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Deposits and evolution of the alluvial infill on the confluence of Roklanský Potok and Javoří Potok streams at the Šumavské Pláně plains

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Abstract
We studied the alluvial infill preserved on the confluence of Roklanský Potok and Javoří Potok streams by means of geomorphic mapping, geophysical profiling, and sedimentological analyses. The conventional radiocarbon dating and archaeological findings helped to reconstruct evolutionary phases that formed the present landscape of central part of the Bohemian Forest (Šumava in Czech), the Šumavské Pláně plains. The Upper Terrace that fringes the valley is a remnant of Pleistocene gravel infill of the valley. The Lower Terrace and active floodplain formed by Holocene sands are most probably result of increased overbank sedimentation caused by extensive deforestation of upper parts of the catchment during the 18th, 19th, and 20th centuries. Recent evolution of the landscape is characterised by vertical and lateral incision caused by anthropogenic modifications of fluvial regime in the upper parts of the catchment.

Keywords: sedimentology, fluvial terraces, palaeochannel, environmental change, erosion/aggradation phases, Bohemian Forest, Šumava Mts.

Introduction

Floodplain landforms and sediments are suitable archives of palaeoenvironmental changes (e.g. Kalis et al. 2003, Macaire et al. 2006, Miall 2006, Brown 2008). They can preserve record of past fluvial processes and predominant river patterns (Lewin & Brewer 2005, Stacke et al. 2014). In the European mountainous and sub-mountainous alluvial archives, evidence of climatically induced palaeoenvironmental changes is well demonstrated, especially for the Last Glacial/Holocene transition (Starkel et al. 2007, Erkens et al. 2011, Turner et al. 2013). Kukulak (2003), Hoffmann et al. (2009), and Brown et al. (2013) have demonstrated extensive human-induced changes of fluvial processes during the last millennium.

The system of alluvial terraces is preserved in many catchments across the Bohemian Forest, including the Roklanský Potok stream. Numerous diverse studies, e.g., the reconstruction of potential natural vegetation in the Šumava National Park (Neuhäuslová et al. 2001), morphostructural analyses of central part of the Bohemian Forest (Jedlička & Mentlík 2003), and studies based on palynological research (Svobodová et al. 2002, Břízová 2004, 2012, Jankovská 2004) can help to reconstruct the palaeoenvironmental evolution of the Roklanský Potok catchment. Recent state of biotic components of the landscape in the Roklanský Potok catchment have been described by, e.g., Holuša (2000), Nováková (2001), Zelenková (2001), and Růžičková et al. (2004). The hydrologic research of the catchment focuses mainly on the rainfall-runoff relations (Hais 2007, Kocum & Jánský 2008, Čurda et al. 2011, Vlček et al. 2012) and the effects of floods (Křížek & Engel 2004, Langhammer & Vajskebr 2004). Recent changes in the dynamics of fluvial processes on the confluence of the Roklanský Potok and Javoří Potok streams have been described by Langhammer et al. (2015a). Although the upper parts of the Bohemian Forest are perceived as only little human influenced, the long record of archaeological findings across the whole Bohemian Forest (Fröhlich 1997, Beneš 1996, Kubů & Zavřel 2007, Šrein et al. 2008) proves the opposite. One of the oldest findings at this elevation are Mesolithic artefacts that were found on the Upper Terrace of the Roklanský Potok stream (Čuláková et al. 2012).

The primary aims of our study are (i) to reveal the characteristic forms and sediments of a fluvial palaeoenvironment on the confluence of the Roklanský Potok and Javoří Potok streams, and (ii) to reconstruct phases of floodplain evolution by deciphering major river pattern changes together with aggradation and incision periods. To understand the complexity of the spatio-temporal evolution of the alluvial infill, a multidisciplinary approach is necessary (Morin et al. 2011, Turner et al. 2013). Therefore, geomorphological, geophysical, sedimentological, and chronological analyses are used to form a complete explorative framework.

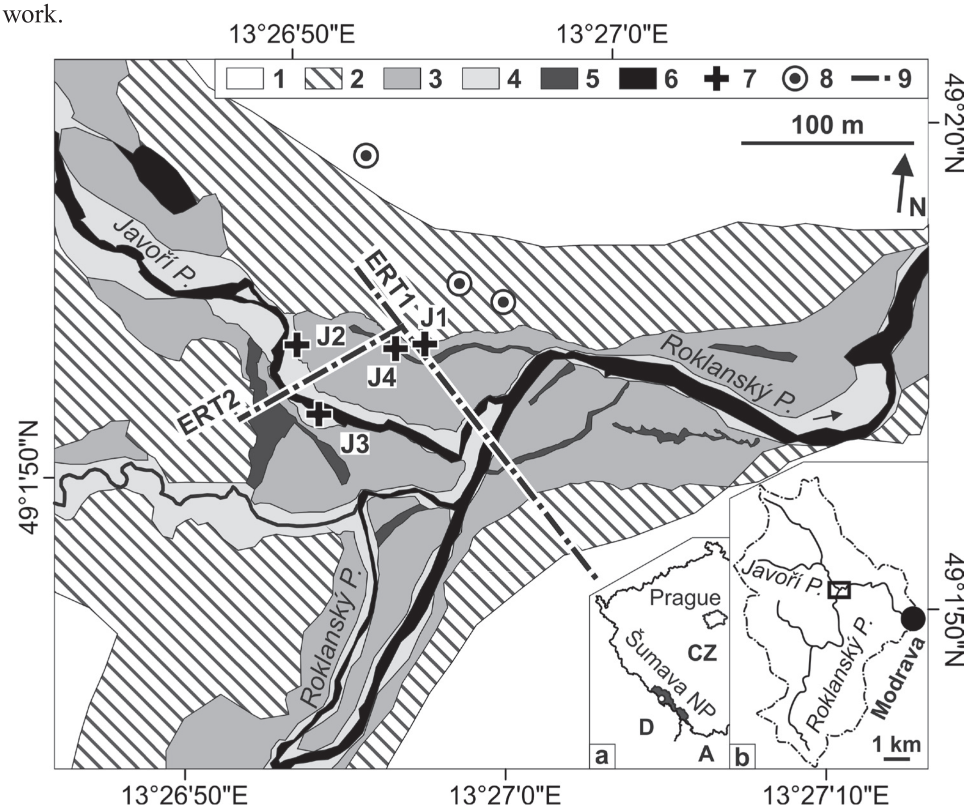

Fig. 1. Map of the studied confluence of the Roklanský Potok and Javoří Potok streams. Location of the catchment within western part of the Czech Republic (a: A – Austria, D – Germany, CZ – Czech Republic) and location of a study locality within the catchment (b). 1 – Valley slopes; 2 – Upper Terrace; 3 – Lower Terrace; 4 – active floodplain; 5 – elongated infilled depressions (palaeochannels); 6 – stream; 7 – location of studied outcrops (J1, J2, J3) and borehole (J4); 8 – location of Mesolithic archaeological findings; 9 – ERT profiles.

Regional settings

The study locality is situated in the catchment of the Roklanský Potok stream in the central part of the Bohemian Forest (Šumava in Czech, Fig. 1). This part of the mountain range, called the Šumavské Pláně plains, is probably a large lifted relict of the Paleogene planation surface (Czudek 2005). The flat relief is intersected by mountain streams with wide valleys. The relicts of the Pleistocene mountain glaciations were recorded at several localities across the mountain range (Raab & Völkel 2003, Mentlík et al. 2013, Vočadlová et al. 2015).

The catchment of the Roklanský Potok stream has the area of 48 km^2, the elevation varies between 980 and 1370 m a.s.l. The bedrock of the catchment is composed of granites and metamorphic rocks (mica schists, gneisses, and migmatites) with isolated granite outcrops (Babůrek et al. 2006). These are covered by Quaternary colluvial and fluvial deposits, as well as by organic accumulations. The study locality is surrounded by extensive complex of peat bogs, which started to develop at the beginning of the Holocene ca. 10 ka BP (Svobodová et al. 2002). The presence of mires in the catchment is supposed to affect the runoff regime of the streams; nevertheless, the maximum discharge is connected with spring thaw (Čurda et al. 2011). The annual mean discharge at the gauge station ca. 4.5 km downstream the study locality is 3.34 $m^3.s^{-1}$ (Langhammer et al. 2015b). The present-day land cover in the catchment of the Roklanský Potok stream was strongly affected by windstorms and bark beetle outbreaks at the end of the 20th and beginning of the 21st century (Šantrůčková et al. 2010). These disturbances also altered the natural runoff regime (Langhammer et al. 2015a).

The study locality is situated on the confluence of the Roklanský Potok and Javoří Potok streams (Fig. 1). The locality is formed by a wide valley bottom where the terrace system has been preserved. The area has low elevation differences with the slope inclination 5–15° and average elevation 1030 m a.s.l. The vegetation cover is dominated by grassland and planted spruce forests.

Materials and methods

We conducted Global Navigation Satellite System (GNSS)-based geomorphic mapping to specify the extent of the active floodplain, terrace levels, and the location of abandoned channels, previously defined from the analyses of digital elevation model (DEM). We used the 4th generation DEM that is based on the data acquired by altimetry airborne laser scanning (regular grid 5×5 m with total standard error 0.3 m in the bare terrain and 1 m in the forested terrain) to perform basic morphometric analyses of the alluvial forms located on the study site. Exposures suitable for further detailed analyses were selected during the geomorphic mapping.

Sedimentary facies and floodplain thickness were observed directly in three outcrops. Infill of elongated depression was observed from the shallow core sampling (depth 1.8 m) retrieved with a peat sampler (Eijkelkamp®).

We reconstructed the architecture and extent of alluvial infill using near-surface geophysical method (Milsom 2003). We applied an Automatic Resistivity System ARES (GF Instruments®) to gather two electrical resistivity tomography (ERT) profiles with a total length of ~400 m. Considering the contrasting conductivity (the reciprocal value to resistivity) of the alluvial sediments with different porosity and grain size characteristics, the ERT method is reliable for determining their extent (e.g. Gourry et al. 2003, Froese et al. 2005, Stacke et al. 2014). We used the 5 m electrode spacing and a ~35 m depth of investigation on the ERT1 profile and the 1 m electrode spacing and a ~12 m depth of investigation on the

ERT2 profile. The Wenner Alpha electrode array, with higher resolution in vertical direction, i.e. sensitive to the horizontal structures (*sensu* Griffiths & Barker 2002), has been used on both profiles.

Three charcoal samples were submitted for conventional radiocarbon dating at the GADAM Centre of Silesian University of Technology. The ^{14}C absolute ages were calibrated with OxCal v4.0.5 (Ramsey 2007) using the calibration curve IntCAL09 (Reimer et al. 2009). The cal. ages are reported with the extremes of 1σ ranges.

For determination of key sections of the alluvial infill, we sampled each layer in three outcrops and sliced the core obtained from the palaeochannel into 5 cm thick increments. The total organic content in the samples from the palaeochannel was determined by the loss-on-ignition at 550°C using the methodology of Heiri at al. (2001). After eliminating organic fragments, the particle size distribution for gravel (<−1φ), sand (−1φ to 4φ), and mud (silt and clay >4φ) was evaluated by wet sieving (Krumbein & Sloss 1963).

We evaluated the low field mass specific magnetic susceptibility at low frequency (χ_{LF}) of samples from the outcrop in the Upper Terrace and from the elongated depression using an MS2 Magnetic Susceptibility Meter (Bartington Instruments®) to describe the mineral magnetic content of the alluvial facies.

Results

Terrace system as documented by geomorphic mapping

A geomorphic survey revealed ~100 m wide valley floor of the Roklanský Potok and Javoří Potok streams that widens up to 200 m on the confluence (Fig. 1). This valley floor is fringed by the ~3 m high Upper Terrace. The valley floor topography is formed by two levels (Lower Terrace and active floodplain, Fig. 2). The surface of the more extensive Lower Terrace is quasiplanar, located 1–1.5 m above the active channel and locally covered by peat bogs. Numerous elongated depressions (palaeochannels) are preserved on the Lower Terrace that is separated by 0.2–1 m high slope from the active floodplain. This slope is clearly visible on 70 m of the ERT2 profile in Fig. 2. The active floodplain with undulated surface is tilted towards the active channel and is 10–40 m wide. Well preserved gravel side bars and point bars and steep erosional banks are located along the active channel. The major portion of active floodplain is regularly flooded during the spring floods from the melting snow and summer cloudbursts. Parts of the Lower Terrace adjacent to active floodplain are flooded during the major flood events.

Geophysical dataset

After comparing our results obtained by the ERT method with the outcrop and core data and geomorphologic mapping, four distinctive sedimentary units were distinguished. In both 2D profiles, relatively low resistive (<500 Ω.m) bedrock formed by intensively weathered granites of the moldanubic pluton was found. The low resistivity of this rock is most probably caused by intensive weathering as well as by its position below the groundwater level. The bedrock is covered by relatively more resistive loose slope material (2000–5000 Ω.m) on the outermost flanks of the valley. The most resistive deposits (>10000 Ω.m) are the gravels of the Upper Terrace. Two types of relatively less resistive units overlie the bedrock: extensive sandy deposits and sandy gravel intercalations with resistivity of 1500–5000 Ω.m form the Lower Terrace and active floodplain, and the through-shaped elongated depressions are filled with muddy material with resistivity of 500–1000 Ω.m (Fig. 2).

Facies composition and distribution

The composition of the sediments within the outcrops and core is shown in Fig. 3, photos of studied outcrops are shown on Fig. 4, and the simplified cross-section of the valley infill and facies distribution is shown in Fig. 5. Six sedimentary facies (gravel, sandy gravel, muddy gravel, gravelly muddy sand, sandy mud, and mud) were identified.

The gravel facies (gravel, sandy gravel, and muddy gravel), forming the massive bottom layer of alluvial infill, were observed in the borehole and all outcrops and constitutes the major part of the floodplain deposits. This facies also form the whole volume of the Upper Terrace. In the gravel facies, gravel forms more than 50% of the sediment bulk and the sand or mud do not exceed 25%. The gravel fraction is mainly composed of rounded and semi-rounded granite clasts, with the longest axis varying from 15 to 200 mm. The 10 m thick complex of gravel facies forms the whole profile of the Upper Terrace and the basal ~4 m thick layer in the Lower Terrace. The thickness of this facies complex is less than 2 m in the active floodplain. The surface of this complex is well marked and planar on the Upper Terrace. On the Lower Terrace, the surface is indistinctive and undulated with numerous sandy intercalations and lenses. In the Upper and Lower Terraces, the predominant colour of this complex is dark brown with black layers; in the active floodplain, the colour is beige to light grey with whitish stripes. Branches and charcoal fragments embedded in this facies complex can be found infrequently in the Lower Terrace and active floodplain. The subfossil trunk with diameter ~200 mm was found in the active floodplain. The total organic matter content

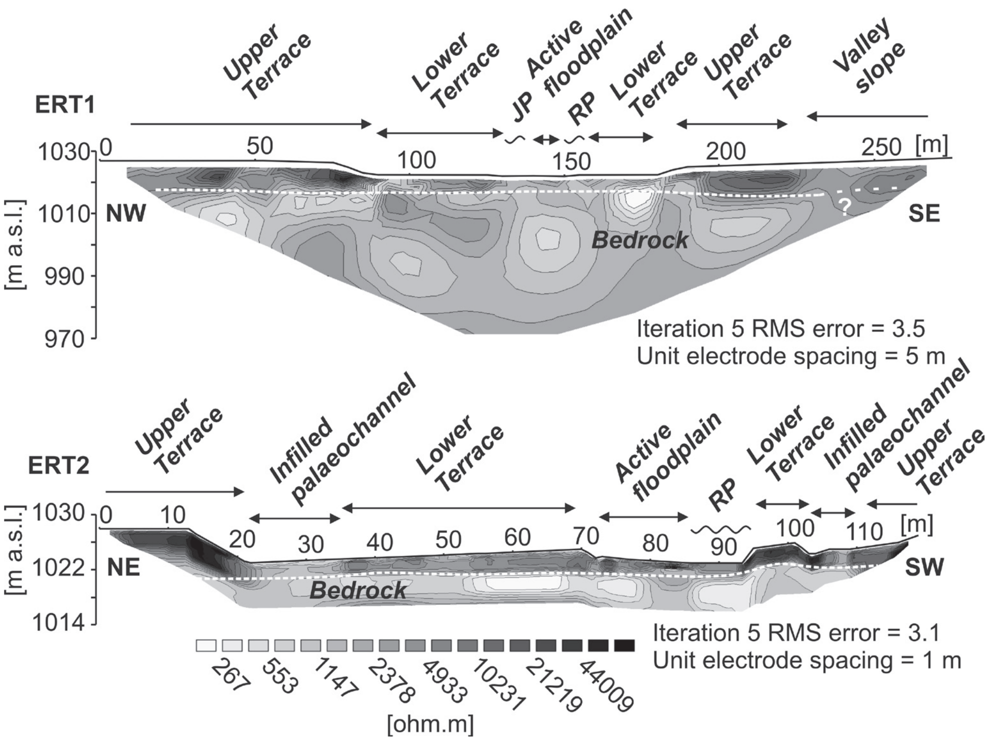

Fig. 2. Electrical resistivity profiles across the valley infill on the confluence of the Roklanský Potok and Javoří Potok streams. For the location of profiles, see Fig. 1. Sine curves indicate the location of the Roklanský Potok (RP) and Javoří Potok (JP) streams. Dashed line indicates the border between alluvial infill and the granitic bedrock.

is negligible in these facies. According to Miall (2006), these facies can be classified as facies Gh (clast supported, crudely bedded gravel) and can be interpreted as genetic element GB (gravel bars and bedforms). The character and occurrence of the gravel suggest a fluvial origin and braided stream environment.

The sand facies (gravelly muddy sand) form the 1–2 m thick blanket of beds overlying gravels on the Lower Terrace and active floodplain. Up to 250 mm thick slightly tilted gravel intercalations are present between the particular sand beds. Single 250 mm thick muddy sand intercalation was found in the elongated depression in the Lower Terrace. Planar laminae and cross-bedding are often present in the sand facies. The sand fraction forms 50–80% of the total bulk of the sand facies; mud and gravel fractions form less than 30%. The organic matter content is 4–8% in the finer beds and less than 5% in the coarser beds. The organic matter content rises up to 80% in the muddy sand intercalation in the infill of elongated depression in the Lower Terrace. The colour of this facies is light to dark grey on the active floodplain and grey to black with ochre streaks on the Lower Terrace. According to

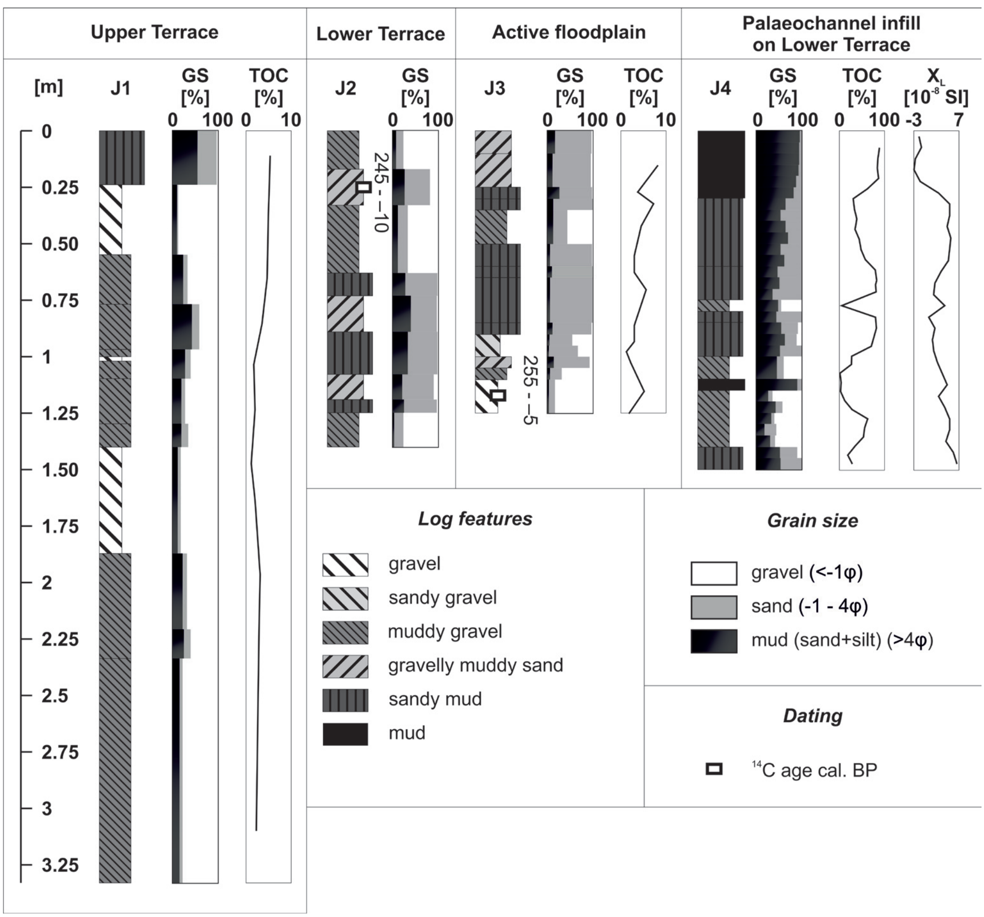

Fig. 3. Facies distribution and composition in outcrops and core. The grain size distribution is expressed as a percentage of the analysed fraction. χ_L – low field mass specific magnetic susceptibility at low frequency ($\times 10^{-8}$ $m^3.kg^{-1}$); TOC – total organic carbon content (note the different scale on sites J1, J3 and J4; for their location, see Fig. 1).

Miall (2006), this facies can be classified as facies Sh and Sl (sand, fine to coarse) and, excluding the intercalation in the palaeochannel infill, can be interpreted as element CS (crevasse splay) and SB (sandy bedforms).

The mud facies (sandy mud and mud) forms the ~1.5 m thick upward fining infill of the elongated depressions in the Lower Terrace. The basal surface is well marked and concave up. Few 150–250 mm thick massive muddy sand and muddy gravel intercalations were found between mud facies. The planar lamination and bedding is present in the mud facies. The clay and silt fractions form more than 50% of the total bulk ratio of this facies of which clay fraction forms less than 10%. The gravel fraction is negligible in this facies. The organic matter content of this facies is highly variable – in the topmost layers reaches 80% and partly decomposed peat is preserved; in the relatively coarser, lower layer it falls to 20%. The colour of this facies is changing downwards from dark brown to black. According to

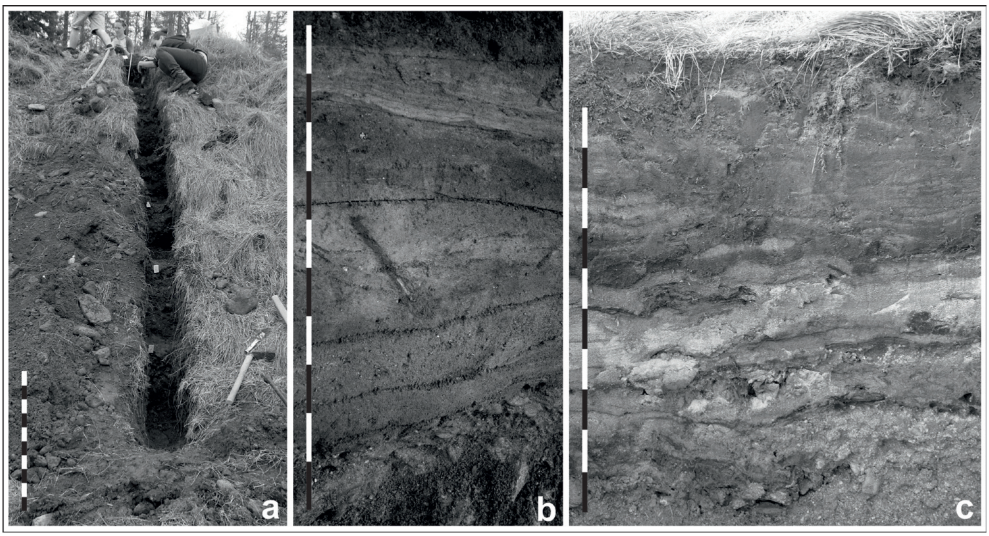

Fig. 4. Photos of studied outcrops: a – J1 (Upper Terrace); b – J2 (Lower Terrace); c – J3 (active floodplain). Scale bar on the left side of each picture is 1 m high.

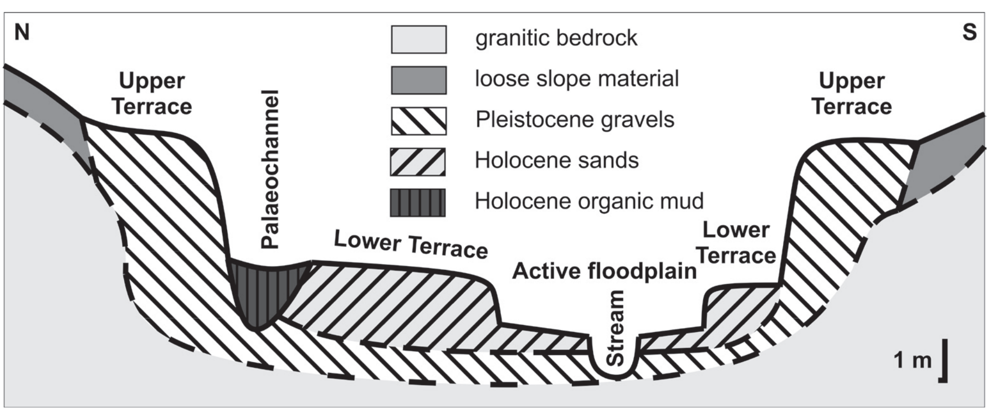

Fig. 5. The simplified cross-section of valley infill on the confluence of the Roklanský Potok and Javoří Potok streams.

Miall (2006), excluding the topsoil of the Upper Terrace, this facies can be classified as facies Fl (sand, silt, mud and mud, silt, respectively) and interpreted as element CH (channels, more precisely – abandoned channels).

Dating of sedimentary sequences

Two conventional radiocarbon dates obtained from the base of active floodplain and the sub-surface of the Lower Terrace are shown in Table 1. Both samples were dated to last three centuries (100.3±0.54 percent of modern carbon (pMC) and 99.7±0.51 pMC, respectively).

We measured the low field mass specific magnetic susceptibility at low frequency (χ_{LF}) in the infill of palaeochannel in the Lower Terrace to prove its very young age. The basal 1.25 m of infill has slightly increased values of $4–7\times10^{-8}$ $m^3.kg^{-1}$. The values of topmost 0.25 m thick layer drop below 0×10^{-8} m^3 kg^{-1}. Overall, the χ_{LF} value is only slightly increased, not dependent on grain size distribution and, except surface 0.25 m, constant with depth. These results indicate that the deposition of these sediments took place before the onset of extensive burning of fossil fuels and use of internal combustion engines (Grygar et al. 2011, Stacke et al. 2014), which is consistent with radiocarbon dating of the Lower Terrace.

Discussion

Holocene floodplain evolution is rarely continuous at the millennial scale (Notebaert & Verstraeten 2010); periods of aggradation alternate with periods of incision and equilibrium state. The morphosedimentary dynamics and the sediment budget in catchments depend on many parameters, including the sediment yield, the degree of slope–floodplain coupling, the fluvial dynamics (Hoffmann et al. 2009, Morin et al. 2011), and human impact, esp. land-cover changes (Stacke et al. 2014). These parameters had a profound effect on accumulation and incision phases, and they varied in space and time. According to the distribution of the lithological facies and dating, four phases of fluvial dynamics were identified at the site. These phases are numbered 1 to 4 from the oldest to the most recent one and correspond either to an accumulation phase (marked with suffix A) or to an incision phase (marked with suffix I). The accumulation units are composed of one or several of the nine defined lithological facies.

The investigated sedimentary infill was deposited into the large valley typical for the Šumavské Pláně plains. The lack of Older Pleistocene deposits points to a major incision phase preceding the evolutionary phases described in this paper. However, we were not able to determine neither the age of incision, nor the character of processes forming the shape of the valley (major single event or sequence of minor incision phases). The minimum age has been provisionally determined by archaeological findings on the surface of the Upper Terrace until numerical dating of the oldest preserved infill is performed.

The oldest documented accumulation phase 1A is marked by deposition of up to a 10 m thick sedimentary unit formed by massive gravel facies with almost complete lack of organic material. The remnants of valley infill formed during the 1A phase are preserved on the valley flanks as a distinctive Upper Terrace. The Mesolitic archaeological findings at the Upper Terrace (Čuláková et al. 2012 – see Fig. 1) postdate this phase to the Early Holocene. The deposits were marked as longitudinal gravel bars and point to a braided fluvial system (Reineck & Singh 1980, Miall 2006). In the Czech Republic, the analogical terraces were described from the catchments of the Bečva and Morava Rivers in the Carpathian Piedmont (Tyráček 1963, Macoun et al. 1965). The harsh climate and sparse vegetation of Last Glacial (Svobodová et al. 2002) led to increased surficial erosion and accelerated slope processes. The high sediment yield in the catchment and increased summer discharges caused high

Table 1. Conventional radiocarbon dates from the valley infill on the confluence of the Roklanský Potok and Javoří Potok streams. The margin of calibrated age BP error is 1σ (standard deviation).

Lab No.	Site	Floodplain level	Analysed material	Stratigraphic position	Depth (m)	Altitude (m a.s.l.)	Age ^{14}C ± error (% of modern C)	Age (AD)	Age cal. BP (±1σ)
GdS-2898	J2	Lower Terrace	Charcoal	Top of surface sandy blanket	0.25	1026	100.3±0.54	1695–1955	255– +5
GdS-2901	J3	Active floodplain	Charcoal	Base of surface sandy blanket	1.15	1024	99.7±0.51	1705–1960	245– +10

amounts of coarse-grained material to be transported from the upper parts of the catchment and deposited by braided stream in the stretches with reduced slope. The same process and evolutionary phase were described in Polish rivers (Starkel 2002, Starkel et al. 2006) and dated to the Late Glacial/Holocene transition.

The lack of sediments dated to the first half of the Holocene suggests the major incision phase 2I. During this phase, the major part of Pleistocene gravel valley infill has been cleared and only remnants of this infill remained as the Upper Terrace. The sinuous planform of the Upper Terrace crest indicates that the lateral erosion was the prevailing process (Gordon et al. 2004, Tisdale 2004). This type of extensive incision indicates efficient soil protection by dense vegetation and high water discharge (Morin et al. 2011). These conditions points to the Atlantic climate optimum as the most probable period when the phase 2I occurred, which is consistent with the reconstructed vegetation of mixed forests that covered the Bohemian Forest during this period (Svobodová et al. 2002).

During the accumulation phase 3A, the extensive 1–2 m thick sandy sedimentary unit filled the valley bottom and multiple deep and relatively narrow abandoned channels were infilled with finer organic-rich muddy material. The charcoal fragments found on the sites J2 and J3 date the final stage of this phase to the latest Subatlantic (base of the sandy infill is pre-dated to 255– +5 cal. BP and its surface is dated 245– +10 cal. BP). Presence of sinuous infilled channel on the outer flank of the Lower Terrace indicates the meandering channel (Gordon et al. 2004, Tisdale 2004). The extensive overbank sedimentation points to an intensified deforestation and accelerated soil erosion in upper parts of the Roklanský Potok catchment. This phase correlates with the period of increased frequency of windstorms and connected bark beetle outbreaks during the 18^{th}, 19^{th} and 20^{th} centuries and the onset of logging in the uppermost parts of the Bohemia Forest after the 1850s (Čada et al. 2013). The relatively low χ_{LF} of the palaeochannel infill suggests that the channel was abandoned and infilled before the increased atmospheric transport of industrial pollutants in the 20^{th} century (Grygar et al. 2011).

The recent incision phase 4I is characterised by a transition from overbank sedimentation to an incision of a single laterally unstable channel. Part of the Lower Terrace was eroded and the active floodplain level emerged during this phase. The active channel laterally cuts into the active floodplain and the Lower Terrace during the major flooding episodes. This incision phase is most likely a result of anthropogenic modification of stream geometry (Langhammer 2007) and drainage of mires in the catchment that took place mainly in the 1970s and 1980s (Bufková et al. 2010), both leading to increased discharges and higher erosional capability.

The studied catchment is unique in a limited human impact and very late onset of extensive logging due to its remoteness and high elevation (Čada et al. 2013). Nevertheless, the abovementioned evolutionary phases are similar to the evolutionary phases described in other Czech mountainous and sub-mountainous rivers. Phase 1A and its deposits has been described in middle and lower reaches of the Bečva and Morava Rivers (Tyráček 1963, Macoun et al. 1965), the Vltava River (Chábera 1965, Chábera & Novák 1975, Chábera & Novák 1976), and the Labe River (Jílek et al. 1995). Stacke et al. 2014 described phases corresponding to phase 2I and 3A in the Bečva River catchment in the Carpathian Piedmont. The recent phase 4I has been described in various studies from the Carpathians and its foreland (e.g. Galia et al. 2012, Škarpich et al. 2013).

Conclusions

Three sedimentary units (Pleistocene gravels, Holocene sands, and Holocene organic muds) of the alluvial infill were distinguished on the confluence of the Roklanský Potok and Javoří Potok streams. The Pleistocene aggradation of gravels was most probably in the Atlantic superseded by major incision phase. This erosion formed the slope of the Upper Terrace that fringes the valley. The Late Holocene evolution was characterised by an extensive overbank sedimentation of sands. Abandoned channels were infilled with organic mud during this phase. The recent incision phase formed the erosional surface of active floodplain and the channel flow is characterised by lateral erosion during major flooding episodes.

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