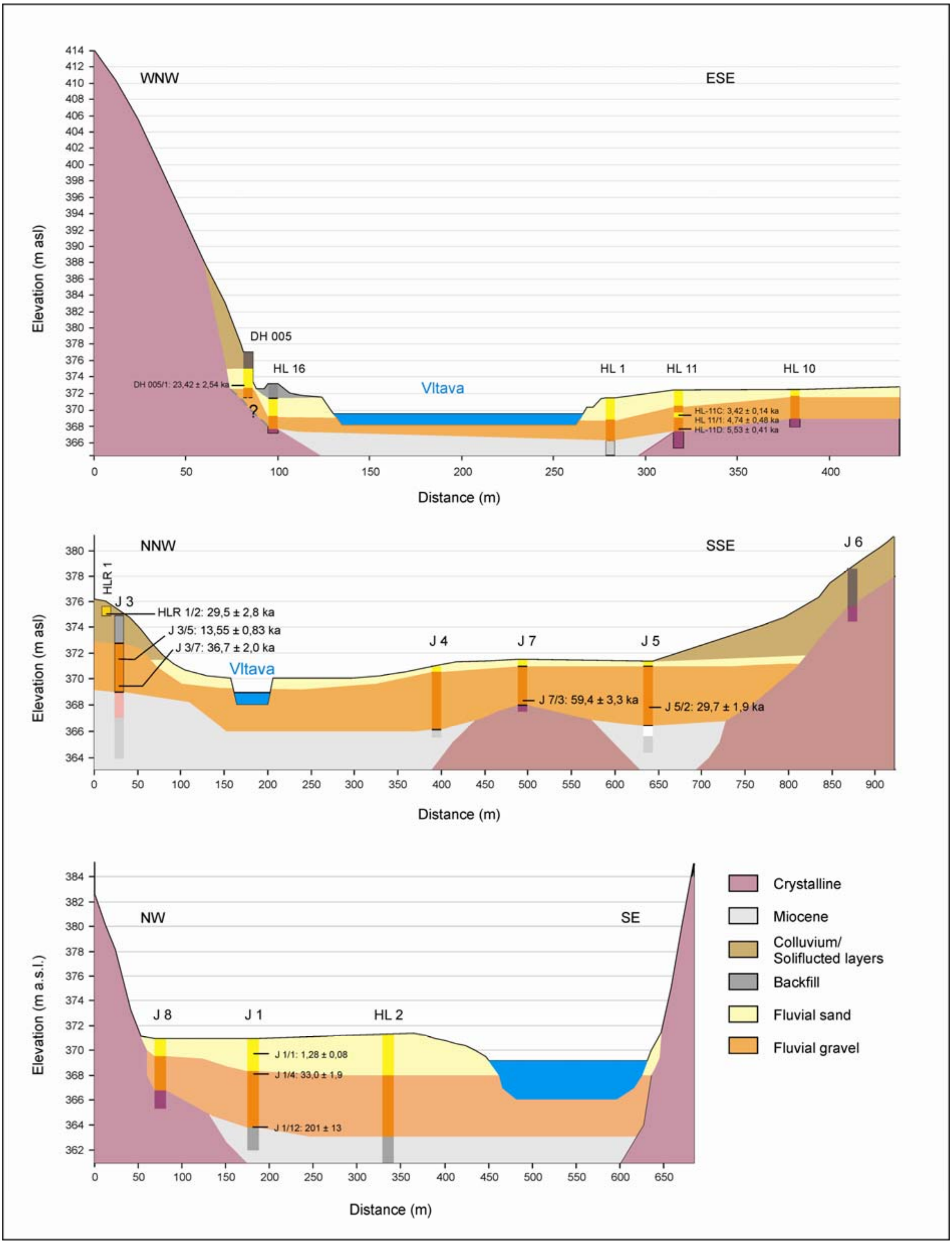

Fig. 30 Cross-sections 1-3 through the Vltava River floodplain in the vicinity of Hluboká nad Vltavou with drillings conducted in this study and luminescence ages of dated sediments. For location of the profile lines see Fig 2.

4.5.2. Terrace level CB 2

The terrace level CB 2 with the gravel base between 0.2 and 0.8 m above the water level occurs in form of small relicts on both sides of the river. Fluvial gravel of this terrace level was reached by the drilling J 3. The terrace material comprising of an up to 2 m thick layer of coarse subrounded fluvial gravel is covered by sandy and loamy material from the surrounding slopes. Two samples from the gravel layer were dated with the luminescence method, showing ages of ~ 14 ka and 37 ka (Fig. 11).

Near the drilling J 3, a sample of fine sand covering the slope from the hand drilling HLR 1 was dated to ca. 30 ka. It probably represents a soliflucted silty sediment deposited on top of the former terrace but this must be verified, because the material under this silty layer was not reached.

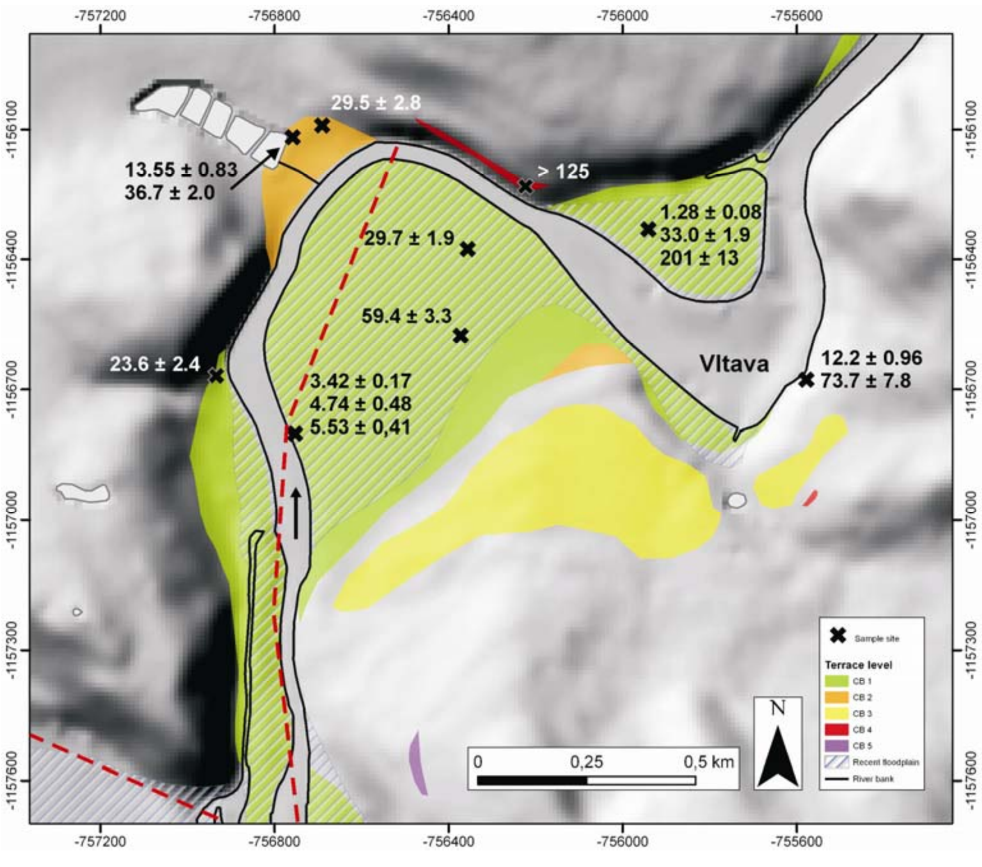

Fig. 31. Terrace levels in the footwall of the Hluboká Fault in the vicinity of Hluboká nad Vltavou with location of samples for luminescence dating and their ages. Red dashed line shows the assumed trace of both branches of the Hluboká fault.

4.5.3. Terrace level CB 3

The second most widespread terrace level in the crystalline basement CB 3 is located on the right bank of the river and does not appear as a morphological terrace. The original flat morphology of the terrace was probably disturbed by gelifluction, which has lead to relocation of the terrace material downslope. The relative elevation of the gravel base ranges from 7 m to 15.5 m above recent Vltava water level following the topography of the area. The terrace material is composed sub- to well-rounded pebbles (predominantly Quartz) of up to 20 cm diameter covered by loamy and sandy colluvial material.

Remnants of this terrace in form of an approx. 0.5 m thick layer of fluvial coarse gravel were observed in the outcrops KR and DH 037. In this case, the coarse gravel was probably redeposited by slope movement/gelifluction and does not represent the terrace in its original position. Luminescence dating of sand layers beneath and above fluvial coarse gravels show ages of 73.7 ± 7.8 ka and 12.2 ± 0.96 ka, respectively (Fig. 12). These ages most likely provide only time brackets for the redeposition event.

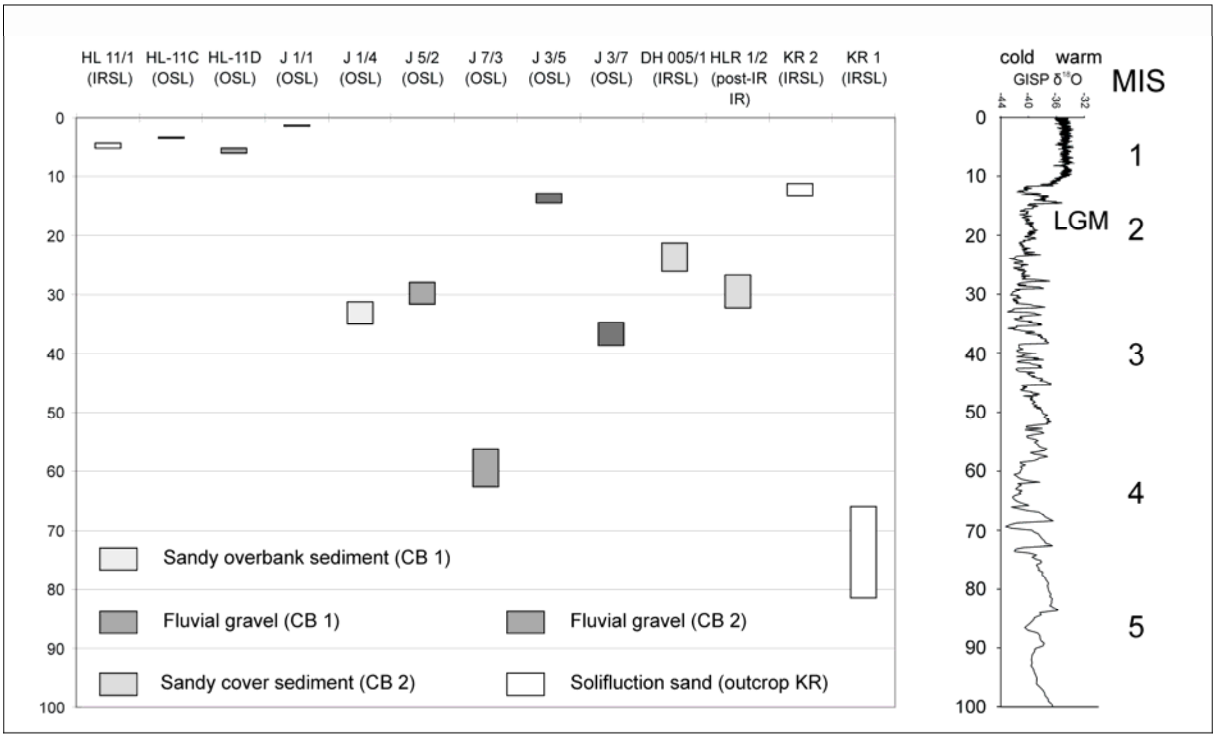

Fig. 32 Luminescence data plot of samples from this study except of HL-11B (backfill), DH 007 (out of range) and J 1/12 (not visualised, because older than 100 ka). Note the overlapping of ages in case of samples from above the floodplain (J 3/5 and J 3/7) and in the floodplain (J 1/4, J 5/2).

4.5.4. Terrace level CB 4

One remnant of the terrace level CB 4 on the left bank of the river appears as a 1.2 m thick sequence of coarse gravel and sand covered by a 0.6 m thick layer of silty material (outcrop DH 007). The profile does not show any disturbances resulting from cryoturbations or gelifluction as this is the case on the other side of the river in the outcrop KR. The gravel base is situated 18.1 m, the gravel top at 19.25 m above recent Vwl. There is also one possible remnant of this terrace level on the right river bank with the gravel base at approx. 20 m above Vwl (Fig. 11).

4.5.5. Terrace level CB 5

The base of terrace level CB 5 on the right river bank, represented by the material in the outcrop DH 008, is situated at an elevation of 415.4 m a.s.l. (45.4 m above Vltava water level). It is questionable, whether this is the original base of the terrace or only the base of fluvial sediments redeposited from higher positions and occurring as a colluvium on crystalline.

Terrace level	Elevation (m asl)	Lumin. age	Relative altitude (m above Vltava water level)
CB 1	Top: 371 - 374 Base: 363 - 369	~ 60 ka to Holocene	Top: 2 - 3 Base: -5 to -0.5
CB 2	Top: 372,5 - 376 Base: 369 - 370	Gravel (J3): 40 - 13 ka Cover sand: ~ 30 ka	Top: 3 - 6,5 Base: 0.2 - 0.8
CB 3	Top: 379 - 388 Base: 376 - 384	no data	Top: 10 - 19 Base: 7 - 15.5
CB 4	Top: 390 - 394 Base: ~ 389	> 125 ka	Top: 21.5. - 25 Base: 20
CB 5	Base: 414	no data	Base: 44.5

Table 13. Summary of mapped terrace levels in the vicinity of Hluboká nad Vltavou.

4.6. Correlation of terrace levels in the footwall and hangingwall of the Hluboká Fault

Following the course of the Vltava River by crossing the Hluboká Fault, no significant change in the thickness of the lowermost terrace level (BB 1 and CB 1) can be observed. The relative elevation of the gravel base under the Vltava water level is also more or less the same on both sides of the fault (Fig. 13).

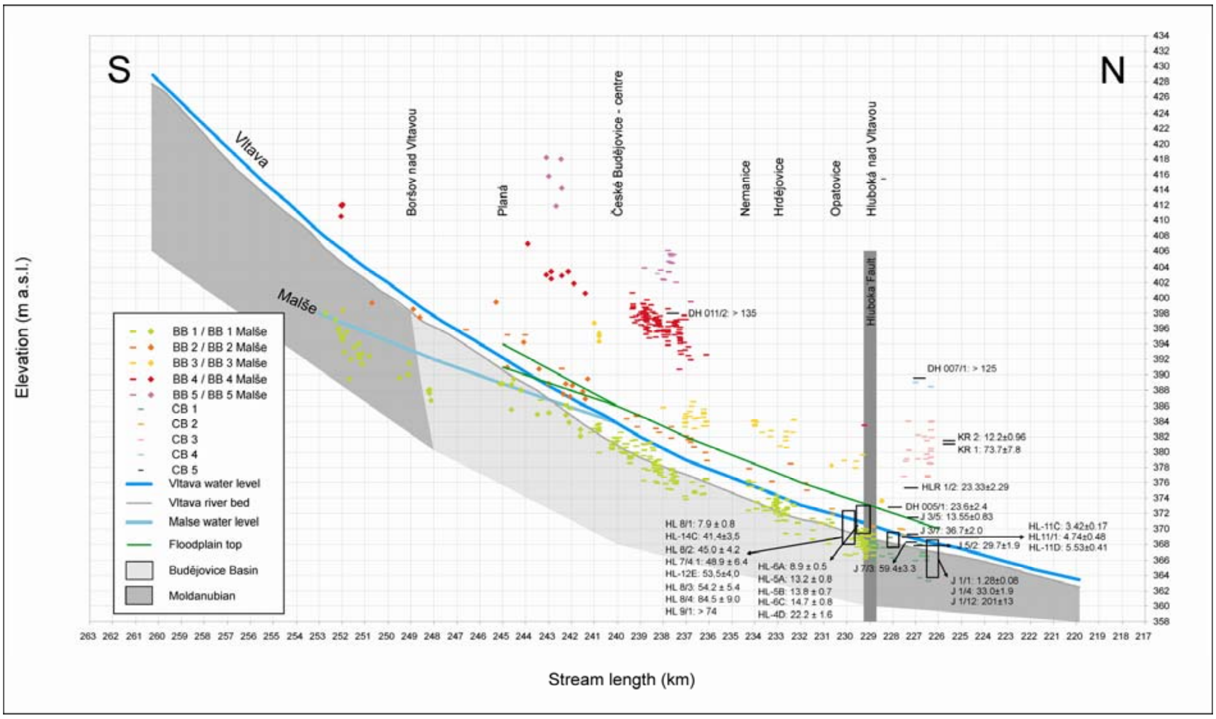

Fig. 33 Longitudinal profile of the river Vltava in the Budějovice basin and the area north of the Hluboká fault (indicated by the grey bar) near stream-km 229. Note the mismatch of relative elevations of terraces above the recent floodplain (BB 2/CB 2 and higher) on both sides of the fault. Visualised are also luminescence ages of samples at their position along the stream profile.

Terrace level	Lumin. age	Relative altitude (m above Vltava water level)	Terrace level	Lumin. age	Relative altitude (m above Vltava water level)
CB 1	~ 60 ka to Holocene	Top: 2 - 3 Base: -5 to -0.5	**BB 1**	~ 90 ka to Holocene	Base: -0.5 to -4 (-7)
CB 2	Gravel: 40 - 13 ka Cover sand: ~ 30 ka	Top: 3 - 6.5 Base: 0.2 - 0.8	**BB 2**	no data	Base: 0-4
CB 3	no data	Top: 10 - 19 Base: 7 - 15.5	**BB 3** **BB 4**	> ~ 50 ka > 135 ka	Base: 4-10 Base: 12-18
CB 4	> 125 ka	Top: 21.5. - 25 Base: 20	**BB 5**	no data	Base: 20-26
CB 5	no data	Base: 44.5			

Table 14. Comparison of terrace levels in the crystalline basement N of the Hluboká Fault and in the Budějovice basin (from Homolová et al., 2012). Definition of the terrace top in the Budějovice basin is problematic due to the tilting of the surface towards the river and is therefore omitted.

Terraces situated above the water level show some mismatch in their relative elevations above the water level (Fig. 13, Table 5) but a correlation based on absolute ages is not possible because the ages of these sediments are beyond the dating range of the luminescence method. Correlations based on absolute ages can only be done with sediments younger than ca. 90 ka, found at elevations close to the recent Vltava water level. In the Budějovice basin (hanging wall of the fault), fluvial sediments from the lowermost terrace level located several meters under the water level show ages ranging between ca. 90 ka and the Holocene. Fluvial sediments of the same terrace level in the foot wall show ages ranging from ca. 60 ka to the Holocene.

Tricky is the occurrence of fluvial coarse gravel above the Vltava River floodplain (terrace level CB 2) in drilling J 3 dated to ~ 37 ka and 14 ka. These ages are typical for fluvial deposits of the lowermost terrace level CB 1 at the elevation of the recent floodplain. Questionable is also the occurence of coarse sand of fluvial origin in the outcrop DH 005, also situated above the recent floodplain and dated to ~ 24 ka. Based on the mineralogical composition, this sediment was transported by the Vltava River (Homolová and Decker, submitted).

The question which arises is why sediments with similar ages transported by the Vltava River (DH 005/1 and J 5/3) occur at in as well as above the present-day water level. In case of a relative uplift of the whole crystalline block north Budějovice basin, sediments of late Plistocene age would appear only above the recent floodplain. We therefore assume a vertical displacement of different blocks of the crystalline basement north of the Budějovice basin along a NNE-SSW-striking branch of the Hluboká fault (Fig. 11). Since this is a strike-slip-fault, showing several parallel branches and horse-tail-splay structures, such an explanation appears to be possible. Further investigations must be carried out to prove this assumption.

5. Conclusions

Based on morphological data in combination with interpretation of drilling cores and luminescence dating, five terrace levels CB 1 to CB 5 with bases ranging from 5 meters below to approx. 45 meters above the recent Vltava water level were mapped. The luminescence ages of sediments from the lowermost terrace level CB 1 range from approx. 60 ka to the Holocene. This sediment body probably represents a stacked fluvial sequence with several distinct packages of river aggradation. Terraces situated above the recent floodplain do not appear as morphological terraces because the original topography was smoothed by periglacial cryoturbation and geli-/solifluction. The identification of these terrace levels was possible only by analyzing drilling profiles and some outcrops. Dating of sediments from the higher terraces was not possible, because their ages are beyond the range of the luminescence method. By following the lowermost terrace levels BB 1 and CB 1 along the Vltava River on both sides of the Hluboká fault, no change in the thickness and relative elevation of the terrace base below the recent water level can be observed. There is a mismatch of relative elevations of terraces situated above the recent floodplain in the Budějovice basin and the area north of the Hluboká fault. The occurrence of ~ 37 ka and ~ 14 ka old fluvial gravel and sand several meters above the recent floodplain north of the Hluboká fault causes some problems by reconstructing the late Pleistocene valley development in this area. These phenomena may be explained by Quaternary active tectonics which may have lead to the vertical deisplacement of the fluvial sediments.

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Curriculum vitae

Name: **Dana Tschegg (born Homolová)**

Date and place of birth: 27.10.1984; Bratislava/Slovakia

Contact: Senická 7, 81104 Bratislava, Slovakia
dana.homolova@univie.ac.at
+421 - 905 - 339917
+43 - 681 - 20303519

Education

2003 Final exam at Gymnasium Bilíkova 24, Bratislava, Slovakia

2003 - 2009 Diploma in Geography, University of Vienna, Austria

2006 - 2007 Georg-August-University Göttingen, Germany; Erasmus exchange programme

2010 - PhD in Geology at the Department of geodynamics and sedimentology, University of Vienna, Austria

Additional education

2004 - 2008 Conservatory in Topoľčany, Slovakia; Flute

09/2009 1st INQUA IGCP 567 International Workshop on Earthquake Archeology and Paleoseismology, Baelo Claudia, Spain.

Working experience

2009 - 2012 AIP - Paleoseismology of Temelin´s Near-Regional Faults; Department of geodynamics and sedimentology, University of Vienna, Austria. Project staff.

Teaching experience

Summer terms 2010, 2011 and 2012

Exercise course in soil gegraphy (Übungen zur Bodengeographie), Department of Geography and Regional Research, University of Vienna, Austria

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