Response of fluvial, aeolian, and lacustrine systems to late Pleistocene to Holocene climate change, Lower Moravian Basin, Czech Republic

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1. Introduction

Central Europe underwent pronounced climatic change during the late Pleistocene to Holocene. Using marine isotope stages (MIS) with ages from Lisiecki and Raymo (2005), alternating relatively temperate late Pleistocene to Holocene. Using marine isotope stages (MIS) with 1. Introduction

Climate change Turbidites Lake Czech Republic Quaternary Keywords: Available online 24 December 2014 Accepted 17 December 2014 Received in revised form 16 December 2014 Received 15 July 2014 Article history:

Late Pleistocene to Holocene Morava River valley-fill of the eastern Czech Republic reflects the geomorphic evolution of the valley as forced by climate change. Valley-fill stratigraphy was studied through measured sections, optically stimulated luminescence (OSL) and radiocarbon dating, ground-penetrating radar surveys of relict sand dunes, archived drill-hole data, and a comparison of elevations and ages of stratigraphic units. Fluvial systems evolved from meandering with floodplains to braided during MIS 3. Braided fluvio-aeolian systems dominated through MIS 2 and the Last Glacial Maximum (LGM). Valley aggradation occurred during arid glacial times of a low water-to-sediment discharge ratio. Most valley-fill was removed at 13 ka with incision by a large-bend meandering river with an estimated bankfull paleodischarge 3× larger than the modern Morava River. The Holocene Morava River has varied from meandering to anabranching with low rates of floodplain aggradation. The Bzenec sand body, up to 36 m thick, represents an erosional remnant bypassed during late Pleistocene incision and consists of interpreted lacustrine turbidites overlain by braided stream and aeolian dune strata. The turbidites consist of laterally continuous, thin, normally graded beds of rounded and frosted sand grains of aeolian or-fluvio-aeolian systems dominated

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loess accumulations deposited since the Pliocene (Kukla, 1975; Havlíček, 1991; Havlíček et al., 1994, 1996, 1997, 2007; Frechen et al., 1999; Tyráček and Havlíček, 2009). The purpose of this paper is to explore the stratigraphic and chronologic relationships of interpreted fluvial, aeolian, and lacustrine strata within a segment of the Morava River valley in which the strata records the response of these depositional environments to climatic change from MIS 3 to the Holocene. Previous work in this area has largely been regional in nature and without a detailed study of the valley-fill stratigraphic architecture and its chronology. This study demonstrates a climate-driven complex history of valley aggradation and incision caused by braided and meandering rivers, respectively. An LGM lake system is identified in which dated facies relationships argue that the lake formed with downstream damming by a braided terminal fan and aeolian dune complex and that lake sedimentation was largely by turbidity currents originating with fluvial undercutting of aeolian dune strata. Results from this study highlight the potential for extracting the climatic record from basins extending from the lower Morava River to its confluence with the Danube River.

2. Geomorphic and geological settings of the study area

The Morava River and its tributaries drain the eastern Czech Republic and adjacent areas of Austria and Slovakia before merging and flowing southward to join the Danube River in Slovakia (Fig. 1). The catchment area of the Morava River (26,658 km²) includes (i) the Upper Moravian Basin that drains highlands composed of Proterozoic crystalline rock and upper Paleozoic marine and continental strata, and (ii) the Lower Moravian Basin that drains Paleogene flysch nappes of the Western Carpathian Mountains (Figs. 1–2). The Dyje River and its tributaries issue from the eastern margin of the Bohemian Massif, which consists largely of Proterozoic crystalline rock. The Dyje River crosses the Carpathian nappes to merge with the Morava River at the southern border of the Lower Moravian Basin. The southern extent of the Morava River is through the broad lowlands of the Záhorská Basin. The Lower Moravian and the Záhorská basins are floored by Miocene marine strata contiguous with the Vienna Basin to the southwest. Bedrock within the Upper and Lower Moravian Basins and the Záhorská Basin are overlain by Quaternary deposits (Fig. 2).

The primary focus of this study is the Bzenec area in the Lower Moravian Basin (Fig. 2). As seen in Fig. 3, the modern Morava River valley is defined to the northwest by incised relict meander bends. These meander bends truncate a Quaternary sand body (hereafter, the Bzenec sand body) that is up to 36 m thick and that has been interpreted as aeolian accumulations (e.g., Vitásek, 1936; Havlíček et al., 2007). Stabilized dune forms are apparent in the digital elevation model (DEM), especially south of Bzenec (Fig. 3). Up to 5 m of Holocene meandering channel and floodplain deposits occur within the modern incised valley and overlie Pleistocene fluvial deposits (Kadlec et al., 2009). In order to place the accumulations in the Bzenec area within the context of the Morava River valley, Quaternary exposures were also investigated southward in the Záhorská Basin, upstream in the Lower Moravian Basin, and in the Dyje River valley (Fig. 2).

3. Methodology

Outcrops are scarce within this heavily vegetated and cultivated area, and most exposures occur within active or abandoned sand quarries. In addition to the sections shown in Fig. 2, numerous other abandoned quarries were explored and new excavations were made. Sections were measured and characterized by lithology, sedimentary structures, and grain size and surface texture. Drill-hole data for the Bzenec sand body, housed at the Czech Geological Survey, were used.
the Carpathian Foredeep Miocene aeolian deposits, (B) Paleogene and Miocene formations (Carpathian nappes) including east. Black dots show locations of sections used in this study: (1) Ba

4. Section descriptions and facies interpretations

4.1. Bažantnica sand quarry (Section 1 on Fig. 2)

The southernmost section occurs within the large Bažantnica sand quarry in which the quarry wall exposes a 12-m sand section overlain by ~1 m dark, deeply rooted soil horizon that forms the modern surface. The sand/soil contact is at an elevation of 186 m, the quarry floor is at 172.5 m, and company borings indicate that Miocene strata occur ~1 m below the quarry floor, thus indicating an ~14.5-m sand section. The exposed section shows (i) an upper cross-stratified, fine- to medium-grained sand unit, and (ii) a lower unit consisting of 2–20 cm thick horizontally stratified beds of gravelly (chert granules to pebbles up to 12 mm) fine- to coarse-grained sand (Fig. 4). The contact between the two units is distinctly erosional, with scour depth varying by meters across the quarry wall, and the scour surface is marked by a surface lag of granules to small pebbles. The capping soil unit is developed within the upper cross-stratified unit and traces of cross-strata are visible within the soil horizon.

Although generally horizontally stratified, the lower unit is heterogeneous vertically and laterally. Planar laminations dominate, but shallow scour, sets of dune and ripple cross-strata, and coarse-grained horizons occur (Fig. 5A–B). Sets of dune cross-strata are most typically low angle (Fig. 5A), and sets of high-angle cross-strata are isolated and fill-scoured depressions (Fig. 5B). Grain size varies markedly between beds, as does bed thickness, mud is distinctly lacking, and the coarse sand grains are well rounded and frosted. Overall, grain size, bed thickness, and scale of sedimentary structures decrease upward in the unit. Wedge-shaped water-escape structures occur near the top of the unit. The overall nature of the lower unit argues for a shallow, braid- ed stream origin. More specifically, the dominance of planar laminar and the occurrence of high-angle cross-strata largely within scoured troughs argue for very shallow flow (i.e., sheet flow) conditions, especially in the upper portion of the unit where the decrease in grain size and scale of sedimentary structures suggests waning fluvial activity.

The cross-stratified upper unit consists of one to a few up to 4 m thick and consisting of grainflow strata (1–3 cm thick) and wind-ripple laminations. The wind-ripple laminae are especially diagnostic of an aeolian origin (Hunter, 1977). The contact between the lower and upper unit is interpreted to represent the transition from braided fluvial to aeolian dune environments within the Záhorská Basin, with deep and irregular wind deflation of the fluvial strata. Within this context, the interpreted waning fluvial activity in the upper part of the lower unit suggests a terminal fan setting. The absence of mud and the presence of well-frosted and -rounded grains suggests active aeolian processes contemporaneous with the braided stream environment or that the fluvial system was sourced from an older aeolian accumulation.

The OSL date from near the base of the quarry floor shows that braided stream conditions existed within the basin by at least 40 ± 5 ka (Fig. 4, Table 1). Error bars for OSL dates from the uppermost fluvial
deposits and the lowermost aeolian dune deposits overlap and bracket the transition from fluvial to aeolian environments to between 21 and 18 ka (Fig. 4, Table 1). Aeolian dunes persisted to at least 13 ± 1 ka, as given by the OSL date higher in the upper unit (Fig. 4, Table 1). Quarry activities elsewhere in the Záhorská Basin show that aeolian dune deposits are widespread. However, the only other OSL-dated exposure is at the Šajdíkove Humence sand quarry (see Fig. 2) where dune cross-strata were sampled 4 m below the quarry upper surface (elevation of 206 m) and yielded a date of 16.13 ± 0.765 ka (Moravcová and Fordinál, 2010).

4.2. Bzenec sand body (Sections 2, 3, 4, 5, GPR1 & GPR2 on Figs. 2–3)

Exposures of the Bzenec sand body occur within the Bzenec–Přívoz sand body, and with a natural outcrop created by incision of a meander bend of the Morava River (Section 3). The apparent relict sand dunes on the surface of the Bzenec sand body were explored by GPR surveys (GPR1, GPR2) and by shallow trenches into relict sand dunes near Vracov (Section 5). In addition, abundant drill holes (dots in Fig. 3) and their archived sediment descriptions supplement the measured sections in characterizing the Bzenec sand body.

4.2.1. Bzenec–Přívoz sand quarry (Section 2 on Figs. 2–3)

The primary section at the extensive Bzenec–Přívoz sand quarry (Section 2) has an upper elevation of 176 m and consists of a 9.5-m sand exposure consisting of at least 110 beds ranging in thickness from 3 to 20 cm (Fig. 6). Beds are laterally continuous at the exposure scale and generally show planar contacts with only local scours. Although cross-strata and parallel laminations occur, the dominant feature of the beds is normal grading, in which a gravelly sand or coarse sand base fines upward to medium or fine sand. Grading occurs largely by a decrease in the maximum grain size upward within a bed, but an overall decrease in mean sand size is less pronounced, and fine-grained sand with an iron-oxide cement commonly caps the beds. Granules and small (< 10 mm) pebbles account for up to 5% of the total grain population. Coarser sand grains are rounded and frosted, and mud is absent.

Laterally within the quarry, remnants of the uppermost portion of the section extend to an elevation of 183 m. This upper section consists of (i) 15–30 cm of cross-stratified, fine-grained sand dominated by
wind-ripple laminae and which is truncated laterally by more recent scour, (ii) ~60 cm of ripple- to dune-scale cross-stratified gravelly sand with intercalated sandy gravel beds, and (iii) normally graded beds typical of the primary section (Fig. 7). Overall, therefore, the Bzenec sand body at this section consists of a lower, middle, and upper unit.

The cross-stratified fine sand upper unit is readily interpreted as aeolian dune deposits. The cross-stratified gravelly sand and bedded sandy gravel middle unit is interpreted as a shallow braided stream in origin. The origin of the lower sand unit, dominated by graded beds and forming most of the Bzenec sand body at this section, will be addressed collectively for all sections in Section 4.2.6.

An OSL date for the upper aeolian unit is 18 ± 4 ka (Fig. 7, Table 1). Even considering their error bars, the OSL dates obtained from the lower unit of the Bzenec sand body are generally inverted, with the oldest beds higher in the section and the youngest beds at the base (Fig. 6, Table 1). This inverted chronology demonstrates that the OSL dates do not represent an upward succession of depositional ages.

4.2.2. Morava River meander cut (Section 3 on Figs. 2–3)

The Morava River outcrop of the Bzenec sand body is 2.8 m (Fig. 8) thick and is dramatically truncated and overlain by Holocene floodplain deposits at both the upstream and downstream reaches of the meander bend (Fig. 9). The outcrop extends up to 180 m in elevation with the upper ~1 m developed into a soil zone. Where well-exposed, bedding is similar to the lower unit at the Bzenec–Přívoz sand quarry (Section 2) and is dominated by laterally continuous beds 5–20 cm thick, with normal grading in which gravelly sand yields upward to medium sand, with an iron-stained fine-grained sand cap (Fig. 8). Cross-strata is locally present, as is scour, but other beds appear structureless or show wavy laminae, the latter suggestive of cryogenic processes (Fig. 8). An OSL date obtained 1.5 m below the top of the soil horizon is 24 ± 3 ka (Fig. 8, Table 1), comparable to dates obtained in the lower portion of the section at the Bzenec–Přívoz sand quarry (Section 2).

4.2.3. KM Beta sand quarry (Section 4 on Figs. 2–3)

The KM Beta sand quarry (Section 4), located 3 km northeast of the Bzenec–Přívoz sand quarry (Section 2) and the outcrop on the Morava River (Section 3), is 19.5 m thick with an upper elevation of 187 m. The section is readily divided into three units (Fig. 10), which correlate well with the section at the Bzenec–Přívoz sand quarry.

The lower unit consists of 16.7 m of laterally continuous, normally graded beds 10–20 cm in thickness. Typically, gravelly sand grades upward to medium sand and then to a fine-grained sand cap (Fig. 11). Local scour occurs with relatively uncommon planar laminations and ripple-scale cross-strata. This lower unit is the same as and correlated with the lower unit at the Bzenec–Přívoz sand quarry (Section 2). An OSL date of 23 ± 2 ka was obtained from the upper portion of the lower unit, whereas an OSL date of 19 ± 2 ka was obtained from the basal portion of the section (Fig. 10, Table 1). The inverse chronology evident for the lower unit at the Bzenec–Přívoz sand quarry (Section 2), therefore, is also present here.

The middle ~1-m-thick unit of the exposure consists of interbedded sandy gravel or gravely sand and sand beds. Ripple- to dune-scale cross-strata dominate in coarser beds, whereas parallel laminations characterize most sand beds. Shallow scour occurs with low-angle cross-strata also occur. The entire unit shows overall wavy deformation, which may reflect cryogenic deformation (Fig. 10). This unit is interpreted as a braided-stream deposit and is correlated with the thin middle unit at the Bzenec–Přívoz sand quarry (Section 2), which occupies the same stratigraphic position (Fig. 7). An OSL date obtained from the lower portion of the unit is 17 ± 2 ka.

The upper 1.8 m of the section consists largely of aeolian dune cross-stratified fine to medium sand or more planar wind-ripple laminae, but two horizons (~10 cm thick) of gravelly sand of probable fluvial origin occur in the lower and upper portions of the unit. The unit overall is correlated with the upper aeolian at the Bzenec–Přívoz sand quarry (Fig. 7). An OSL date of 18 ± 2 ka obtained from the lower portion of the unit (Fig. 10) is similar to that for this unit at Bzenec–Přívoz sand quarry (18 ± 4 ka; Fig. 7, Table 1), but more tightly constrained by its error bars. The error bars for the dates from the middle fluvial (17 ± 2 ka) and upper aeolian (18 ± 2 ka) units at the KM Beta sand quarry (Section 4) largely overlap, arguing that the period of braided stream conditions was relatively brief.

4.2.4. Vracov trench (Section 5 on Figs. 2–3) and GPR surveys (GPR 1, GPR 2 on Fig. 3)

The apparent relicl aeolian sand dunes on the now heavily forested upper surface of the Bzenec sand body trend roughly N–S (Fig. 3) and, in the field, the forms are rounded and subdued; but most show asymmetry with a gentler western flank (5°) and a steeper eastern flank (~20°), and range in height from 6 to 8 m. The GPR surveys, trending E–W and perpendicular to the crest (GPR 1, GPR 2 on Fig. 3), confirm that these forms are relics of aeolian sand dunes (Fig. 12). The internal architecture shows steeply dipping strata to the E in agreement with the surface morphology. Bounding surfaces, at the level of the morphological interdune area, separate cross-strata within the dune forms from older dune cross-strata below (Fig. 12). Overall dune migration was toward the E, but the poor quality of the exposures did not allow for a more detailed reconstruction of the constructive winds (e.g., Eastwood et al., 2012).

A 2.5-m trench with an upper elevation of 197 m was excavated into a relic dune within an abandoned sand quarry 1 km southwest of Vracov (Section 5 on Figs. 2–3). Although the upper 1 m of the section was entirely pedogenic, dune cross-strata consisting of well-developed wind-ripple laminae and faint grainflow strata were evident lower in the trench. This sand section rests upon a gray clay interpreted as
weathered Miocene strata. An OSL sample taken 20 cm above the sand/clay boundary yielded an age of $13 \pm 2$ ka (VR in Table 1). Because this age was taken from a relict dune on the surface of the Bzenec sand body, it can be taken as the age of stabilization of the dune field; whereas the initiation of the dune field is given as $18 \pm 4$ ka (Section 2) and $18 \pm 2$ ka (Section 4) by the basal aeolian deposits (upper unit).

### 4.2.5. Drill-hole data

The nature of the drill-hole data allows for only a distinction between sand, gravelly sand, or sandy gravel and Neogene bedrock; but used in conjunction with the measured sections, generalized cross sections across the Bzenec sand body and into the modern Morava River valley can be constructed (Fig. 13). An older Morava River incision into the Neogene bedrock is evident in all cross sections. The highest

<table>
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<th>Th-232 (ppm)</th>
<th>K (%)</th>
<th>Water content (%)</th>
<th>Cosmic ray dose (mGy/a)</th>
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<td>$2.30 \pm 0.64$</td>
<td>$1.15 \pm 0.03$</td>
<td>$25 &amp; 12$</td>
<td>$150 \pm 30$</td>
<td>$1.4 \pm 0.1$</td>
<td>$24 \pm 3$</td>
</tr>
<tr>
<td>Section 4</td>
<td>BZ 1</td>
<td>100</td>
<td>$26 \pm 1$</td>
<td>$0.71 \pm 0.16$</td>
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<td>$1.09 \pm 0.1$</td>
<td>$10 \pm 5$</td>
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<td>$1.4 \pm 0.1$</td>
<td>$18 \pm 2$</td>
</tr>
<tr>
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<td>$2.24 \pm 0.6$</td>
<td>$1.31 \pm 0.1$</td>
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</tr>
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<td>Section 4</td>
<td>BZ 3</td>
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<td>$0.71 \pm 0.13$</td>
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<td>$6.43 \pm 1.6$</td>
<td>$1.48 \pm 0.13$</td>
<td>$25 &amp; 12$</td>
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<td>$2.1 \pm 0.2$</td>
<td>$19 \pm 2$</td>
</tr>
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<td>$0.60 \pm 0.02$</td>
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<td>$0.91 \pm 0.07$</td>
<td>$12 \pm 10$</td>
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<td>BOR 1</td>
<td>47</td>
<td>$46 \pm 0.2$</td>
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<td>$8.81 \pm 0.15$</td>
<td>$1.08 \pm 0.08$</td>
<td>$12 \pm 10$</td>
<td>$194 \pm 19$</td>
<td>$2.2 \pm 0.3$</td>
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<td>$2.43 \pm 0.02$</td>
<td>$10 \pm 5$</td>
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<td>$48 \pm 4$</td>
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<td>$3.15 \pm 0.81$</td>
<td>$2.43 \pm 0.02$</td>
<td>$10 \pm 5$</td>
<td>$124 \pm 25$</td>
<td>$3 \pm 0.2$</td>
<td>$61 \pm 6$</td>
</tr>
</tbody>
</table>
The lower unit of the Bzenec sand body is simply projected in the cross sections and allowed to onlap the Neogene bedrock. The lowest elevation of the lower unit seen in exposures occurs at the Bzenec–Přívoz sand quarry (Section 2) and is 166.5 m. The drill-hole logs show an abrupt transition from sand to gravel at an elevation of ~165 m (Fig. 13), which is interpreted to represent the transition from the base of the Bzenec sand body into underlying Pleistocene gravelly stream deposits. Unfortunately, the overlying middle fluvial and upper aeolian units of the Bzenec sand body cannot be distinguished with confidence in many of the logs, and these units are combined in Fig. 13, albeit that aeolian dune deposits almost certainly form most of the sand body at higher elevations over the Neogene bedrock. Holocene Morava River strata overlie the interpreted Pleistocene gravel unit where the Bzenec sand body has been erosionally removed (Fig. 13).

4.2.6. Origin and age of the Bzenec sand body

Summarized from the above, the Bzenec sand body consists of three depositional units: (i) an upper aeolian dune and sand sheet forming the upper unit of Sections 2 and 4, probably most of the sand body at higher elevations in Fig. 13, and relict sand dunes on the surface; (ii) a middle braided fluvial unit exposed at Sections 2 and 4, and forming the lower portion of the upper part of the sand body in Fig. 13; and (iii) the lower unit that forms most of the sand body housed within the incised Morava River valley.
Interpretation of the lower unit is not straightforward. Although the unit is clearly not aeolian as originally interpreted, the style of bedding and sedimentary structures also contrast with those of the braided stream deposits evident in the middle unit (Figs. 7–10). Any interpretation of the lower unit must account for the (i) laterally continuous thin beds; (ii) dominance of normal grading within the beds, (iii) presence of localized cross-strata and planar laminations, (iv) frosted and rounded sand grains, small percentage of granules and pebbles beyond the range of aeolian transport, and absence of mud; (v) stratigraphically inverted OSL dates; and (vi) housing of the lower unit within the incised Morava valley.

Bed lateral continuity and dominance of graded beds strongly argue that sediment was rapidly deposited from suspension and in a quiet water setting, as would characterize a coarse-grained turbidity current. Localized cross-strata and planar laminae could represent fluvial processes, but could also represent traction transport associated with turbidity currents (e.g., Eyles et al., 1987; Zavala et al., 2011). The frosted and rounded sand grains and the absence of mud argue for an aeolian history for the sand, but the presence of grain sizes beyond the transport capacity of the wind also indicates grains transported by fluvial processes. The inverted OSL ages are best reconciled as representing an unroofing process, in which strata were slumped and transported en masse without bleaching from sunlight. Fluvial undercutting and subsequent slumping of aeolian strata, which gives rise to sandy sediment-gravity flows composed of aeolian (mostly) and fluvial sediments (c.f., Luzón et al., 2012), substantially explain the nature of the deposits. However, reconciling the lack of subsequent current reworking and sunlight bleaching of the deposits with a braided stream environment is difficult. However, all depositional aspects of the lower unit of the Bzenec sand body, including its housing within the incised valley, are addressed where fluvial undercutting of older aeolian strata and generation of sandy turbidity currents occur within a quiet-water lake. Beginning with damming of a braided stream and a valley-fill consisting of aeolian dunes and their strata, rising lake level and slumping (without bleaching) of the aeolian strata would lead to the progressive unroofing of the aeolian strata and its redeposition as turbidites. As addressed below (Section 5.3), this interpretation requires a (i) downstream

Fig. 7. Preserved remnant of the upper portion of the section at the Bzenec–Přívoz sand quarry (Section 2). (1) Aeolian cross-stratified unit, removed to the left by more recent scour. OSL date for this unit is 18 ± 4 ka (SPE in Table 1). (2) Ripple-to-dune scale cross-stratified sand with sandy gravel beds, interpreted as braided stream deposits. (3) Normally graded sand beds similar to the primary section (Fig. 6).

Fig. 8. Measured section at the Morava River meander cut (Section 3). OSL sample and date indicated by stratigraphic position. Upper 90 cm of structureless sand and pebbly sand is pedogenic and may be of fluvial origin. Beds consist of normally graded gravelly coarse to fine sand (1), structureless fine or medium sand (2), cross-stratified medium sand (3), structureless fine sandy gravel (4), and medium to coarse sand with wavy laminae of possible cryogenic origin (5).
dam and (ii) a climate that fostered a fluvi-oaeolian environment within the Morava River valley.

Age of emplacement of the Bzenec sand body can be bracketed from the OSL dates. Dates for the aeolian upper unit of 18 ± 4 ka (Section 2) and 18 ± 2 ka (Section 4), and for the middle braided fluvial unit of 17 ± 2 ka (Section 4) indicate that emplacement of the lacustrine turbidites had ended by 19 ka. The youngest ages of the basal lacustrine turbidites is 19 ± 2 ka (Section 4), which can be taken as representing the age of contemporaneous dunes or the youngest dune strata slumped and transported without bleaching. Strictly by error bars, therefore, the lake and its filling are bracketed as between 21 and 19 ka. The oldest age for the turbidites derived from aeolian sands is 36 ± 3 ka (Section 2), which is in agreement with the interpretation made above (Section 4.1) that braided stream and aeolian dune environments were contemporary environments within the Morava River valley by 40 ± 5 ka. The apparent brief reestablishing of braided stream environments (middle unit) in the area of the Bzenec sand body by 19 ka was followed by widespread aeolian dune fields over the Bzenec sand body and deposition of the upper aeolian unit until general stabilization ~13 ka.

4.3. PW-1 core (Section 6 on Figs. 2–3)

The relict meander bends that truncate the Bzenec sand body are direct evidence for the onset of meandering streams within the Morava River valley after emplacement of the Bzenec sand body. The elevation of the modern floodplains is 165 m in this area, the uppermost preserved braided stream deposits (Section 4) are at 185 m, thus indicating incision of at least 20 m. A geophysical resistivity survey and push-coring were performed at an abandoned meander bend (Section 6 on Figs. 2–3) in order to estimate incision depth below the modern floodplains and age of the sediments contained within the relict meander bend. The resistivity survey showed that depth to interpreted Neogene bedrock is 10 m, but this thickness may include deposition within the abandoned meander and yet older Pleistocene stream deposits (see Section 4.2.5 above). Coring was possible to only 3.34 m, and this section consisted of (from top to bottom): (i) 194 cm of organic material interpreted to have originated within the current floodplains, (ii) 104 cm of interpreted fluvial sand, and (iii) 36 cm of organic material underlain by sand, which is interpreted to represent the abandoned meander-bend environment. The ASM radiocarbon calibrated age for the basal organic material is B.C. 11,162–10,776 years (13,112–12,726 YBP), which is taken as the age for the presence of a meandering system in the area.

As evident in Fig. 3, the scale of the abandoned meander bends are significantly greater than those of the modern Morava River. These outsized relict bends appear similar to many reported for temperate latitude rivers during the period from 14,000 to 9,000 YBP (Knox, 1995). Given that downcutting ~20 m occurred with emplacement of the relict meander bends, it is reasonable to assume that these meandering streams transported large volumes of water and sediment. Using the preserved portions of 16 bends in the area and Google Earth Pro, we estimate radii of curvature ranging between 250 and 761 m, with a geometric mean value of 461 m. The same analysis performed on 12 bends of the modern Morava River yields radii of curvature ranging between 212 and 244 m, with a geometric mean value of 217 m.

Estimating discharge for the paleochannels requires a measure for bankfull channel width and an appropriate set of equations describing the hydraulic geometry of sand-bed rivers (Wilkinson and Parker, 2011). Channel paleowidth is estimated in two ways. The first is directly from satellite images where seven measurements of paleowidth range between 87 and 189 m, with a geometric mean value of 135 m. The second method uses a characteristic value for the ratio of bend radius of curvature to channel width and the estimates of bend size reported...
Fig. 12. GPR surveys across stabilized aeolian dunes, as indicated in Fig. 3. Internal cross-strata conform to the subdued dune asymmetry and show dune transport to the east. The cross-strata within the relict dune forms are separated from older cross-strata by a bounding surface at the level of the interdune area. Dunes are stabilized by vegetation and occur within a forest.
above. Williams (1986) assembled a large data set demonstrating that all values for the ratio of bend radius of curvature to channel width are between 1 and 7, with the central two-thirds of the distribution falling between values of 1.6 and 3.4. Because this range is broad, we determined the ratio for the modern Morava River and applied this to the relict bends and channels. Fifteen measurements of bankfull channel width for the modern river range between 60 and 72 m, with a geometric mean value of 65 m. This value for channel width applied to the 12 modern bends yields a geometric mean value for the ratio of bend radius of curvature to channel width of 3.34, a value that is consistent with the earlier summary analysis of Williams (1986). This value for the ratio of bend radius of curvature to channel width applied to the 16 paleobends yields an estimated geometric mean value for paleochannel width of 138 m, surprisingly close to the 135-m estimate derived from measurement of the smaller set of preserved channel fragments.

Accurate estimates of paleodischarge using hydraulic radius relationships also require a measure of grain size for the channel-bed material. We assumed that the median size for the >20-m-thick section of the Bzenec sand body being mined by the paleochannel is a reasonable estimate for the characteristic size of its bed material. Numerous grain size samples from the Bzenec sand body yield a median grain size of 300 μm. Applying this grain diameter and a channel width of 137 m to the hydraulic geometry relationship of Wilkerson and Parker (2011) yields a best estimate for paleodischarge of 577 m³/s. The Wilkerson and Parker (2011) hydraulic geometry relations were also applied to the channel width and grain size for the modern Morava River, yielding an accurate estimate for bankfull discharge of 180 m³/s. Apparently, the meandering river system that developed during the late Pleistocene and incised through the Bzenec sand body had a bankfull water discharge 3.2 times greater than the modern Morava River.

4.4. Boršice gravel quarry (Section 7 on Fig. 2)

The Boršice gravel quarry is the only exposure upstream of the Bzenec sand body in the Lower Moravian Basin (Fig. 2). Within this upper portion of the Lower Moravian Basin, the Morava River valley is incised into alluvial fans issuing from the adjacent Carpathian Mountains (Fig. 1). The 3.8-m exposure, with an upper elevation of 207 m, consists of (i) an upper unit 1.3 m thick and consisting of crinkly, thinly bedded (1–2 cm) silty fine sand with uncommon medium sand laminae and (ii) a lower unit 2.5 m thick and consisting of sandy gravel with angular clasts up to cobble size (Fig. 14). The contact between the two units is scoured and shows a highly deformed clay and gravel horizon (Fig. 14). An OSL date from near the base of the upper unit is 21 ± 3 ka (Fig. 14, Table 1), thus contemporaneous with the Bzenec sand body, although the elevation is over 20 m higher. The lower unit clearly represents alluvial fans truncated by the Morava River and can be traced laterally into relict fan morphology. In adjacent areas of this abandoned quarry, several additional meters of beds
of conglomerate and dune-scale, cross-stratified sand are exposed. Given the OSL age near the LGM, the deformed horizon separating the lower and upper units is interpreted to result from cryoturbation of a paleosol developed on the alluvial fan deposits. The upper unit, however, is enigmatic on three levels. First, the absence of any well-defined structures such as ripple cross-strata limits interpretation of deposition processes. However, settling from suspension within a lake, with a probable loess component, is compatible with the thin bedding; and the crinkly appearance argues for post-depositional cryogenic processes. Second, although the age is compatible with the Bzenec sand body, the exposure is isolated and cannot be traced laterally into the Bzenec sand body. Third, although the thinly bedded strata are over 20 m higher in elevation than the lacustrine beds of the Bzenec sand body, these strata could represent deposition within the upper reaches of the lake. However, tectonic uplift could account for elevation differences in the exposure is isolated and cannot be traced laterally into the Bzenec sand body. Third, although the thinly bedded strata are over 20 m higher in elevation than the lacustrine beds of the Bzenec sand body, these strata could represent deposition within the upper reaches of the lake. However, tectonic uplift could account for elevation differences in the upper unit, which ranges in thickness from 3.8 m in the SE to 1.3 m in the NW. An OSL age from the upper bed of the lower unit is 61 ± 6 ka.

In contrast to the clay-rich lower unit, the upper channel unit is a pebbly fine- to coarse-grained sand with a notable absence of mud. Channel-fill architecture consists of (i) basal beds, with apparent preserved bar forms, that progressively thin and onlap the rising channel base; (ii) downlapping beds from the SE that laterally yield to dune-scale cross-strata; (iii) downlapping beds from the NW; and (iv) final trough-fill in the channel center (Fig. 15). Finer scale structures within the beds consist of shallow scours, low-angle truncations, parallel laminations, pronounced grain-size segregation, and ripple-scale cross-strata. The ripple-scale cross-strata typically show critical or super-critical climb where these occur in the sheltered lee of larger bar forms. An OSL age from the upper unit is 48 ± 4 ka (Fig. 15, Table 1).

Although the deposits at the Pouzdřany sand quarry well pre-date the Bzenec sand body, the section is significant in defining a change in fluvial styles within the greater Morava drainage network. The muddy, stratified lower unit is interpreted to represent floodplain deposition, with the thin cross-stratified unit representing a probable cravasse-splay. This mud-rich floodplain is most compatible with a meandering or anastomosing fluvial system and stands in marked contrast to the sandy channel unit with its absence of mud. The channel-fill architecture of basal onlapping, then downlapping from alternate sides, with final channel-center fill distinctly represents undercut units (ranging from 0.5 to < 1 m in thickness) within the overall channel, in which none of the units extends over the depth of the channel. The overall character of the upper channel unit is best interpreted as a braided stream, but one in which the initial channel was subsequently occupied and filled by undercut streams and bars. Given the braided stream interpretation of the channel fill, the undercut nature of the fill units, and the absence of mud, the overall channel morphology seems best

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Fig. 14. Exposure at the Bořislíce gravel quarry (Section 7). Upper unit (1) of crinkly laminated silty sand of probable lacustrine origin with cryogenic deformation overlies a scoured and highly deformed clay and gravel horizon interpreted to represent cryogenic deformation of a soil zone. The underlying unit (2) is a sandy gravel with clasts up to cobbly size of alluvial fan origin. OSL sample and date for the upper unit indicated.

Fig. 15. Sketch of the exposure at the Pouzdřany sand quarry (Section 8) constructed from measured sections (vertical arrows at section top) and photomosaic, showing the lower unit, upper channel unit, and overlying Holocene soil zone (slope sandy loam with scattered pebbles). The lower unit, interpreted as floodplain deposits, consists of (1) clayey silt beds alternating with horizontally bedded medium sand, (2) cross-stratified medium sand interpreted as a crevasse-splay, (3) fine silty sand with pedogenic root structures, (4) structureless medium sand intercalated with silty laminae, and (5) laminated medium sand. The upper channel unit, scouring ~5 m into the lower unit, consists of pebbly fine to coarse sand showing shallow scours, low-angle truncations, parallel laminae and ripple-scale cross-strata. Mud is absent from the channel-fill. The larger channel-fill architecture consists of (1) basal beds with preserved bar morphology that onlap the rising channel surface (arrows), (2) downlapping beds from the SE (dotted arrow), (3) downlapping beds from the NW (dashed arrow), and final trough-filled center. Note that the architectural elements are underfit in scale with none extending over the entire channel depth. Note location of OSL samples and their ages.
interpreted as a larger inherited (i.e., antecedent) meandering channel that was subsequently occupied and filled by underfit braided streams. This interpretation envisions that with climatic or other changes that cause the change from meandering to braided streams, existing channels will be initially occupied by the new style of fluvial systems. Based upon the OSL date in the lower portion of the section at the Bažantnica sand quarry (Section 1), braided stream conditions were given as existing within the Morava River valley by 40 ± 5 ka. To the east in the Bzenec area, Petrová et al. (1999) cited braided-stream deposition as occurring within the basin since 46.75 ± 3.94/−2.63 ka. This age is comparable to the 48 ± 4 ka for the onset of braided stream conditions at the Pouzdřany sand quarry.

5. Summary and discussion

5.1. Climatic-driven environmental succession within the Morava River valley

Fig. 16A summarizes the sections within the Morava River valley by age, and although the number of outcrops and ages are relatively few, a broad succession of environments emerges. The transition from probable meandering/anastomosing to braided fluvial systems (Section 8) occurred between 61 ± 6 ka and 48 ± 4 ka, or within MIS 3. Braided systems then characterize the Morava River valley through glacial MIS 2 and the LGM (Sections 1, 4), with a return to meandering conditions.

Fig. 16. (A) Summary of sections by age, with dates (sample names) grouped by depositional environment. See Section 5.1 for discussion. (B) Summary of sections by elevation with OSL dates (sample names) in stratigraphic position. Stratigraphic columns are also labeled by depositional environment. Note profile of the modern Morava River. See Section 5.2 for discussion. (C) Diagrammatic interpretation of the contemporaneous environments during the LGM, consisting of downstream dam formed by braided terminal fan and aeolian dune complex (Section 1), and upstream lake filled by turbidites (Sections 2–4). Extent of lake is conjecture. Note vertical exaggeration of 60×. See Section 5.3 for discussion.
by ~13 ka (Section 6). The ages of the turbidite sands of an interpreted aeolian origin (Sections 2, 3, 4), the cross-stratified aeolian units (Sections 1, 2, 5, Sajdikove Humence), and the rounded and frosted sand grains within braided stream deposits (Section 1) argue that aeolian dune fields coexisted with the braided fluvial systems from at least 40 ± 5 ka and persisted through the end of the Pleistocene. Although periodic reactivation of the stabilized dunes on the Bzenec sand body is reported from historical accounts, a general stabilization of active dune fields by vegetation by 13 ± 2 ka (Section 5) is coincident with the transition from braided to meandering streams by ~13 ka, and both are credited to the onset of a distinctly wetter climate. Strict bracketing of error bars for dates of the lake and turbidite deposits within the Morava River valley constrain the lake as a relatively short-lived LGM feature between 21 and 19 ka (i.e., error bars for BZ2, BZ4).

The succession of environments within the Morava River valley broadly parallels a common succession documented in much of northwestern and central Europe and is interpreted as climate-driven. Although not without exceptions, fluvial systems during MIS 3 have been generally characterized as ephemeral anastomosing with braided patterns emerging during glacial MIS 2 after 25 ka (see review in Mol et al., 2000; Kasse et al., 2007). Braided stream conditions, however, characterized the Morava River valley by 48 ± 4 ka (MIS 3), and a fluvi-aeolian system is evident throughout the valley during later MIS 3 and MIS 2 (Fig. 16A). The earlier onset of braided streams within the Morava River valley may reflect earlier climatic change at the higher uplift elevation, in comparison to the better studied examples from The Netherlands, Germany, and Poland (Mol et al., 2000; Kasse et al., 2007). Regional arid, periglacial conditions occurred during the LGM (e.g., Tyrš, 1995; Hubberten et al., 2004) with dominance of fluvi-aeolian systems (Mol et al., 2000; Kasse et al., 2007), loss accumulation (Frenchen et al., 2003), and development of aeolian deposits (Older Coversand I; Kasse, 2002; Kasse et al., 2007). The change in the fluvial systems of the Morava River valley from braided to meandering at ~13 ka is seen regionally (Mol et al., 2000).

5.2. Depositional/erosional pattern within the Morava River valley

Fig. 16B summarizes the sections along the Morava River valley by elevation. Foremost, as seen from the profile of the modern Morava River and elevations of the Pleistocene sections, the preserved sections are erosional remnants bypassed during fluvial incision during the latest Pleistocene. This incision with the onset of meandering systems beginning at ~13 ka, commonly with outsized meander belts, is widely documented regionally (Knox, 1995; Mol et al., 2000). Controls on fluvial aggradation vs. incision, and meandering vs. braided systems include fluvial discharge, sediment supply (including controls by permafrost), and vegetation, with most change in fluvial systems occurring at periods of climatic change (see discussions in Bridge, 2003; Mol et al., 2000; Schumm, 1977; Vandenberghhe, 2003). For the Morava River valley, aggradation occurred during braided fluvi-aeolian conditions during glacial times of aridity and low, probably seasonal, fluvial discharge. Incision occurred with meandering streams with the onset of a warmer, wetter climate with greater fluvial discharge, as evident by the broad relict meander bends seen in Fig. 3. Especially considering the interpretation of a terminal fan in the Lower Morava Basin (Section 1), the cumulative control is most simply viewed as the water-to-sediment discharge ratio. Aggradation occurred during a period of a low water-to-sediment discharge ratio when fluvial discharge was insufficient to transport the supplied sediment out of the valley, culminating in the formation of a downstream terminal fan. Incision occurred during a period of a high water-to-sediment discharge ratio, when water was sufficient to transport large volumes of sediment and incise the valley-fill. After incision of more than 20 m, the Holocene meandering system is thought to have relaxed to the Holocene pattern of smaller meander bends, with relatively low aggradation rates (Kadlec et al., 2009).

5.3. Origin of the Lower Morava River valley lake during the LGM

The interpretation of the lower unit of the Bzenec sand body as largely emplaced by sandy turbidites derived through slumping of aeolian strata within a river valley lake requires a climatic environment conducive for lake formation and a downstream dam (see Section 4.2.6). In terms of the climatic regime, as given in Fig. 16A, the lake is bracketed within the latter part of the LGM and is contemporaneous with the fluvio-aeolian system that occupied the valley. As discussed above, this period would have been a time of cold aridity with greatly reduced, probably seasonal, fluvial discharge. Damming of fluvial valleys to give rise to relatively short-lived lakes could occur with a variety of causes including ice-damming during glacial times (e.g., Mangerud et al., 2004) or tectonic movement or associated landslides in mountainous terrains (e.g., Adams, 1981). However, no geomorphic or tectonic evidence is evident for lake creation in the area of the Bzenec sand body, including at the confluences of the Morava and the Dyje and Danube rivers. Stratigraphically, however, the age of the lake is the same as the interpreted terminal fan and overlying aeolian dune complex downstream at Section 1 (Fig. 16A), and the terminal fan and dune complex occur at an elevation ideal for a dam (Fig. 16B). Based upon these age and elevation data, the lake is interpreted to have originated upstream of the dam complex created by the terminal fan and the dunes (Fig. 16C). In this model, although fluvial discharge was reduced to nil downstream at the terminal fan during this arid period and the dune field complex formed across the entire valley, at least seasonal discharge continued upstream in the more confined valley in the Bzenec area. With downstream damming, the upstream braided stream gave rise to a lake with fluvial undercutting, slumping and unroofing of aeolian strata housed within the valley. The lake was terminated probably by breaching of the downstream dam, and braided stream discharge resumed (middle unit of the Bzenec sand body). As evident in Fig. 16B–C (i.e., elevation differences of fluvial deposits overlying the turbidites in Sections 3–4), this resumption of fluvial discharge scoured upper portions of the lower unit. The overall fluvio-aeolian system then continued until ~13 ka with widespread aeolian deposition spreading from the valley to elevations over 200 m (Sections SH and 5).

Few details of the morphology of the lower turbidite unit of the Bzenec sand body or the lake that housed it within the Lower Moravian Basin can be determined because of the fragmentary preservation of the sand body. The turbidites may have been deposited on a prograding deltaic structure or simply represent deposition within the scoured valley. Although the highest elevation of the lake turbidites is 184 m within the Bzenec sand body, water depth must have reached higher elevations. No evidence for wave or other shallow-water reworking of the turbidites occurs, but the intermountain basin provided a sheltered environment and the possibility that lake surface was ice-covered cannot be discounted in this periglacial environment. Spatial extent of the lake within the Lower Moravian Basin valley is also unknown. Regional drill-hole data show a thinning sand body extending over 25 km downstream from a maximum thickness in the Bzenec area, but it is not possible to determine if these represent lake deposits. However, the interpreted shallow lacustrine deposits at the Boršice gravel quarry (Section 7, 207 m elevation) may represent the upper lake level (see Section 4.4). In addition, horizontally bedded sediments interpreted as fluvial lacustrine in origin have been described near Milotice, 10 km west of Bzenec at an elevation of 180–190 m (Zeman et al., 1980). Small isolated occurrences of lacustrine deposits have also been identified in the Dyje River catchment near Dolní Věstonice and Nové Město (Brčák, 1970; Zeman et al., 1980) at elevations of 180 m, with the age of the deposits at Nové Město given as Late Glacial based upon mollusk content (Blízová et al., 1997). Potentially, all of these lake sediments belong to the same lake system.

The Lower Moravian Basin lake represents the specific case of lacustrine turbidite deposition within a periglacial lake housed within a fluvial valley, in which the downstream dam consists largely of aeolian
dunes and the turbidites are derived from slumping of aeolian sands. Although an exactly analogous example was not found in the literature, component aspects are well documented. Lacustrine turbidites are well known (e.g., Houbolt and Jonker, 1968; Lara and Sanders, 1970), including those in glacial or periglacial environments (e.g., Church and Gilbert, 1975; Gruszka, 2007; Sauerbrey et al., 2013). Examples of dune-dimming of fluvial channels include those from the Pleistocene and Holocene Nebraska Sands Hills (Loope et al., 1995; Muhs et al., 2000) and the Holocene of the Lake Superior area (Loope et al., 2004).

6. Conclusions

The late Pleistocene and Holocene geomorphic and stratigraphic record of the Morava River valley shows the response of fluvial systems to climate-driven changes. Muddy meandering or anastomosing systems were replaced by braided systems during the overall cooling trend of MIS 3 at ~48 ka. The onset of braided systems is earlier than seen in most systems in northwestern and central Europe and may reflect climatic trends at higher elevations. Braided fluvo-aeolian systems persisted through MIS 2 and the LGM within an arid periglacial climate characterized by greatly reduced and probably seasonal fluvial discharge. Valley aggradation occurred with braided streams that had a low water-to-sediment discharge ratio, and aeolian dune fields extended from the valley to flank adjacent upland slopes. At ~13 ka valley incision of ~20 m occurred with emplacement of a meandering system. Incision is interpreted to have occurred because of greatly increased fluvial discharge with a wetter climate, which is also evident in general increases in aeolian sands and coversands of the type locality Grubbenvorst (southern Netherlands). During the Younger Dryas cold spell, the Younger Dryas cold spell — a quest for causes. Glob. Planet. Chang. 21, 219–237.


Gruszka, B., 2007. The Pleistocene glaciolacustrine sediments in the Bečov nad Teplou oduio-aeolian system representing perhaps the largest preserved fluvi-aeolian system represented largely of laterally continuous, thin, normally graded beds of sands showing rounded and frosted grains of an aeolian origin. The Bzenec sand body represents perhaps the largest preserved fluvi-aeolian system characterized by larger channel bends and channel widths, with an estimated bankfull discharge that was 3.2 times greater than the modern Morava River. After this incision with the onset of a more temperate climate, the Holocene meandering system has been characterized by smaller meanders and relatively low rates of floodplain aggradation.

The MIS 2 and LGM valley-fill occur as fragmentary erosional remnants bypassed during incision by the latest Pleistocene meandering system. The Bzenec sand body represents perhaps the largest preserved erosional remnant within the Lower Moravian Basin. The lower unit of the sand body consists largely of laterally continuous, thin, normally graded beds of sands showing rounded and frosted grains of an aeolian origin. The beds are interpreted as lacustrine turbidites derived through fluvial undercutting and subsequent slumping of aeolian accumulations. This interpretation is supported by inverted OSL ages of the beds, consistent with unroofing processes. Error-bar bracketing of OSL ages dates constrain the lake to 21–19 ka or within the latter part of the LGM. The age and elevation of the lower unit are the same as those of a downstream interpreted braided-stream terminal fan and aeolian-dune complex, which are believed to have formed the dam for the lake during a period of low fluvial discharge. Because of the fragmentary stratigraphic record, the depth and lateral extent of the lake are unknown, but isolated outcrops suggest a widespread lacustrine setting within the valley. This short-lived lake was apparently lost with dam breaching and reestablishment of a final fluvo-aeolian system represented by the braided-stream middle and aeolian upper units of the Bzenec sand body.

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