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Distinguishing Quaternary and pre-Quaternary clastic sediments in the vicinity of České Budějovice (Southern Bohemian Massif, Czech Republic)

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KEYWORDS

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Bulk mineralogy
Heavy minerals
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Abstract

This study outlines sediment-petrology methods for easily distinguishing between fine-grained Quaternary and pre-Quaternary clastic sediments from the north-eastern part of the Budějovice Basin (Czech Republic), using standard sedimentological techniques such as X-ray powder diffraction on bulk samples as well as heavy mineral analysis. There are significant differences in both the mineralogical composition and the heavy mineral content of the two sedimentary units. The main components of pre-Quaternary sediments are quartz, alkali-feldspar, muscovite, and kaolinite, reflecting longer periods of chemical weathering. Quaternary deposits additionally contain the less weathering-resistant phases plagioclase and chlorite and have only minor amounts of kaolinite. Quaternary sediments transported by the Vltava River generally contain significant amounts of amphiboles; these are missing in the recent alluvia from 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 allow Quaternary sediments to be distinguished from pre-Quaternary deposits of the Budějovice Basin in places where optical characteristics do not allow this. Further, different types of Quaternary sediments can be distinguished, mainly those transported by the Vltava or its small local tributaries.

Die Studie folgt einer zweckmäßigen Methode zur einfachen Unterscheidung von feinkörnigen Quartären und pre-Quartären Sedimenten vom nordöstlichen Teil des Budweiser Beckens (Tschechische Republik) durch eine Kombination von sedimentpetrographischen Standardanalysen, wie der Bestimmung der Gesamtmineralogie mit Hilfe von Röntgendiffraktometrie in Verbindung mit Schwermineralanalyse. Die Sedimentgruppen zeigen signifikante Unterschiede in ihrer mineralogischen Zusammensetzung sowie im Schwermineralgehalt. Die wichtigsten Bestandteile des Gesamtmineralspektrums von prä-Quartären Sedimenten sind Quarz, Alkalifeldspat, 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 Alluvionen 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 Ergebnisse dieser Studie zeigen, dass sedimentpetrographische Methoden eine sichere Unterscheidung quartärer von pre-quartären Ablagerungen im Budweiser Becken ermöglichen. Petrographische Charakteristika erlauben ausserdem, zwischen fluviatilen Sedimenten der Moldau und Ablagerungen kleiner, lokaler Zuflüsse zu unterscheiden.

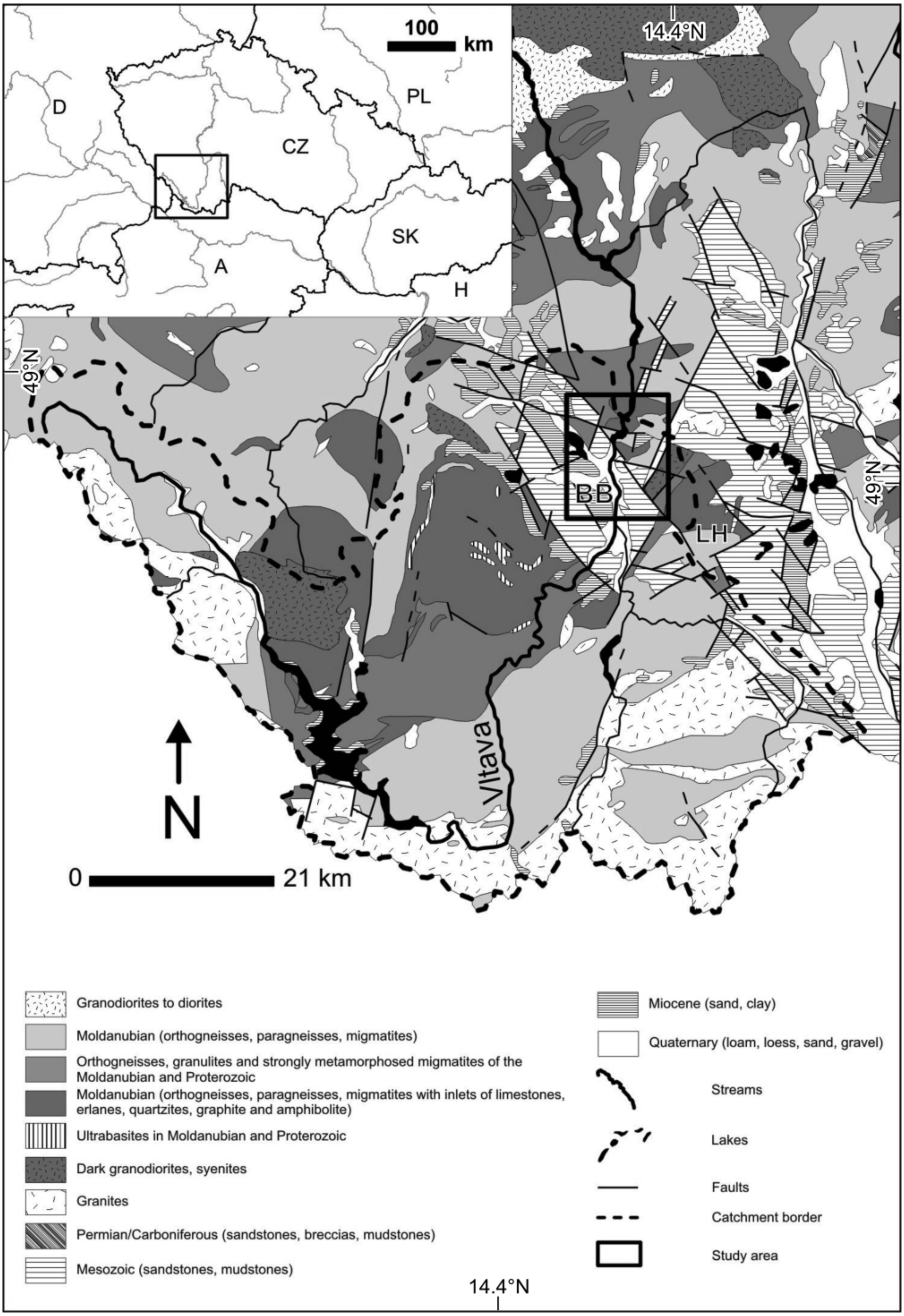
1. Introduction

The sedimentary fills of the two southern Bohemian sedimentary basins - the Budějovice and Třeboň basins - are dominated by Cretaceous and Miocene deposits, on top of which Quaternary sediments form only a relatively thin layer of up to several meters thickness (Homolová et al., 2012). These Cretaceous and Miocene sediments have been extensively described, with several studies documenting their petrography (Slánská, 1963 and 1976) and paleontological content (Pacltová, 1961; Malecha and Pícha, 1963; Řeháková, 1963; Gabrielová et al.1964). In contrast, much less attention has been paid to the Quaternary sediments.

In most studies of the Quaternary sediments deposited in the southern Bohemian basins, the morphology of terrace staircases formed by rivers crossing the basins was described in detail (Chábera, 1965; Chábera and Vojtěch, 1972; Novák, 1990; Homolová et al., 2012) whereas the sedimentary petrography was mentioned only marginally and was generally reduced to pebble analyses of the fluvial gravels.

Extensive petrographic investigations on fluvial sediments of Bohemian rivers, including grain-size and pebble analyses as well as heavy mineral analyses, were done by Kodymová (1960, 1962, 1963 and 1966). These studies, however, focussed solely on sediments from recent river alluvia. Sediments

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.


14.4°N
100
km
D
PL
CZ
SK
A
H
49°N
49°N
BB
LH
Vltava
N
0
21 km
Granodiorites to diorites
Moldanubian (orthogneisses, paragneisses, migmatites)
Orthogneisses, granulites and strongly metamorphosed migmatites of the Moldanubian and Proterozoic
Moldanubian (orthogneisses, paragneisses, migmatites with inlets of limestones, erlanes, quartzites, graphite and amphibolite)
Ultrabasites in Moldanubian and Proterozoic
Dark granodiorites, syenites
Granites
Permian/Carboniferous (sandstones, breccias, mudstones)
Mesozoic (sandstones, mudstones)
Miocene (sand, clay)
Quaternary (loam, loess, sand, gravel)
Streams
Lakes
Faults
Catchment border
Study area
14.4°N

from Pleistocene terraces of rivers were analysed at a very few locations along the middle and lower course of the Vltava and currently there are no data for other types of Quaternary sediments in the study area at all.

In both the Budějovice and the adjacent Třeboň Basin, fine-grained sediments from Quaternary and pre-Quaternary units look very similar, making their stratigraphic assignment difficult. This causes problems when analysing drilling-cores in places where Quaternary sands or gravels lie directly on Miocene or Cretaceous deposits.

In studies dealing with fluvial terraces of the Vltava and Malše Rivers in the Budějovice Basin (Chábera, 1965; Homolová et al., 2012) and Lužnice River in the Třeboň Basin (Chábera and Vojtěch, 1972), only fluvial sandy gravels of the main rivers were identified as the marker lithology of undoubtedly 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 the 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. Furthermore, terrace correlations are also important for identifying displacements at active normal faults in South Bohemia. Such analyses can also 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 the Quaternary as well as in the Miocene and Cretaceous successions and the facies are generally not distinctive (Nehyba and Roetzel, 2010). A crucial part of this study, therefore, was to find reliable parameters to distinguish fine-grained sediments of Quaternary age from those of older stratigraphic units using sediment-petrologic analyses such as X-ray powder diffraction and/or heavy mineral analysis.

Another important issue was characterising the different Quaternary sediments originating from the Vltava and ist tributaries. Distinguishing fluvial sands and gravels from the lowermost terrace level, forming the present-day Vltava floodplain from alluvia deposited by small tributaries near their confluence with the Vltava is very difficult. Only if clear differences between the sediments from these two depositional sources have been defined, can sediments of ambiguous morphological position be correctly assigned.

2. Regional and geological setting

Both the Budějovice Basin and the Třeboň Basin to the east are here referred to as the South Bohemian Basin System; this lies within the Bohemian Massif. The characteristic elongate shape of both basins is controlled 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).

The study area comprises the Budějovice Basin as well as areas northeast of the Hluboká Fault, which delimits the sedimentary fill of the Budějovice Basin from its Moldanubian crystalline basement to the northeast (Fig. 2).

The depocenter of the Budějovice Basin lies in the eastern part of the basin, where the sediment thickness reaches c. 340 m (Homolová et al., 2012). The distribution and offset of Permian, Cretaceous and Miocene sediments allows the repeated reactivation of faults at or close to the basin margin to be reconstructed; movement on some of the faults may have continued into the Quaternary. Strong evidence for recent vertical displacements is indicated by geomorphological data from the Hluboká (Jáchymov) Fault and the Rudolfov Fault (Vyskočil, 1973 and 1979) that form the NE and E margins of the Budějovice Basin, respectively.

The Moldanubian crystalline complex forming the basement to the Budějovice Basin consists of Precambrian to Paleozoic high-metamorphic grade mica-schists, gneisses and migmatites as well as of igneous rocks forming the Central Bohemian and Moldanubian Plutons (Slánská, 1976). Upper Carboniferous to 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 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). This is the most widespread stratigraphic unit in the southern Bohemian basins, covering large areas of the Budějovice Basin (Fig. 1). Palynology, carpology and the macroflora all indicate that these fresh-water, fluvio-lacustrine sediments are of Late Turonian to Santonian age (Knobloch, 1985). The main sediment sources during the Cretaceous were the kaolinite-rich eluvia of granitoid rocks and sillimanite-biotite gneisses; these were strongly weathered as a result of 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 assemblages throughout the Klikov Formation. Less weathering-resistant minerals such as apatite, andalusite, garnet, amphiboles and epidote group phases 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). These formations either directly overlie the crystalline basement or Cretaceous sediments.

The Zliv Formation, which reaches a maximum thickness of

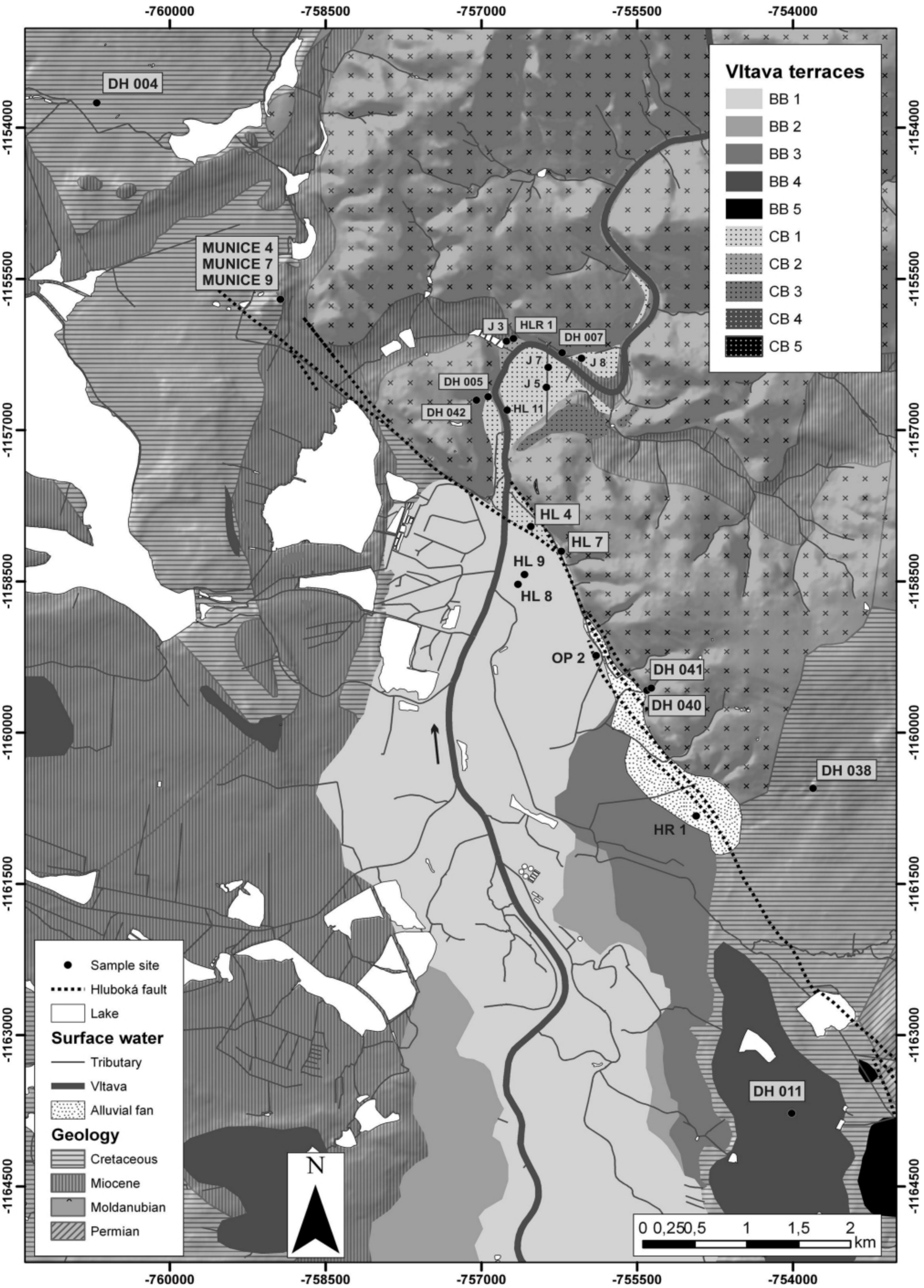


FIGURE 2: Location of sample sites underlain by a hillshade view of a digital elevation model (DEM) and a simplified geological map showing the main stratigraphic units of the study area. The extent of Vltava river-terraces in the Budějovice Basin and north of the Hluboká fault is taken from Homolová et al. (2012).

15 m, comprises grayish-green sandy clays at the base, coarsening 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 early studies, the Zliv Formation was considered to be the uppermost part of the Cretaceous Klikov Formation but later it was assigned to the Miocene (Ottnangian), based on its diatomaceous flora, similar to that of the Mydlovary Formation. Fresh water, as well as brackish and marine diatoms are preserved (Svoboda 1966).

The Mydlovary Formation, which is up to 60 m thick and covers only small areas, mainly in the north-western part of the Budějovice Basin, consists of grayish-green clayey sands and sandstones to olive-green clays with layers of dark-grey coaly clays, xylites and greenish diatomaceous clays (Svoboda, 1966). These well-sorted sediments consist mainly of quartz, kaolinite, illite, montmorillonite, organic matter and, in places, calcite. Apart from stable heavy minerals, less stable phases such as amphiboles, andalusite, epidote and sillimanite occur (Slánská, 1963).

The Pliocene Ledenice Formation occurs in both the Budějovice and Třeboň basins 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). The age is constrained by palynological data (Pacltová, 1963) and diatoms (Řeháková, 1963).

Quaternary sediments consist of fluvial sandy gravels and pebbly sands deposited by the Vltava and Malše, alluvial fans of their tributaries, solifluction loams and loess loams deposited on slopes surrounding the basin. Sandy overbank deposits are found on 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).

During the Pleistocene and probably in even earlier times, the two main rivers, the Vltava and Malše, accumulated terrace bodies of different horizontal and vertical extents and 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 that occurred during the last glacial period and most probably also during all previous cold stages. The lowermost terrace level, corresponding morphologically with the present day floodplain, represents a complex sediment 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 Vltava and Malše (Fig. 2).

The lithological composition of the fluvial sediments deposited by the two main rivers reflects the bedrock properties of their total catchment areas. The sediments, therefore, consist mainly of subangular to well-rounded quartz pebbles and clasts of Moldanubian crystalline rocks such as 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 of quartz and only local lithologies such as sillimanite-biotite gneiss, leucocratic migmatite as well as clasts of Cretaceous and Permian sedimentary fragments, which survived the short transportation event. An example of such deposits is the sandy gravel of Kyselá voda in the vicinity of Úsilné; this consists of quartz pebbles, gneiss and mudstone clasts of Permian age (Špaček et al., 2011).

In recent alluvia of the 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 tributaries of the Vltava. Sampling locations and site types are shown in Fig. 2 and Table 1. The position of samples within drilling cores and outcrop profiles is summarized in Figs. 3 and 4. 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 from the nearby surface and therefore only the location is given.

Samples were collected from all sediment types of pre-Quaternary and Quaternary age, including Cretaceous and Miocene sandstones, claystones, clay, and sand and Quaternary fluvial gravel and sand of the 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 similar sediment types can be found in all different stratigraphic units occurring in the study area (Slánská, 1963; Huber, 2003). Thus this characteristic cannot be used to make a clear assignment of sediments to the different stratigraphic units; essentially, a detailed grain size analysis would not improve on 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

Thirty-two samples from various stratigraphic units were analyzed with X-ray powder diffraction (XRD) 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,

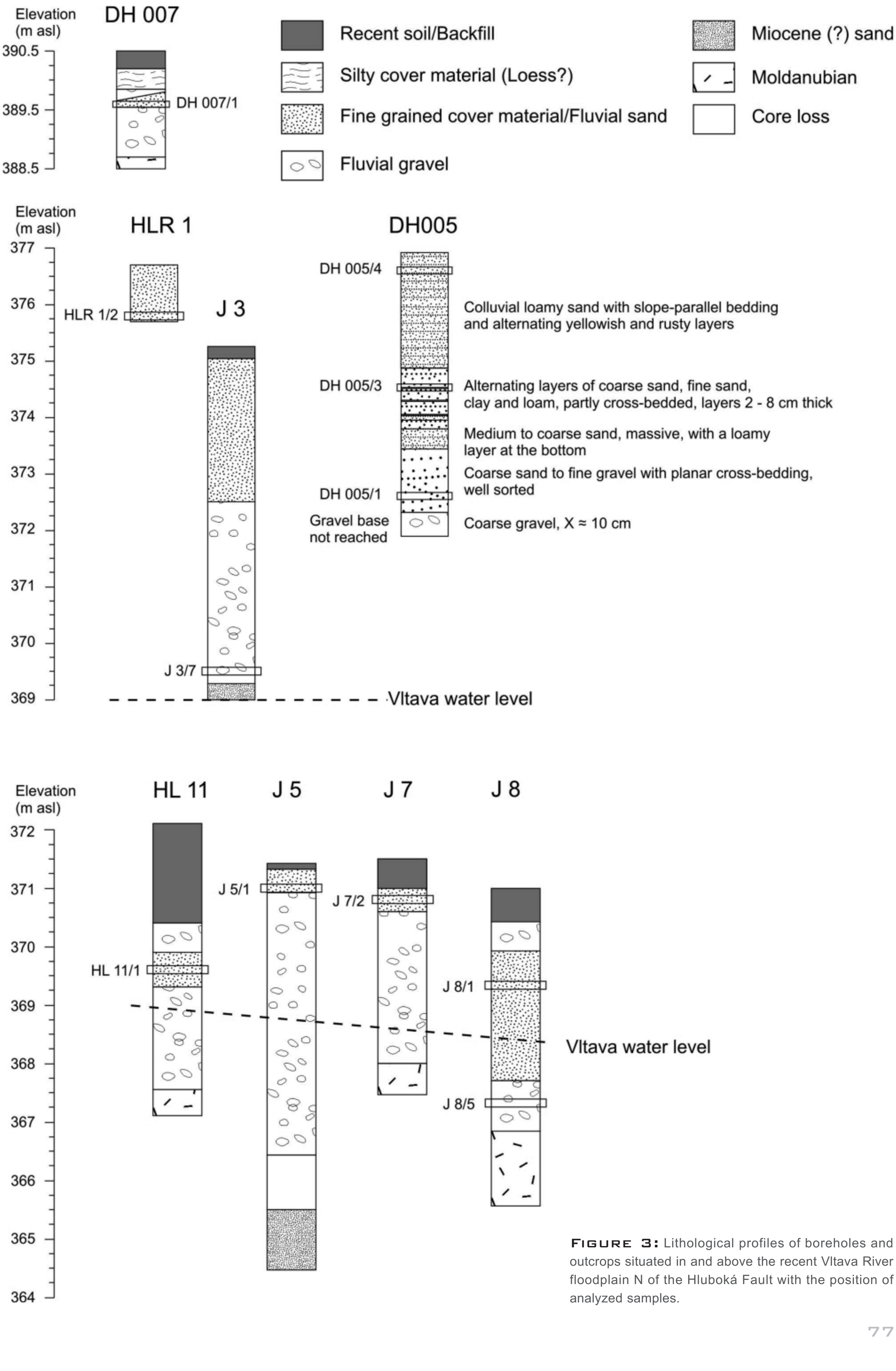


Figure 3: Lithological profiles of boreholes and outcrops situated in and above the recent Vltava River floodplain N of the Hluboká Fault with the position of analyzed samples.

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.

3.4 Heavy mineral analysis

For heavy mineral analysis, samples were first treated with dilute acetic acid for 7 days, wet sieved to separate the 0.063 - 0.4 mm fraction, 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/cm³. The separated minerals were subsequently washed with acetone and dried. A portion of the prepared material was then dispersed on a glass microscope slide, embedded with Canada Balsam (refractive index 1.54) and protected with a cover-glass.

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

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

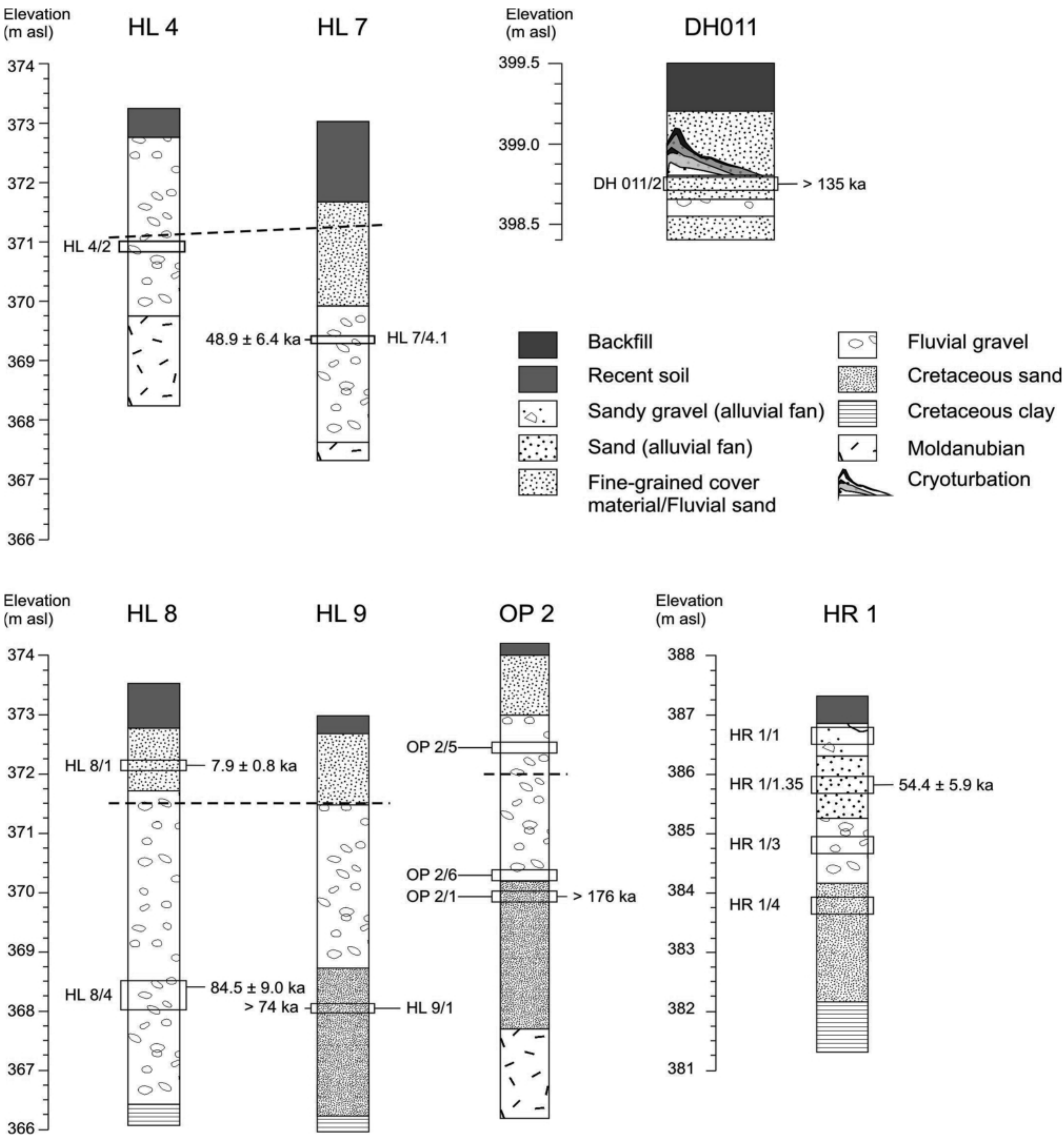


Figure 4: Lithological profiles of boreholes and the outcrop DH 011 situated in and above the recent Vltava River floodplain in the Budějovice Basin with the position and luminescence ages (from Homolová et al., 2012) of analyzed samples. Dashed line represents the mean Vltava water level.

Sample site	Site type	X[a]	Y[a]	Long (E)	Lat (N)	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.

microscope analyses.

4. Results

4.1 Cretaceous and Miocene sediments

4.1.1 Grain size and color

Samples collected from outcrops and drillings assigned to the Cretaceous and Miocene show a relatively large variability in sediment/rock type, grain size, and color. The sediment/rock types range 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.

4.1.2 Bulk mineralogy

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

4.1.3 Heavy minerals

The heavy mineral assemblages of pre-Quaternary sediments show a clear dominance of the stable minerals zircon and tourmaline (Table 3, 4 and Fig. 6). In sample DH 038/2, anatase was recognised by XRD (Fig. 5). Relatively unstable phases make up only a maximum of 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 assemblages of Cretaceous and Miocene sediments

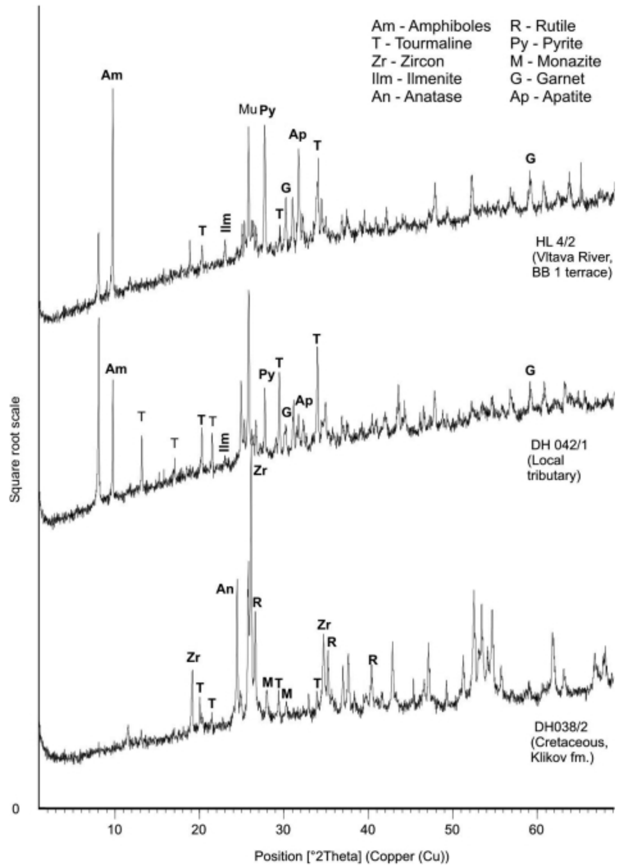


Figure 5: Diffractograms of heavy mineral separates. Note the dominance of stable minerals and the absence of amphiboles in the Cretaceous sample DH 038/2. See also the lower amount of amphiboles and higher amount of tourmaline in sample DH 042/1 (Vltava tributary) compared to sample HL 4/2 (Vltava River sediment). Bold printed minerals were detected in all diffractograms below.

	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[d], CB[e] 4	Sand	10 YR 5/4	Yellowish brown	Silty coarse sand with fine gravel
	DH 011/2	1.0	Q, BB[f] 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[g]	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[h]	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

[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] Q - Quaternary
[e] CB - Terrace level on crystalline
[f] BB - Terrace level in Budějovice Basin (from Homolová et al., 2012)
[g] AF - Alluvial fan
[h] TA - Tributary alluvium

Table 2: Sample data: Depth, stratigraphy, sediment type/grain size, color and lithofacies.

are significantly higher than in samples of Quaternary age, exceeding 50 %. There are no significant differences between the heavy mineral contents of the Cretaceous and Miocene samples.

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 contents of coarse grains. In general, Quaternary sediments are uncemented and much less consolidated than Miocene or Cretaceous sediments.

A large variety of yellow and brown colours characterises all the 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 both south and north of the Hluboká Fault also contain significant amounts of chlorite and amphiboles. The high amphibole content was seen in both the XRD patterns of the bulk samples and in the optical analysis of the heavy minerals (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) show no evidence for amphibole in the XRD analyses of bulk samples. Samples J 3/7 and HLR 1/2, from 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.

4.2.3 Heavy minerals

The heavy mineral content of the Quaternary sediments is much more variable than that of pre-Quaternary samples, showing a clear dominance of relatively unstable minerals. These are mainly amphiboles and garnets from the non-opaque mi-

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

[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

Table 3: Bulk mineralogy and heavy mineral content of analyzed samples.

Stratigraphy		Sample/Mineral	Opaque	Nonopaque	Tourmaline	Zircon	Rutile	Monazite	Staurolite	Garnet colourless	Garnet pink	Apatite	Titanite	Silimanite	Kyanite	Epidote group[a]	Andalusite	Pyroxene group[b]	Amph. misc[c]	Amph. green	Amph. green	Others	Weathered	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

[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 colourless grains
[d] Percent of all grains counted (opaques + non-opaques)
[e] Percent of 200 non-opaque grains counted

Table 4: Heavy mineral content of analyzed samples.

nerals and ilmenite from the opaques (identified using XRD; Table 4, Fig. 5). Other phases are pyroxenes (mainly enstatite and diopside), minerals of the epidote-group, sillimanite, andalusite and apatite. The relative amounts of heavy mineral components are variable, depending on factors such as the horizontal or vertical position of the sample within the former river bed. Together, zircon, rutile and tourmaline (the stable minerals) make up ≤ 15 % of all non-opaque grains.

The relative amounts of opaque grains in the heavy mineral content of Quaternary sediments is < 40%, significantly lo-

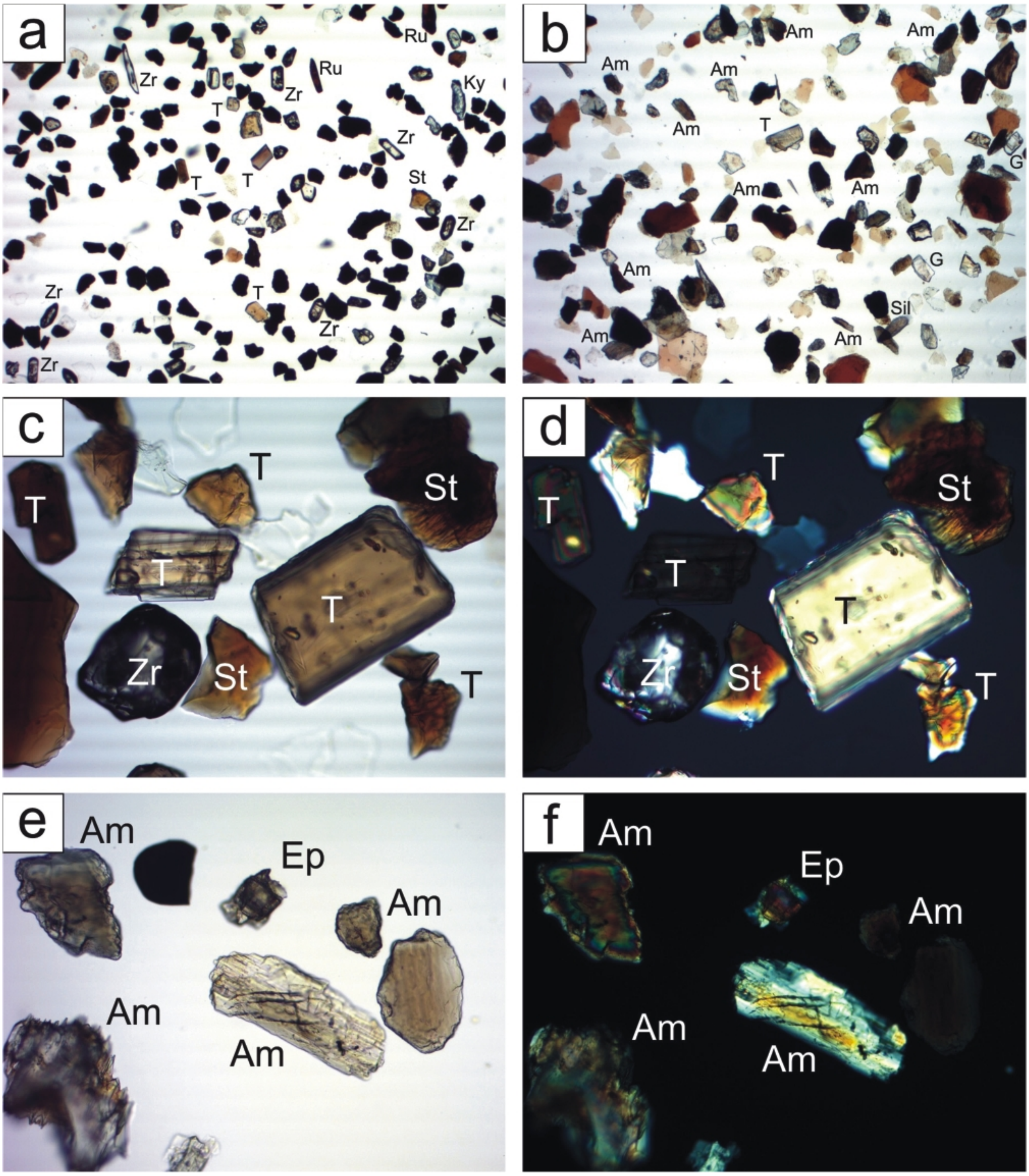


Figure 6: Photomicrographs of representative heavy mineral separates from different stratigraphic units found in the study area. a) HL 9/1, 2.5 times enlarged, b) HL 7/4.1, 2.5 times enlarged, c) OP 2/1, 10 times enlarged, d) OP 2/1, 10 times enlarged with crossed nicols, e) OP 2/5, 10 times enlarged, f) OP 2/5, 10 times enlarged with crossed nicols. Note the high relative amount of opaque grains and weathering-resistant minerals zircon (Zr), tourmaline (T) and rutile (Ru) in samples HL 9/1 and OP 2/1 assigned to the Cretaceous. Samples HL 7/4.1 and OP 2/5 from the Quaternary show lower amounts of opaque grains and higher amounts of less weathering-resistant minerals such as amphiboles (Am), garnets (G) and minerals of the epidote group (Ep). Cretaceous samples also show a better sorting compared to samples from the Quaternary. Ky - kyanite, St - staurolite, Sil - sillimanite.

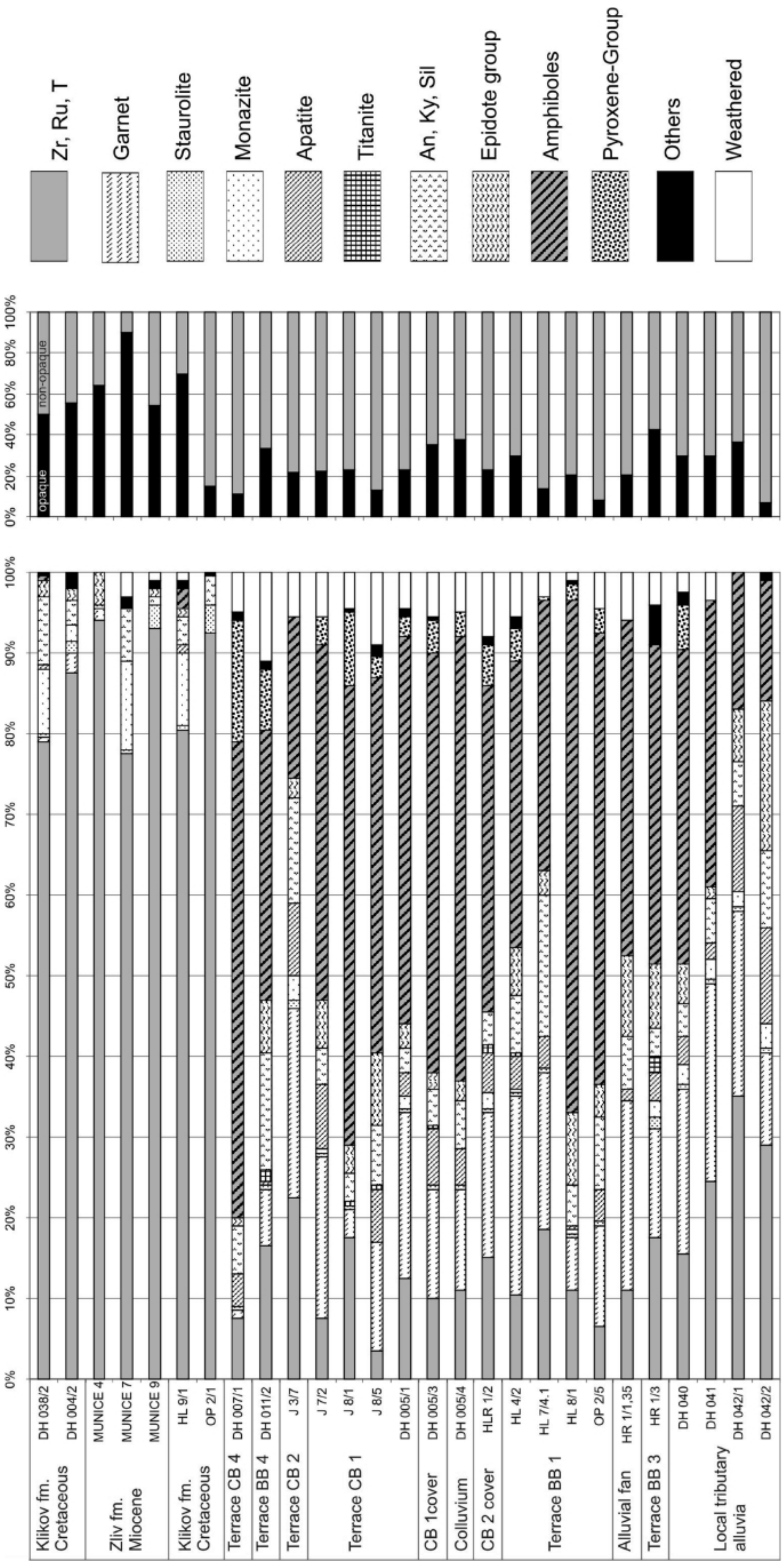


Figure 7: Distribution of non-opaque heavy minerals (simplified) and relative amounts of opaques and non-opaques in the heavy mineral suites of analyzed samples. Note the dominance of stable minerals zircon, rutile and tourmaline (Zr, Ru, T) in pre-Quaternary sediments as well as the dominance of amphiboles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

wer than in pre-Quaternary samples (Table 4). Older terrace deposits in the Budějovice Basin (DH 011/2 and HR 1/3) show slightly higher amounts of opaques 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.

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 compositions as well as in the heavy mineral contents of Quaternary and pre-Quaternary sediments. With the sediment-petrologic methods applied here, 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), consistent 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 indicates that tropical and subtropical kaolinitic weathering occurred during the Late Cretaceous and Miocene (Slánská, 1976; Nehyba and Roetzel, 2010). Samples MUNICE 4, MUNICE 7 and MUNICE 9, bearing significant amounts of smectites, most probably belong to the Miocene Zliv Formation. This also conforms to the geological map (Základní Geologická Mapa ČSSR 1:25.000, 1982). None of the samples analysed in this study can be assigned to the Miocene Myd-lovary Formation.

Compared to pre-Quaternary deposits, Quaternary sediments also contain plagioclase and have only low amounts of kaolinite (Table 3). Most of the Vltava 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 consistent with the young age and cold weathering conditions of these deposits.

A comparison of the heavy mineral content of pre-Quaternary and Quaternary deposits shows a clear dominance of ultra-stable minerals in the first group (Fig. 6 and 7). 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 range of heavy minerals is preserved.

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

The remarkable presence of amphiboles in the Vltava River sediments is due to the high abundance of amphibole-bearing lithologies (amphibolites, granulites, igneous plutons and orthogneisses; Slánská, 1963) found in the river catchment (see Fig. 1). The source areas of local tributaries are significantly smaller and geologically comprise 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. 6) underline the strong influence of local lithologies on the overall mineralogical composition as well as on the heavy mineral content of these sediments. The higher amount of tourmaline in recent creek alluvia compared to the Vltava River sediments was shown to be significant by the Students T-Test (T-Value: -3.358; Significance: 0.003). The absence of chlorite is also a characteristic of local creek alluvia and alluvial fan material.

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

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: Student T-Test for the groups „Quaternary“ and „Miocene/Cretaceous“.

5.2 Application of obtained data for stratigraphic assignment of sediments

The results of this study have been applied to samples of doubtful stratigraphic assignment, where field 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 the material (Fig. 10). Samples of pre-Quaternary age (OP 2/1 and HL 9/1) contain mainly quartz, kaolinite and muscovite with a minor amount of alkali-feldspars and smectites. Quaternary sediments additionally contain plagioclase, chlorite and amphiboles. In profile OP 2, a decrease in plagioclase, chlorite and amphiboles and an increase of kaolinite with depth are recorded. The heavy mineral spectra of those samples underline these results.

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 clearly assigned to the pre-Quaternary. They are probably part of the Cretaceous Klikov Formation underlying the Quaternary fluvial gravels in this area. The samples also contain small amounts of smectites, but this is probably because they are overlain by several meters of Quaternary deposits, from which smectite could have been washed down.

A more complicated situation is observed in the profile HR 1, exposing sediments of a large alluvial/colluvial fan that was deposited on top of an old Vltava river-terrace. In the uppermost two meters of the profile, unsorted sub-rounded coarse

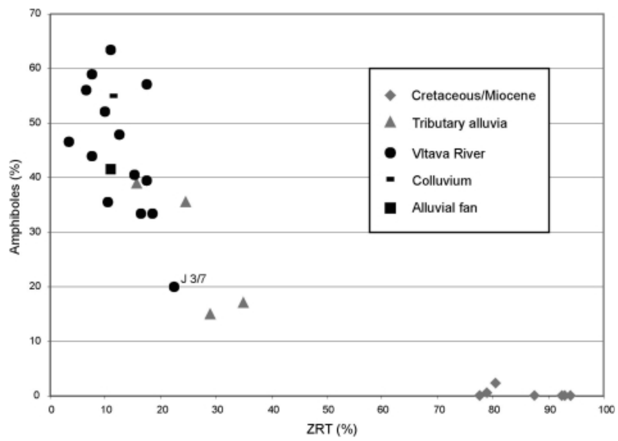


Figure 8: Discrimination diagram showing the relationship between the content of weathering-resistant heavy minerals zircone (Z), rutile (R) and tourmaline (T) and amphiboles in all analyzed samples of Quaternary and Cretaceous/Miocene age. Based on this relationship, a clear assignment of samples to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

Chrono-logic 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 local lithologies, mainly unstable minerals	Not dated
			Vltava overbank sediments	2	Clay to sand	Same as BB 1	Same as BB 1	OSL/IRSL (Homolová et al.,2012)
	Pleistocene	Late	Solifluction loams	3	Unsorted reworked material with variable grain	Quartz, Alkali-Feldspar, Plagioclase, Mica, Kaolinite	Amphiboles, Garnet, Apatite, Sillimanite, Kyanite, Epidote, Andalusite, Zircone,Tourmaline,	OSL/IRSL (Homolová et al., 2012)
			Alluvial fans	15				
			Vltava River terraces: BB 1	8	Fluvial sandy gravel and pebbly sand	Quartz, Alkali-Feldspar, Plagio-clase, Muscovite, Amphiboles, Chlorite	Amphiboles, Garnet, Apatite,Sillimanite, Kyanite, Epidote, Andalusite, Pyroxenes, Zircone, Tourmaline, Rutile	
		Early - Middle	BB 2	5		No data	No data	Not dated (approx. assignment based on relative elevation above recent Vltava floodplain)
			BB 3	3				
			BB 4	4		Quartz, Alkali-Feldspar, Plagioclase, Muscovite, Kaolinite	Amphiboles, Garnet, Sillimanite, Kyanite, Epidote, Andalusite, Pyroxenes, Zircone, Tourmaline	
			BB 5	3		No data	No data	
Neogene	Pliocene		Ledenice Fm.	10	Sandy clays	Quartz, Illite, Limonite (Huber, 2003)	No data	Palynomorphs (Pacltová, 1963), diatoms (Řeháková, 1963)
	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)	Diatoms (Řeháková, 1963)
			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.

gravel mixed with sand (HR 1/1) is underlain by silty sand; this sequence probably represents redeposited Vltava fluvial sediments. The presence of amphiboles in the bulk analysis of HR 1/1.35, dated by the luminescence method to 54.4 ± 5.9 ka (Homolová et al., 2012) supports this. 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 lies between these two samples.

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

In lowermost parts of profile DH 005, well sorted, cross-bedded fluvial coarse sand overlying sandy gravel occurs (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 a 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 (DH 005/4). This succession, which has a dip of 10° to 20°, parallel to the surface slope, is interpreted as colluvium.

Since the bulk sample of the coarse sand overlying the fluvial gravel (DH 005/1) contains amphiboles, it must have been transported/deposited by the Vltava River. 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 marks the major difference between sediments originating from the Vltava River and ist tributaries. The heavy mineral composition shows significantly higher contents of tourmaline compared to the Vltava River sediments, pointing to the strong influence of the local

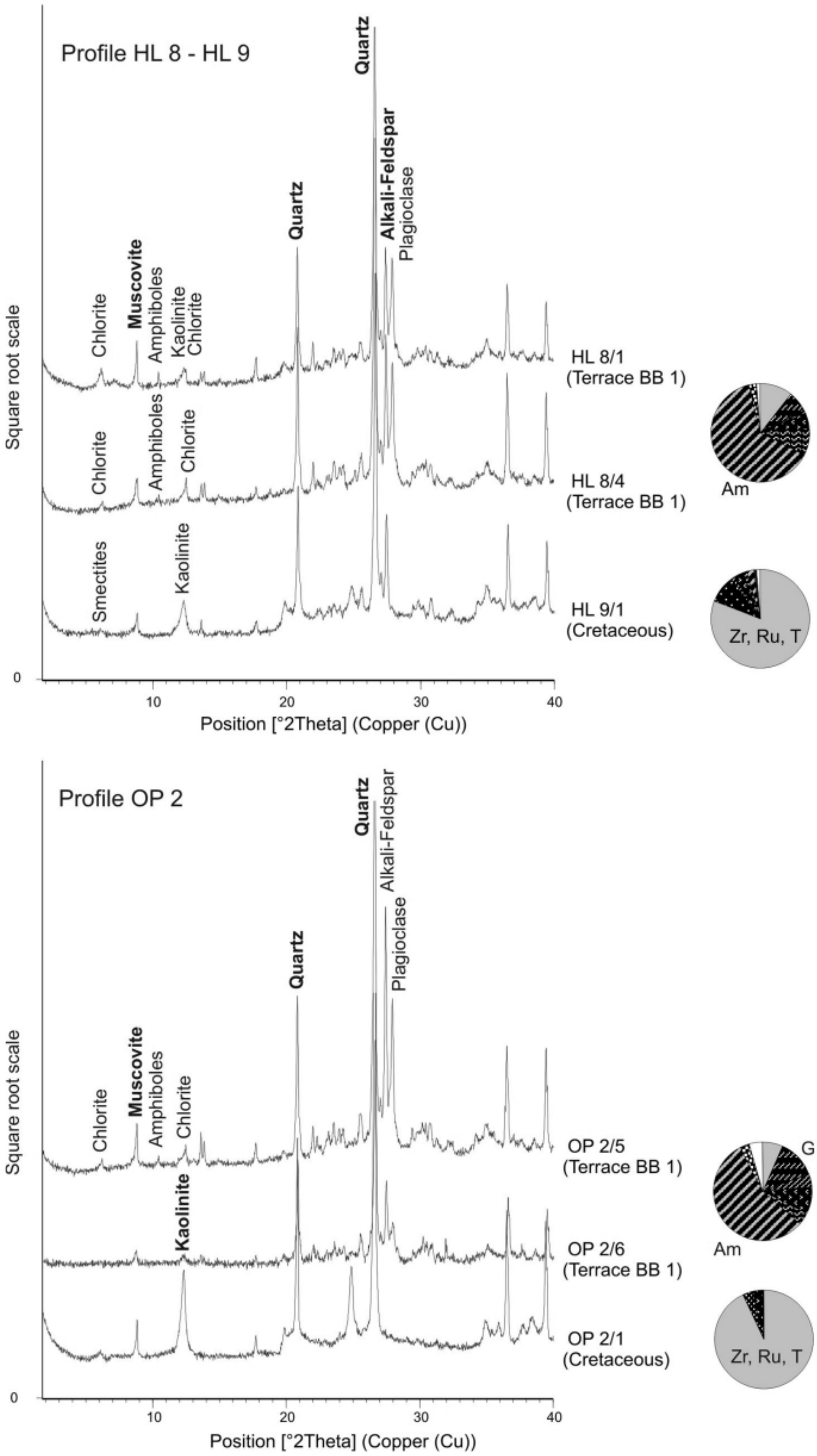


FIGURE 10: Diffractograms and heavy mineral composition of samples in drillings HL 8, HL 9 and OP 2. Note the different mineralogical content of Quaternary (HL 8/1, HL 8/4, OP 2/5 and OP 2/6) and pre-Quaternary samples (HL 9/1 and OP 2/1). The heavy mineral spectra underline the stratigraphic assignment of the samples. Bold printed minerals were detected in all diffractograms below. Am - amphiboles; Zr, Ru, T – Zircon, Rutile, Tourmaline; G - garnet.

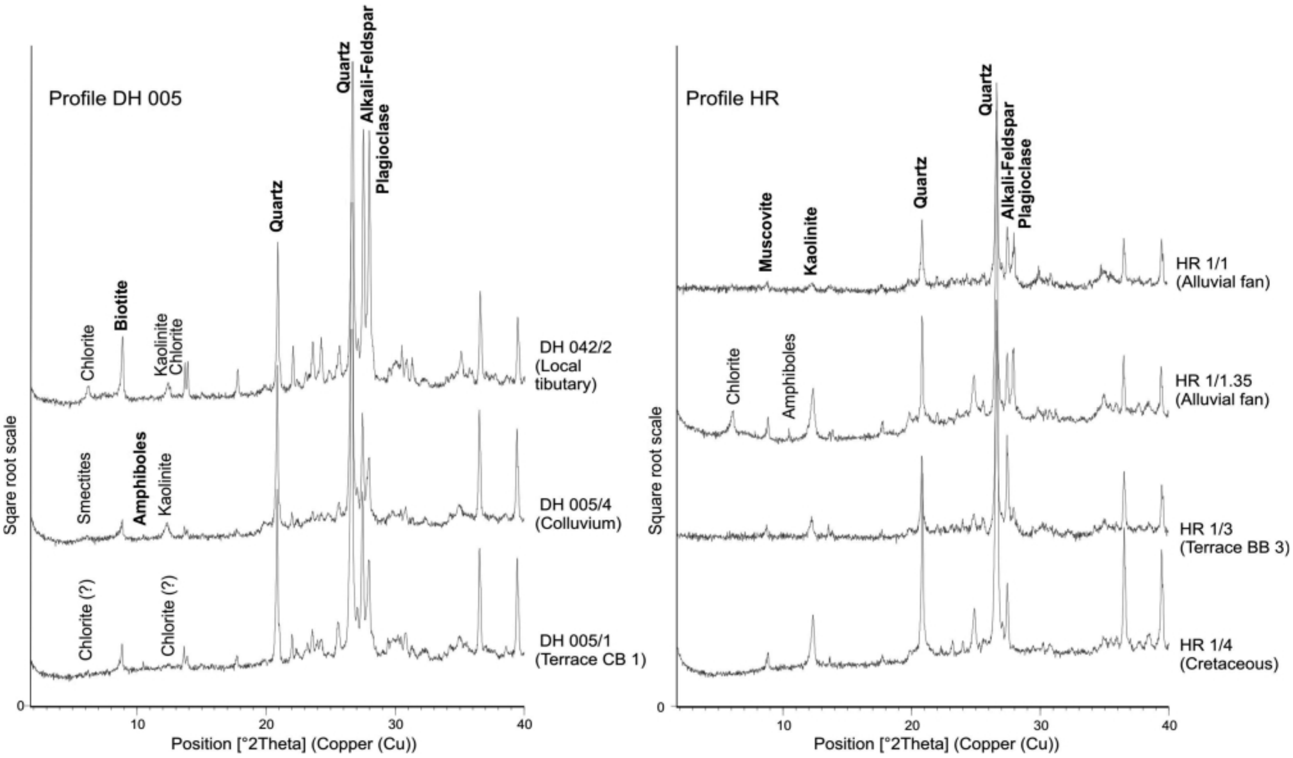


Figure 11: Diffractograms of samples from outcrop DH 005 and a sandy tributary alluvium DH 042. Note the missing amphibole peak in sample DH 042/2. The profile HR is revealing sediments of an alluvial fan (HR 1/1, HR 1/1.35) deposited on fluvial gravel from terrace BB 3 (HR 1/3) and Cretaceous sandstone (HR 1/4). Bold printed minerals were detected in all diffractograms below.

basement lithologies.

6. Conclusions

The study presents sediment-petrological characteristics of clastic sediments from the Budějovice Basin and adjacent areas. By using basic sedimentological methods, such as X-ray powder diffraction of bulk samples and heavy mineral analysis, a clear differentiation of pre-Quaternary from Quaternary sediments is possible. The bulk components of pre-Quaternary sediments are predominantly quartz, alkali-feldspar, muscovite as well as kaolinite, due to long-lasting weathering processes. In contrast, Quaternary sediments additionally contain minerals less resistant to weathering, such as plagioclase and chlorite and only small amounts of kaolinite, ruling out longer periods of chemical weathering. The Vltava River sediments further contain significant amounts of amphiboles; these are absent 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 the sediments were exposed to.

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