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# Sedimentary evidence for an ice-sheet dammed lake in a mountain valley of the Eastern Sudetes, Czechia

MARTIN HANÁČEK[1],*, DANIEL NÝVLT[2,3], ZUZANA SKÁCELOVÁ[3], SLAVOMÍR NEHYBA[1],
BARBORA PROCHÁZKOVÁ[4] and ZBYNĚK ENGEL[4]

[1] *Department of Geological Sciences, Faculty of Science, Masaryk University, Kotlářská 267/2, 611 37 Brno, Czechia*
[2] *Department of Geography, Faculty of Science, Masaryk University, Kotlářská 267/2, 611 37 Brno, Czechia*
[3] *Czech Geological Survey, Klárov 3, 118 21 Praha, Czechia*
[4] *Department of Physical Geography and Geoecology, Faculty of Science, Charles University in Prague, Albertov 6, 128 43 Praha, Czechia*
**corresponding author*

## ABSTRACT:

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An accumulation of glacial sediments is located near Písečná village in the depression between the Sokol Ridge and Zlaté Hory Highlands NNE of Jeseník town (Eastern Sudetes). The accumulation lies at the lateral side of the mountain valley of the Bělá River and fills a preglacial palaeovalley of this river. Research combining facies analysis of outcrops, ground penetrating radar survey, interpretation drilling survey, and modelling of the preglacial relief was undertaken at the site. According to the results obtained, the upper part of the sedimentary accumulation represents a coarse-grained terminoglacial glaciofluvial delta of the Gilbert type. The development of the accumulation has dominantly been driven by the preglacial morphology. Facies typical for foresets of coarse-grained deltas represented mainly by high-density flows, cohesionless debris flows, debris falls and less common low-density flows were found in the outcrops. The delta near Písečná prograded into a lake dammed by the ice-sheet front in the north. The lake was bounded by the slopes of Sokol Ridge, Zlaté Hory Highlands and Góry Parkowe on other sides. The lake level reached an altitude of up to 430 m a.s.l., as the coarse-grained delta plain base lies at this level.

**Key words:** Terminoglacial glaciofluvial Gilbert-type delta; Foreset facies; Preglacial morphology; Ice-dammed lake; Pleistocene; Central Europe; Písečná Site.

## INTRODUCTION

Terminoglacial depositional basins evolved in front of the ice sheet in the Sudetes Mts. during the mid-Pleistocene continental glaciations. They were bounded by rising landscape to the South and by an ice sheet front to the North. Diverse depositional environments evolved in these basins, the origin of which was dependent on the landscape morphology, ice sheet front behaviour, amount of thawing water and availability of clastic material. Important phenomena of these basins have also been ice-dammed lakes.

In the easternmost part of the Sudetes Mts. with a less rugged landscape (the Opava Mts.) shallow temporal lakes evolved located in the original wide river valleys dipping towards the ice sheet. The only barrier damming the lake formed the ice sheet front which embraced the corresponding valley (Salamon 2008a, b). These lakes were quite shallow in many cases, therefore no proglacial deltas evolved along their margins (Salamon 2008a). Larger and longer lasting lakes with considerable deposition from suspension have been described from the morphologically similar but less dynamic foothills of the Nízký Jeseník Mts. and the Eastern Sudetes (Macoun *et al.* 1965). Moderate shallow lakes evolving on the proglacial outwash plain are also known from the Moravian Gate. These lakes, however, were not dammed by ice, as they originated in the late deglaciation phase (Nývlt *et al.* 2008).

The western part of the Eastern Sudetes Mts. and the Central Sudetes Mts. are characterised by a more dynamic mountainous landscape. Hence, the lakes here evolved in various conditions. The distant Sudetic Foreland in southern Poland is rather flat; therefore the prerequisites for lake origin were similar to those applying in the hilly Opava Mts. and the Nízký Jeseník Mts. The lakes evolved here in ice sheet dammed river valleys and landscape depressions (Przybylski 1998; Salamon *et al.* 2007, 2013), or on kame terraces between the ice sheet margin and margins of river valleys partly filled by an ice sheet (Pisarska-Jamroży *et al.* 2010). These lakes were small, shallow and temporal. The ice sheet blocked V-shaped river valleys situated at the foothills directly below, or between individual mountain ranges. An ice sheet front and steep valley sides have thus delimited the rising basins. Deep mountain terminoglacial lakes evolved in these depressions (Kowalska 2007; Krzyszkowski 2013). Similarly disposed deep lakes existed in the mountain relief of the North American Cordilleras (Johnsen and Brennand 2006), or in the hilly landscape of the Weser Mountains (Winsemann *et al.* 2004, 2007, 2009).

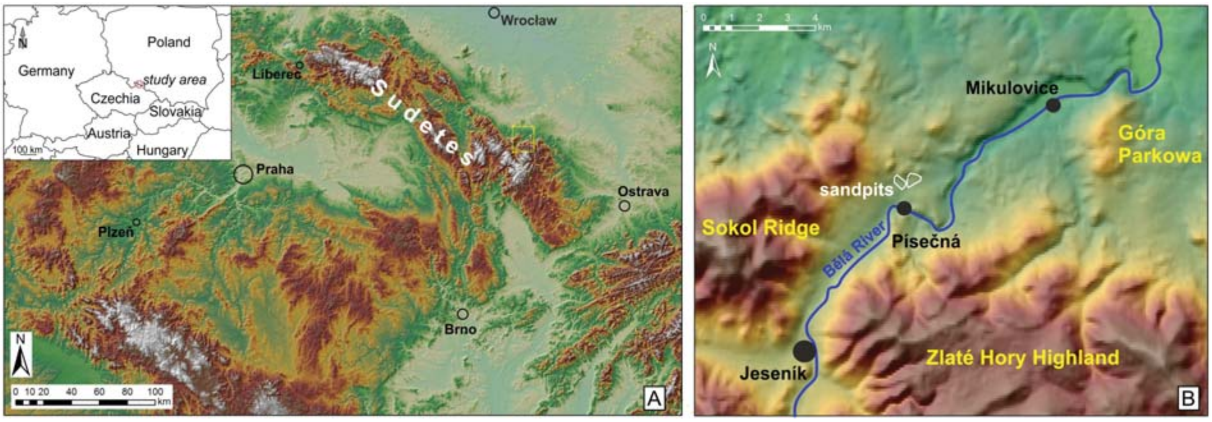
Lakes located in hilly landscape of the Sudetic Foreland originated in different phases of glaciation. The first example represents lakes evolving along the front of the advancing ice sheet, which had covered the lacustrine basins entirely after these had been filled by sediments (Salamon *et al.* 2013). In the second example, the lakes bordered the ice sheet when the front stopped in the Otmuchów depression and did not reach the Sudetes Mts. (Przybylski 1998; Salamon *et al.* 2007). Terminoglacial lakes in the mountain landscape of the Sudetes Mts. evolved during the maximum extent of the ice sheets in this area (Kowalska 2007; Krzyszkowski 2013). The stratigraphic ranking of glaciations, which invaded the mountain range of Central and Eastern Sudetes (the Góry Sowie Mts., the Rychleby Mts. and the Zlaté Hory Highlands), is a matter of discussion (Krzyszkowski 2013). The latest studies correlate the maximum advance of the ice sheet in this region with the Elsterian (Nývlt *et al.* 2011), whilst the first Saalian (Odra, Drenthe) ice sheet front stopped along the Nysa Kłodzka river valley (Przybylski 1998).

Varves are traditionally regarded as the main proof of the glaciolacustrine environment. On the other hand coarse-grained lake sediments of subaqueous fans and deltas were often interpreted as glaciofluvial, or kame sediments (Winsemann *et al.* 2007). This is also the case for the Písečná site, the sediments of which were also regarded as subaerial (Gába 1981; Prosová 1981). The new research at the Písečná site combines the facies analysis of outcrop, ground penetrating radar (GPR) survey, facies interpretation of a drilling survey, modelling of the preglacial relief, and re-interpretation of the available data in the light of present literature. This lead to a new interpretation of the Písečná site as a glaciolacustrine subaqeous fan and coarse-grained delta. Therefore, the site brings together evidence for the existence of a mountain lake dammed by an ice sheet.

## GEOLOGICAL SETTING

The glacial sediments studied are located along the northern foothill of the Eastern Sudetes Mts (Text-fig. 1A). They lie between the Sokol Ridge (easternmost part of the Rychleby Mts.) and the Zlaté Hory Highlands (Text-fig. 1B). The valley of the Bělá River flowing from the Hrubý Jeseník Mts. towards Poland lies between the two above-mentioned geomorphological units. The palaeo-Bělá River started to erode the valley already in the Neogene (Cháb et al. 2004). The river flows along the contact of the Sokol Ridge and the Zlaté Hory Highlands in southwestern part of the valley. The slopes of the valleys are covered by colluvial sediments (Text-fig. 2). The river turns suddenly to the east and later to SSE at Písečná village. The river loop is evidently related to neotectonic movements along the NW-SE trending fault. The river subsequently follows the foothills of the Zlaté Hory Highlands, where a wide valley with well-developed fluvial terraces can be found. The area west of the river valley is relatively upthrown and protected thus from fluvial erosion (Cháb *et al.* 2004; Žáček *et al.* 2004).

The study area is composed mainly of metamorphic complexes of Neoproterozoic to Devonian age



Text-fig. 1. A – Ortophotomap of the Bohemian Massif and Outern Western Carpathians with the study area delimited. B – Bělá River Valley in Eastern Sudetes Mts

(paragneisses, orthogneisses, quartzites, phyllites, schists, marbles and amphibolites; Cháb *et al*. 2004). The Variscan Žulová Massif lies north-west and north of the depression between the Sokol Ridge and Zlaté Hory Highlands (Sawicki 1995; Žáček *et al*. 2004).

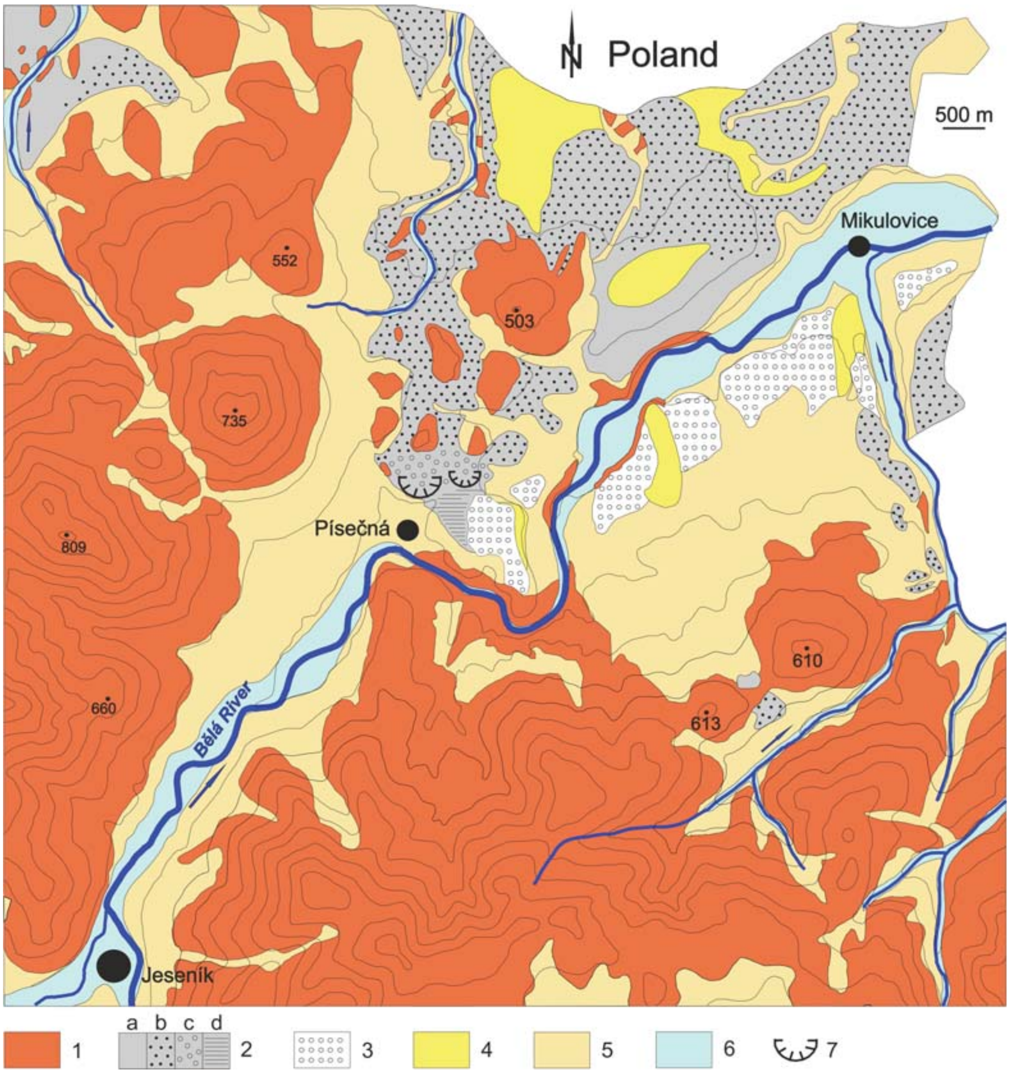
Continental glaciation sediments are preserved at two places in the study area (Text-fig. 2). The first consists of relics in the Zlaté Hory Highlands, where subglacial tills are preserved near a col (between height points 613 and 610 m) at an altitude of 530–545 m. The tills together with glaciofluvial sediments of a gravely-sandy terminoglacial fan were described at an altitude of 485–545 a.s.l. in the adjacent valley (Gába 1972; Prosová 1981; Cháb *et al*. 2004; Hanáček 2011, 2012). The second occurrence of glacial sediments is in the western part of the depression between the Sokol Ridge and the Zlaté Hory Highlands north of Písečná village, these rising as a plateau above the incised valley of the Bělá River. The sediments have been preserved here from post-glacial fluvial erosion. This accumulation lies mostly in the altitudinal range of 390 and 445 m. a.s.l. Glaciofluvial sand and gravel occupy here a relatively continuous large area. They reach a thickness of between 5 and 50 m dependent on the basement morphology and the type of depositional environment (Žáček *et al*. 2004). Sediments of subglacial valleys incised into the bedrock (Gába 1987) and proglacial outwash plains (Hanáček 2012) have been found here. Tills cover a substantially smaller area. They are mostly described as subglacial tills (Cháb *et al*. 2004), however in spite of that ablation till has also been identified here (Gába 1977). The accumulation near Písečná village, which is the point of interest in this study, lies on the contact of the elevated plateau and the Bělá River valley (Text-fig. 2). The stratigraphy of the glacial deposits here is ambiguous. Based on older studies (Gába and Dudziak 1979; Prosová 1981), the sediments are ranked to the Saalian (Drenthe) glacial. Newer studies date the higher-lying relics in the Zlaté Hory Highlands to the first Elsterian glacial and arealy-extensive lower lying sediments on the elevated plateau west of the Bělá River valley to the second Elsterian glacial (Cháb *et al.* 2004; Nývlt *et al*. 2011). Small relics of glaciofluvial sediments ranked to the second Elsterian glacial can also be found on the eastern side of the Bělá River.

Other Quaternary sediments are represented by the Pleistocene fluvial gravel of the Bělá River, and the Weichselian loess loams, Pleistocene to Holocene colluvial sediments and Holocene fluvial deposits of the Bělá River (Cháb *et al.* 2004; Žáček *et al.* 2004).

## THE RECENT KNOWLEDGE ABOUT THE PÍSEČNÁ SITE

The Písečná locality is composed of two neighbouring abandoned sandpits at the northern margin of Písečná village, 7 km NNE of Jeseník town (Text-figs 1B, 3A, 4). The western sandpit lies left of the Písečná-Supíkovice road. The pit has been active since the 1950s to 1980s and represents one of the most important outcrops of continental glaciation sediments in the Czech foothills of the Sudetes Mts. A previous eastern sandpit existed earlier (until 1964) to the right of the mentioned road. Both sandpits were opened in one accumulation of glacial sediments.

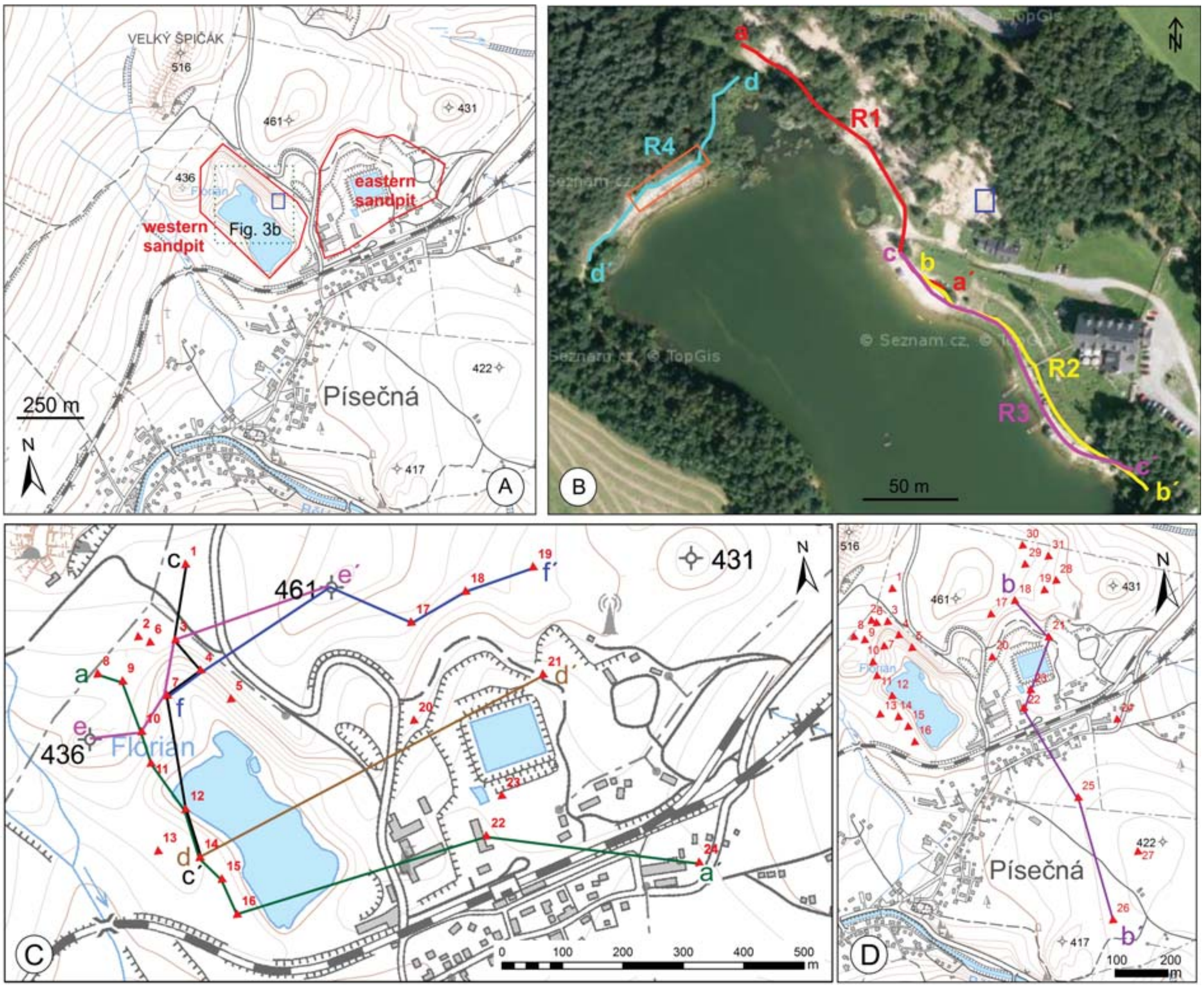
The accumulation is located on the left sideslope of the Bělá River valley (Text-figs 1B, 2, 4), where



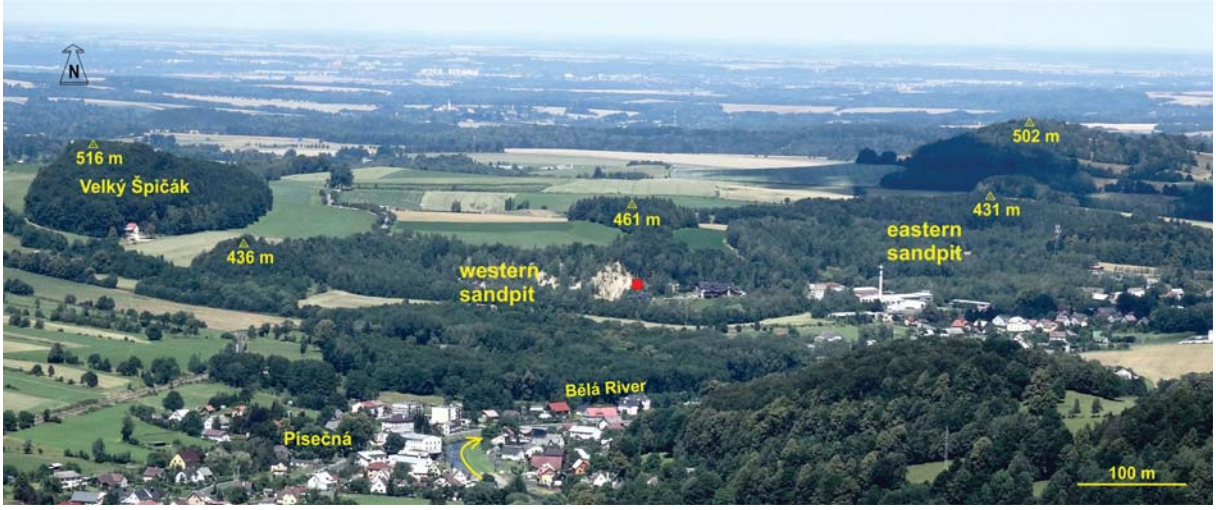
Text-fig. 2. Geological map of the Bělá River Valley. 1 – Pre-Quaternary basement (Proterozoic–Paleozoic metamorphic rocks, Variscan magmatite rocks); 2 – Glacial sediments (a – tills, b – glaciofluvial sediments, c – coarse-grained deltaic sediments, d – fine-grained deltaic and glaciolacustrine sediments); 3 – Fluvial terrace sediments (Middle Pleistocene); 4 – Loess loams (Upper Pleistocene); 5 – Colluvial sediments (Pleistocene–Holocene); 6 – Floodplain sediments (Holocene); 7 – Sandpits near Písečná. Contour interval 50 m. Modified from Otava (1992), Žáček (1995), Cháb *et al.* (2004), Žáček *et al*. (2004) and results presented in this paper

it rests on crystalline basement (complex of amphibolite, paragneiss, quartzite and marble) with a dip of 2–9°, the elevation sloping up to 13–21° (Gába 1981). The bedrock generally dips towards the South. The preglacial Bělá River valley headed northwards, roughly in the middle of the present sandpits, basing on the former drilling survey. Gravelly-sandy to clayey-silty sediments filling a palaeochannel to a thickness of ~17–23 m has been detected below the sandpits' floor. The base of the palaeochannel lies at ~377 m a.s.l. The exploited sediments cover the western slope of the palaeovalley, at 390–440 m a.s.l. and 400–440 m a.s.l. in the western and eastern sandpit, respectively. The thickness of the glacial deposits vanishes promptly on the northern edge of the Bělá River valley, roughly at the line of the southern margin of Velký Špičák Hill at the spot height 461 m. It fades out more slowly on the southern margin and is partly covered by fluvial sediments associated with the middle Pleistocene terrace of the Bělá River (Text-fig. 2).

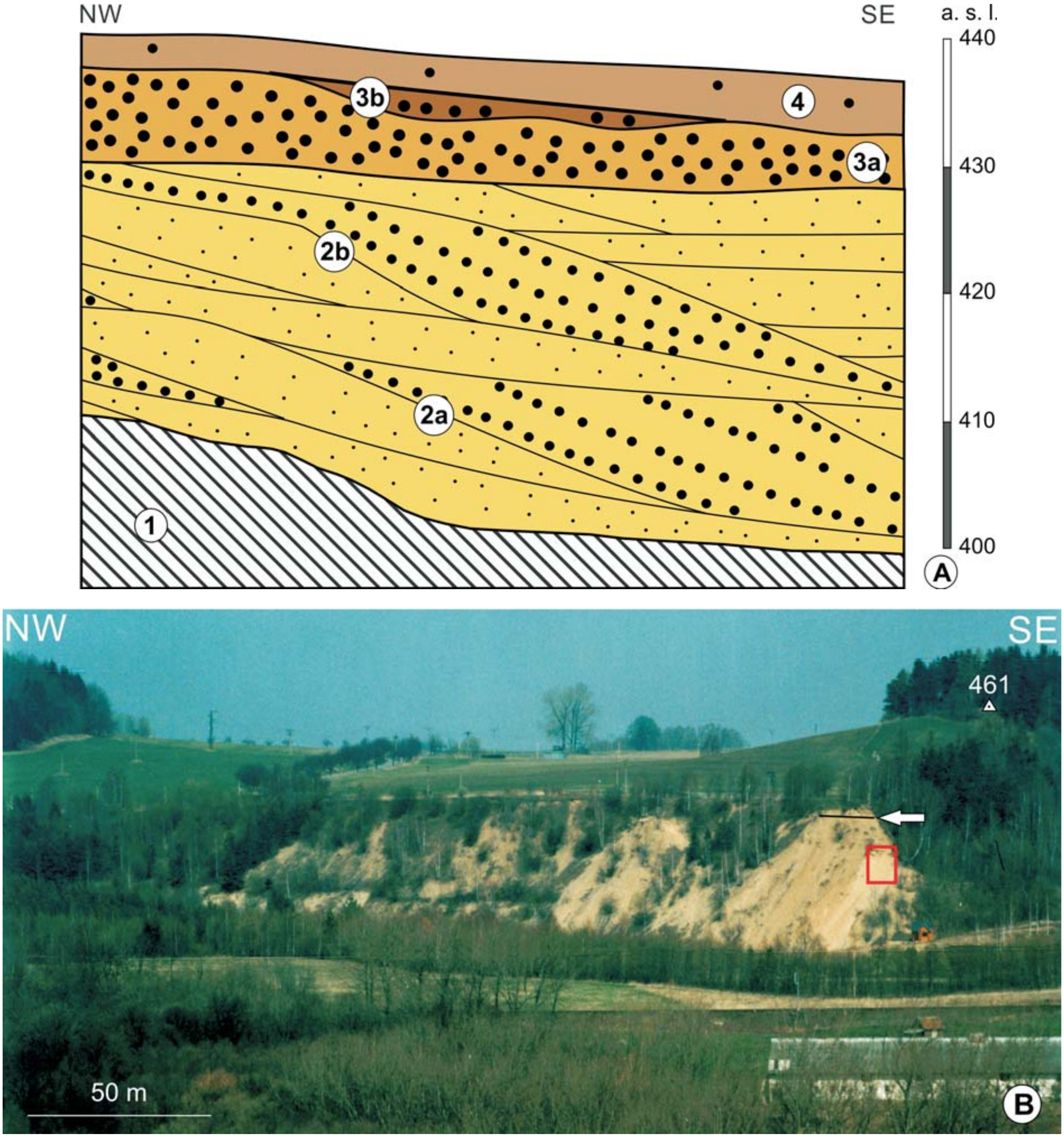
The basic description of the sediments in the western sandpit has mainly been given by Gába (1981), see also Text-fig. 5A. A thin eluvium layer



Text-fig. 3. A – Map of the study area with the location of both sandpits. Blue rectangle represents the section shown in detail in Text-figs 7 and 8. Dotted green rectangle: inset Figure 3B. Contour interval 5 m; B – Map of GPR profiles. Orange rectangle in the R4 track represents a bedrock (amphibolite) outcrop. Blue rectangle represents the section shown in detail in Text-figs 7 and 8; C, D – Maps of the studied drillings and geological cross-sections locations. Contour interval 5 m



Text-fig. 4. View of the study area from the north-western slope of the Zlaté Hory Highlands. Red rectangle represents the section shown in detail in Text-figs 7 and 8



Text-fig. 5. A – Sketch of the sedimentary architecture according to Gába (1981) and its interpretation in this study: 1, Amphibolite bedrock; 2a, Lower foreset (subaqueous fan? slope); 2b, Upper foreset (Gilbert-type delta slope); 3, Gilbert-type delta topset (3a, fluvial massive gravel, 3b, lower diamicton of catastrophic outbursts deposits?); 4, Upper diamicton (basal till or flow till?); B – North-eastern face of the western sandpit in 2002. Black line indicated by an arrow: topset/foreset boundary. Red rectangle represents the section shown in detail in Text-figs 7 and 8

made of blocks of amphibolite in a muddy matrix rests on the amphibolite basement. Laminated silts to clays with a thickness of only few tens of cm are present in the basal part of the glacial sequence. The middle part is composed of sand, gravelly sand and sandy gravel units with trough and planar cross-stratification, rarely with horizontal stratification. The two gravely-sandy sedimentary bodies with large-scale cross-stratification are superimposed (Text-fig. 5A). Cross-stratification generally dips by 15–31° to the SSE (azimuth 150°). Large-scale channel infills are common. Indistinctive down-fault structures with dislocation planes oriented in the E-W direction can be found in some places. These sands and gravels form the laterally most extensive and thickest (> 20 m) part of the whole succession. A laterally continuous tabular gravelly body with a thickness of 1–7 m lies above the large-scale cross-stratified sand and gravel sediments (Text-fig. 5A). The gravelly body is composed of horizontal and subhorizontal layers of cobble gravel, which alternate with pebble gravel and gravelly sand layers (Text-fig. 6). Flat and elongated cobble clasts are subhorizontally oriented. The topmost part of the sedimentary succession is made of two till units. The lower one is represented by a coarse-grained till with boulder admixture; it has ~45% gravel, ~44% sand and ~11% of silt-clay fraction. This till has a rather variable thickness and is not continuous. It crops out mostly in the highest positioned NW corner of the sandpit. It fills depressions, where it can reach up to 2.7 m thickness. The upper till is much finer. It contains only ~6–9% gravel, ~49–55% sand and ~38–42% silt-clay and is laterally more continuous. The thickness ranges between 1 and 8 m and increases towards the SW. The clasts in the upper till are often oriented with the slope of the surface. Lenses of angular bedrock debris appear occasionally in the upper till. Local rocks (feldspar quartzite ~40–50% and Žulová Massif granitoids ~16–29%) predominate in the gravel material. Nordic rocks and the rocks from Polish territory are rather rare, but steadily present (~2–4%); the share of quartz clasts varies between ~15% and 45%.

The available data from the eastern sandpit are much scarcer and were given by Gába (1981), Prosová (1981) and Cháb *et al.* (2004). Sand predominates here; gravel is much rarer than in the western sandpit. Trough and planar cross-stratification predominates over horizontal stratification within the sediments of the eastern sandpit. Gravely sand and gravel with large-scale cross-stratification dipping towards the SE and SW have been documented from an altitude of 425 m (Cháb *et al.* 2004). The coarsest deposits are located in the middle part of the western sandpit according to the drilling records and the descriptions of Gába (1981) and Prosová (1981). Gravels appear in a subordinate amount on the western margin of the western sandpit. Sand, silt and clay predominate in the Bělá River palaeochannel infill below the eastern sandpit and in the centre of the Bělá River valley (around the height point 422 m).

The locality has been described as an accumulation of terminal moraine made of gravely sand by Macoun *et al.* (1965). Later on, the sediments have been interpreted as two glaciofluvial outwash fans, which lead to the Bělá River valley. The ice sheet front rested north of the river valley and fans prograded down the slope to the river valley centre, where they entered moderate lake (Prosová 1981; Gába 1981). This interpretation remains the only valid one and only the terminological designation of the fans has changed. The locality is considered to be the proximal part of sandur accumulation, or a terminoglacial fan (Cháb *et al.* 2004), or a waterlain deposit-dominated ice-marginal fan (Hanáček 2012, according to the classification of Krzyszkowski and Zieliński 2002). Based on these interpretations the fan represents the terminal accumulation of the second continental glaciation in this area.

Text-fig. 6. Topset sediments from the upper part of the north-eastern face of the western sandpit. Subhorizontally-stratified cobble gravel, pebble gravel and gravelly sand layers. Scale is 20 cm long

## METHODS

The following methods were used during the research of the Písečná site.

### Facies analysis of the outcrops

The present state of both sandpits in Písečná village does not allow the undertaking of full facies analysis and the reconstruction of the sedimentary architecture. No clean walls are available in the eastern sandpit anymore. The facies at a temporary fresh outcrop in the northeastern wall of the western sandpit were analysed in detail in this study. This is the largest outcrop in the western sandpit now. The facies in the outcrop were defined based on the shape of the sedimentary bodies, grain-size and stratification type. The conclusions are based on the interpretation of all used methods and on the re-interpretation of the previous studies by Gába (1981) and Prosová (1981).

### GPR survey

The GPR survey was carried out using an unshielded 50 MHz and shielded 250 MHz antennas and RAMAC CU-II unit (MALA GeoScience 2005). The signal acquisition time was set to 247 ns for 250 MHz antenna and 443 ns for 50 MHz antenna, and the scan spacing was 0.05 m. The position for the corresponding trace numbers was given by a Garmin GPSMAP 60CSx receiver (Garmin International 2009). GPR data were processed and interpreted using the Reflex software version 7.0 (Sandmeier 2012). Two-way travel times to depths were converted assuming a wave velocity of 110 m $\mu s^{-1}$ reported by Huggenberger (1993) for gravel and gravelly sand of the glaciofluvial environment. The raw GPR profiles were filtered using a manual gain (y) function, subtract-mean (dewow), background removal and static correction.

### Reconstruction of the preglacial relief and facies analysis of the drilling records

The survey of the accumulation near Písečná was rather extensive in the past. Twenty-seven core drillings located in the western and eastern sandpit and their closest surroundings were chosen for this study (Text-figs 3C, D). All drillings penetrating to the preglacial bedrock were chosen, as well as the drillings with large thicknesses of sediments. Other four drillings were located south of both sandpits and they enable correlation of the sediments in the sandpits with those in the central part of the valley. Geological cross-sections were reconstructed from the drilling records used. The topography of the preglacial bedrock was reconstructed according to the real altitudes of the bedrock surface in drillings data. The sediments were generally described only granulometrically in the drilling records. Therefore, we defined the facies from the drillings in this study based only on the grain-size distribution. Individual facies could not be interpreted basing on grain-size distribution only. Three granulometrically distinct units were differentiated basing on their vertical and lateral distribution. The units defined according to their grain-size were genetically interpreted using the following approaches: the facies they contain, the correlation with outcrops, the general geometry of the units and the vertical and lateral relationships between the units.

### Creation of the 3D model of the preglacial relief and definition of granulometric units

The model of the preglacial relief was constructed based on the real altitudes of the preglacial bedrock in individual drillings in both sandpits and the surrounding area. The shape of the granulometrical units was modelled according to the altitude of their bases and the surfaces in the drilling records. An ASCII file containing coordinates of the object (drilling point, geophysical measurements point) and bedrock surface altitude was created using SURFER® software. A rectangular-polygon grid specified by maximum and minimum coordinate values was calculated from this file. The kriging method was used for a gridding model of a splined continuous surface between the points.

## RESULTS

### Facies analysis of temporary outcrop

This section was uncovered in the north-eastern face of the western sandpits, at an altitude of 410–415 m (Text-figs 3A, B and 5B). Large-scale cross-stratified gravel and sand generally dip to the south-east with angles of ~20°–30°. The section is ~5 m high (Text-figs 7A, B, 8). Eight sedimentary facies have been defined in three facies associations (Table 1). The section corresponds to the cross-bedded gravel and sand units described from the western sandpit by Gába (1981) and from the eastern sandpit by Prosová (1981) and Cháb *et al.* (2004).

Facies association FA1 is at least 3 m thick and primarily comprises facies SGg and SGs (Text-fig. 7F). Facies SGs grades upwards to GSs facies. Outsize pebbles are common. Thin layers of Go facies appear occasionally. An isolated incised trough-shaped body of the facies Sb with initially upslope-inclined, later horizontal and finally downslope-inclined bedding appears in the upper part of the association (Text-fig. 7G).

Facies association FA2 comprises facies Gms, Gcs and Go (Text-figs 7E, 8). The association forms a wedge-shaped body with a thickness decreasing downslope from 1.5 to 1.0 m. It overlies the FA1 facies association with an undulating base. The clasts reach up to 15 cm in a-axis. The largest clasts lie at the base of the association (cobbles with 25 cm in a-axis). The whole association has an upward fining trend. Some layers of the Gcs facies evolve downslope from the Gms facies and coarsen downslope. The thickness and grain-size of the thick layers of the facies Go

| Facies | Description | Interpretation |
|---|---|---|
| SGg | Gravel sand with inverse and normal gradation. Inverse grading trends: very coarse pebbly sand – clast supported pebbles, coarse sand – granules and pebbles. Normal grading trends: clast supported pebbles – very coarse sand – coarse sand, pebbles – granules – coarse sand. The intervals are 5–8 cm thick. Interspersed pebbles with a-axis dipping downslope. | Flow wit alternations lower and higher rates of deposition, $Tb_{3a}$ facies sensu Postma and Cartigny (2014); deposition in conditions variable aggradation rate, type IIb layer sensu Cartigny *et al.* (2013); hindered settling, spaced planar lamination sensu Talling *et al.* (2012); HDTC high density turbidity current, traction carpets deposits (divisions S2) and suspension fallout (division S3) sensu Lowe (1982). |
| SGs | Gravelly sand with sharp lamination. Laminae of coarse sand, very coarse sand and rarely medium sand 5–10 mm thick. Interspersed outsized pebbles and cobbles with a-axis or b-axis dipping downslope or upslope. | Alternating periods of erosion and deposition, $Tb_2$ facies sensu Postma and Cartigny (2014); deposition in conditions periods erosion and deposition, type IIa layer sensu Cartigny *et al.* (2013); turbulent heavily sediment-laden flow, Ggu and Gsa facies sensu Gobo *et al.* (2014, 2015); HDTC – high density turbidity current, fully turbulent current (division S1) sensu Lowe (1982). |
| GSs | Sandy gravel with sharp stratification. Interbedded layers of pebbles and layers with coarse sand and granules. Layers thickness in first cm. Layers with pebbles are clast supported, or have opework texture. | Alternating periods of erosion and deposition, $Tb_{3b}$ facies sensu Postma and Cartigny (2014); deposition in conditions periods erosion and deposition, type IIa layer sensu Cartigny *et al.* (2013); turbulent heavily sediment-laden flow, Ggu and Gsa facies sensu Gobo *et al*. (2014, 2015); HDTC – high density turbidity current, fully turbulent current (division S1) sensu Lowe (1982). |
| Sb | Gravelly sand with through cross-stratification. Distinct trough base. Interbedding of layers with coarse and very coarse sand with layers with s granules and pebbles. Gravelly layers coarsen downslope. Layers thickness 1–2 cm. | Through scoured upflow of hydraulic jump and filled by backset, facies 1.2 sensu Lang and Winsemann (2013); turbulence associated with hydraulic jump (Nemec 1990; Massari 1996). |
| Gms | Matrix supported gravel. Matrix consists of granules, smallest pebbles (<10 mm), very coarse sand and coarse sand. Pebbles and cobbles dipping mostly downslope, rarely upslope. Length of pebbles and cobbles usually 5–15 cm, occasionally 25 cm. | Cohesionless debris flow (Sohn *et al.* 1997; Kostic *et al*. 2005; Gobo *et al.* 2014, 2015). |
| Gcs | Clast supported gravel. Admixture of sandy-smallest pebble matrix. Pebbles and cobbles dipping mostly downslope, rarely upslope. Length of pebbles and cobbles usually 5–15 cm, occasionally 20 cm. | Debris fall (Nemec 1990; Sohn *et al*. 1997; Gobo *et al*. 2014, 2015). |
| Go | Openwork gravel without matrix. Pebbles and cobbles dipping mostly downslope, rarely upslope, some are subvertically oriented. | Debris fall (Nemec 1990; Sohn *et al.* 1997; Gobo *et al*. 2014, 2015). |
| Fl | Laminated to nearly massive silt and clay. Laminae tenths of mm thick. | Subcritical nonstratified turbulent flow, facies $T_e$ sensu Postma and Cartigny (2014) turbulent mud density flow, facies $T_{E-1}$ and $T_{E-2}$ sensu Talling *et al.* (2012), LDTC – low density turbidity current sensu Lowe (1982) |

Table 1. Facies description and interpretation of the foreset outcrop in the western sandpit

increase downslope; the layers diminish gradually upslope. Thin layers of the Go facies are often indistinctly separated from Gcs and Gms facies. Short upward coarsening intervals can be found at places. Large pebbles and cobbles in the Gms facies have a mostly downslope dipping, rarely upslope dipping clast orientation; in the Gcs facies the clasts have mostly a downslope dipping orientation. The stratification in the lower part of FA2 becomes indistinct in the downslope direction (dashed line in Text-fig. 8) and it passes finally into the massive texture of the Gcs facies.

Facies association FA3 reaches a thickness of at least 3 m (Text-fig. 8). The tabular bodies of facies GSs and SGs interbed with the tabular to wedge-shaped bodies of facies Gms, Gcs and Go. The unit thickness is in the tens of centimetres. The boundaries of the units are slightly undulating, in the case of the GSs facies also slightly trough-based. Facies Fl in layers less than 5 cm thick appears subordinately (Text-fig. 7D). The largest cobbles occur in facies Go and reach up to 20 cm. Outsized pebbles and cobbles oriented upslope are common in facies SGs. Upslope fining of the cobble-pebble clusters (facies Gcs, Go) appears in facies Gms and GSs, see colourless arrows in Text-fig. 8.

## Ground penetrating radar survey

Four GPR profile tracks (Text-figs 3B, 9) were conducted on the floor of the western sandpit. Ten radar-

| Facies | Antenna | Description | Interpretation |
|---|---|---|---|
| RF1 | 50 MHz | Sharp convex-up reflection or sharp continuous slightly undulating oblique reflection. | Bedrock (according to its position in western sandpit) |
| RF2 | 50 MHz | Sharp continuous straight oblique reflections, parallel-subparallel. | Jökulhlaups deposits (Cassidy *et al.* 2003), large channels of braided streams (Lunt *et al.* 2004), eskers (Burke *et al.* 2008), foreset of coarse-grained Gilbert-type deltas (Roberts *et al.* 2003). |
| RF3 | 50 MHz | Continuous concave-up and slightly undulating reflections. Short straight or concave-up reflections are obliquely oriented to continuous systems. Reflections dip under low, as well as steep angles. | Cross-stratification in channels, bars and dunes of braided rivers (Lunt *et al.* 2004, Smith *et al.* 2005) or large-scale channels on the surface of the subaqueous fan slopes (Winsemann *et al.* 2009). |
| RF4 | 50 MHz | Continuous slightly convex-up, subhorizontal and slightly oblique parallel reflections. | Coarse-grained Gilbert-type delta foreset (Winsemann *et al.* 2009, Eilersten *et al.* 2011). |
| RF5 | 250 MHz | Continuous straight densely crammed steeply dipping parallel reflections. | Jökulhlaups deposits (Cassidy *et al.* 2003), large channels of braided streams (Lunt *et al.* 2004), eskers (Burke et al. 2008), foreset of coarse-grained Gilbert-type deltas (Roberts *et al.* 2003). |
| RF6 | 250 MHz | Short steeply oblique reflections, which bends sharply subhorizontal direction. Subhorizontal parts of reflections are continuous, partly straight or undulating concave-up and convex-up. | Cross-stratification in channels, bars and dunes of braided rivers (Lunt *et al.* 2004, Smith *et al.* 2005) or large-scale channels on the surface of the subaqueous fan slopes (Winsemann *et al.* 2009). |
| RF7 | 250 MHz | Continuous undulating parallel reflections | Coarse-grained Gilbert-type delta foreset (Winsemann *et al.* 2009, Eilersten *et al.* 2011). |
| RF8 | 250 MHz | Continuous straight horizontal reflections, sharp and slightly convex-up reflections, oblique reflections, reflections in the shape of an inverted V letter (also recurrent) and hyperbolic diffractions. | Bedrock (Ékes and Friele 2003) and according to bedrock outcrop in the GPR profile track. |
| RF9 | 250 MHz | Hyperbolic diffractions and inverted V-shaped reflections. | Bedrock (Ékes and Friele 2003). |
| RF10 | 250 MHz | Continuous subhorizontal, oblique, concave-up and convex-up reflections, partly parallel. Occasionally hyperbolic diffractions. | Glaciofluvial deposits (Beres *et al.* 1995) or subaqueous fan deposits (Winsemann *et al.* 2009). |

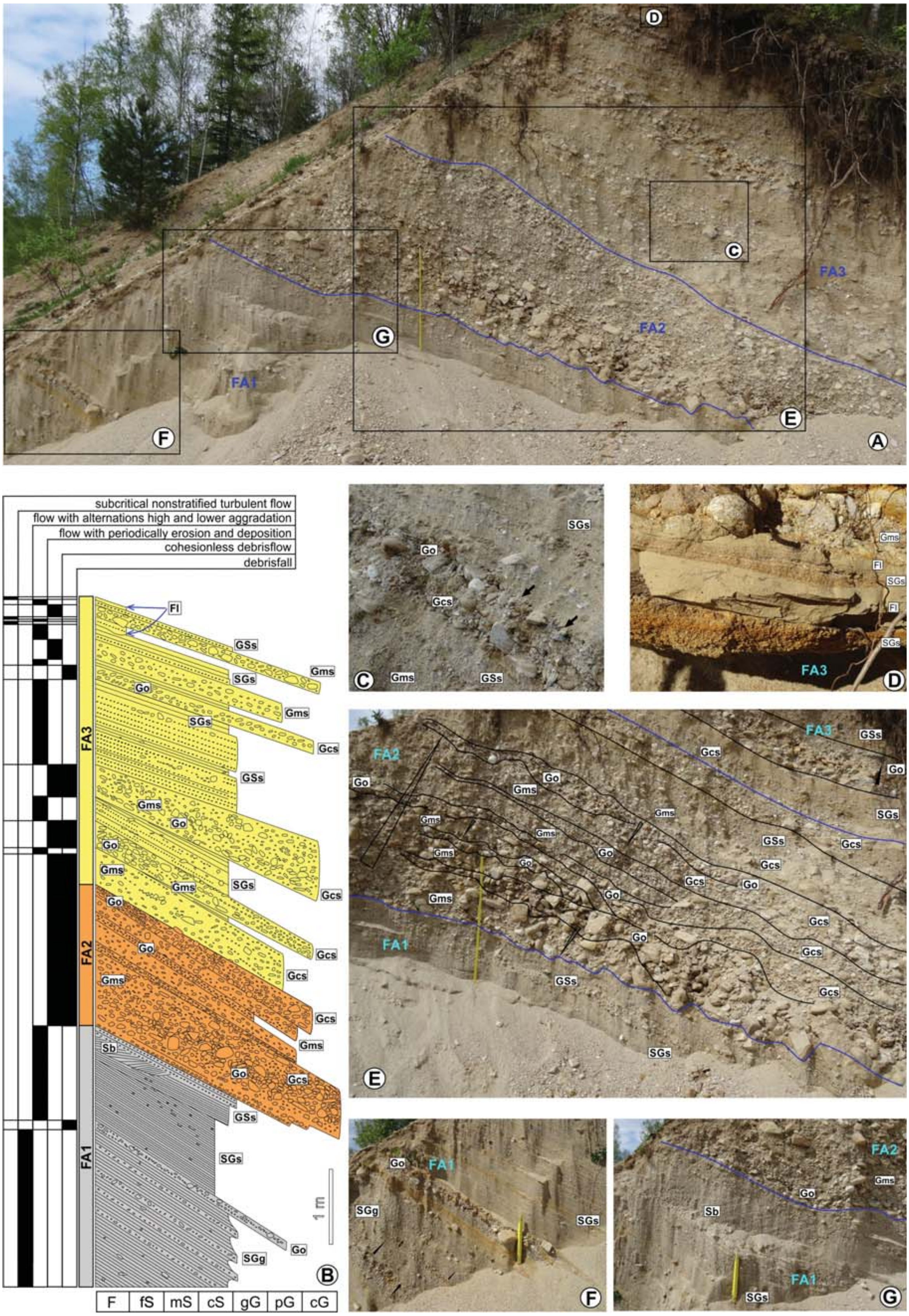
Table 2. Radarfacies description and interpretation from GPR profiles

facies have been defined in GPR profiles (Table 2). The profiles R1 and R2, in which radarfacies RF1–RF4 were described, were processed using a 50 MHz antenna. The profiles R3 and R4, in which radarfacies RF5–RF10 were described, were processed using a 250 MHz antenna. The altitude of all profile tracks is 400 m a.s.l.

Radarfacies RF1 defines clearly convex shapes which extend from a depth of 4.5 m to a depth of 13 m (at least to the level of 387 m a.s.l.) in profile track R1. The RF1 radarfacies at the SE end of profile track R1 resembles the same facies in the NW part of profile track R2 because of the partial overlap of both profiles. Two convex-up features 5–9 m below the surface, i.e. at an altitude of ~395–391 m appear in the R2 profile. Radarfacies RF2 and RF3 converge into the space between the convex shapes of radarfacies RF1. Radarfacies RF2–RF4 are oriented at different angles to one another.

Profile track R3 runs along the same line as profile track R2 and a part of profile track R1. Profile R3 shows the detailed structure of the upper part of pro-

Text-fig. 7. Foreset section in the north-eastern face of the western sandpit (sandy-gravelly unit, 410–415 m a.s.l.). For facies codes see Table 1. → **A** – Overall view of the section with insets in subsequent figures. Scale is 1 m long; **B** – Sedimentary log with indicated facies, facies associations and types of depositional processes. Codes in Text-fig. 12B: F – fines (silt+clay), fS – fine-grained sand, mS – medium-grained sand, cS – coarse-grained sand, gG – granule gravel, pG – pebble gravel, cG – cobble gravel; **C** – Contact of debris fall sediments (Gcs and Go facies) with high-density turbidites deposited during periodic changes of erosion a deposition (GSs and SGs facies) in facies association FA3. Black arrows indicate clast imbrication caused by turbulent effect of turbidity current onto the debris fall sediments. Height of the section is 80 cm; **D** – Sediments of subcritical nonstratified turbulent flow (low-density turbidity current, facies Fl) within the facies association FA3. Thickness of facies Fl is 8 cm; **E** – Alternating sediments of cohesionless debris flows (Gms facies) and debris falls (Gcs and Go facies) within the facies association FA2. Scale is 1 m long; **F** – High-density turbidites deposited during high and low aggradation (SGg facies), debris fall sediments (Go facies) and high-density turbidites deposited during periodic changes of erosion and deposition (SGs facies) within the facies association FA1. Scale is 20 cm long; **G** – Backset (Sb facies) erosionally incised to high-density turbidites deposited during periodic changes of erosion and deposition (SGs facies) within the facies association FA1. Scale is 20 cm long


A
C
D
E
F
G
FA1
FA2
FA3
B
subcritical nonstratified turbulent flow
flow with alternations high and lower aggradation
flow with periodically erosion and deposition
cohesionless debrisflow
debrisfall
Fl
GSs
Gms
SGs
Go
Gcs
Sb
SGg
1 m
F
fS
mS
cS
gG
pG
cG

Text-fig. 8. Upper part of the foreset section in the north-eastern face of the western sandpit (sandy-gravelly unit, 410–415 m a.s.l.). For facies codes see Table 1. Scale is 1 m long. Colourless arrows: cobble-pebble upslope fining clusters; white arrows: isolated cobbles and pebbles turbulently eroded from the surface of debris flow and debris fall deposits and deposited in high-density turbidites originating during periodic changes of erosion and deposition

file R2 and partly of profile R1 due to the shallower reach and more detailed resolution of the 250 MHz antenna. Radarfacies RF5, RF6 and RF7 are identical with radarfacies RF2, RF3 and RF4, respectively.

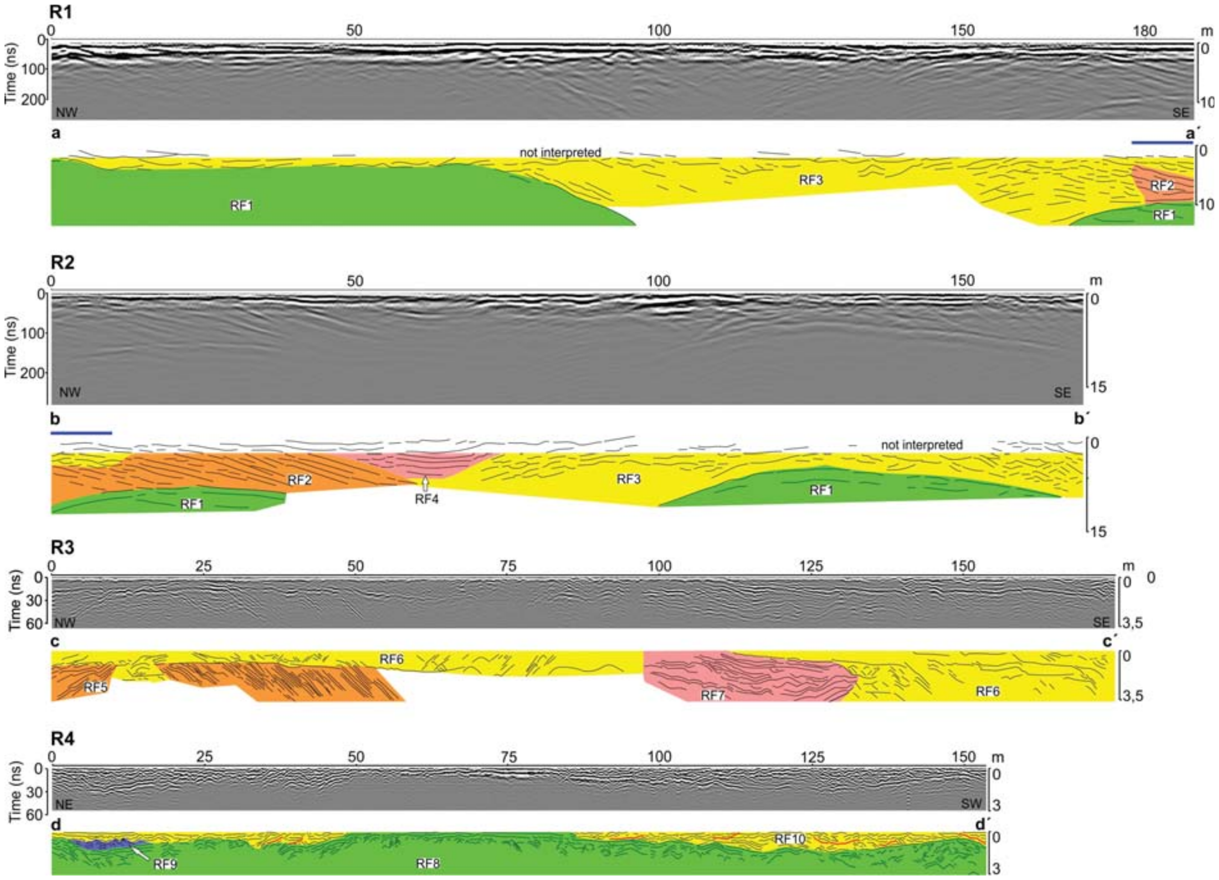
Radarfacies RF8 and RF9 differ from the other radarfacies acquired by the 250 MHz antenna by their inverted V-shaped reflexes and hyperbolic diffractions. Radarfacies RF10 resembles radarfacies RF6.

## Facies analysis of drilling documentation and model of preglacial relief

Ten facies were defined in the drillings based on their grain-size distribution (facies A–J, see Table 3, Text-fig. 10). Geological cross-sections were constructed from the most important drillings (Text-figs 3C, D and 10). A model of the preglacial relief around the study site was constructed based on the bedrock level position in individual boreholes (Text-fig. 11A). The facies I surface was used as a bedrock surface in

| Facies | Description |
|---|---|
| A | Sandy, clayey mud with sporadic transition to sand |
| B | Sandy clay, clay, clay with intercalated sand layers |
| C | Clayey, fine- to medium sand; clay occasionally making thin layers |
| D | Fine-grained, less medium- to coarse-grained sand |
| E | Fine-grained sand with 1–2 cm pebbles, medium-grained sand with 1–10 cm pebbles, occasionally fine-grained partly clayey sand with pebbles up to 10 cm |
| F | Coarse-grained, muddy to sandy gravel with pebbles up to 5 cm |
| G | Sand with admixture of cobbles up to 20 cm |
| H | Sandy to muddy gravel with cobbles up to 20 cm |
| I | Clay, sandy clay, less sand with angular clasts of amphibolite, marble, gneiss from bedrock (diamicton with angular clasts) |
| J | Mud to sandy clay with rounded cobbles up to 20 cm (diamicton with rounded clasts) |

Table 3. Facies description from drilling documentations



Text-fig. 9. GPR profiles taken in the western sandpit. Profiles R1 and R2 (50 MHz antenna) are not exaggerated. Thick blue line below the R1 and R2 profiles indicates the overlap of these profiles. Profiles R3 and R4 (250 MHz antenna) 2.5-times exaggerated

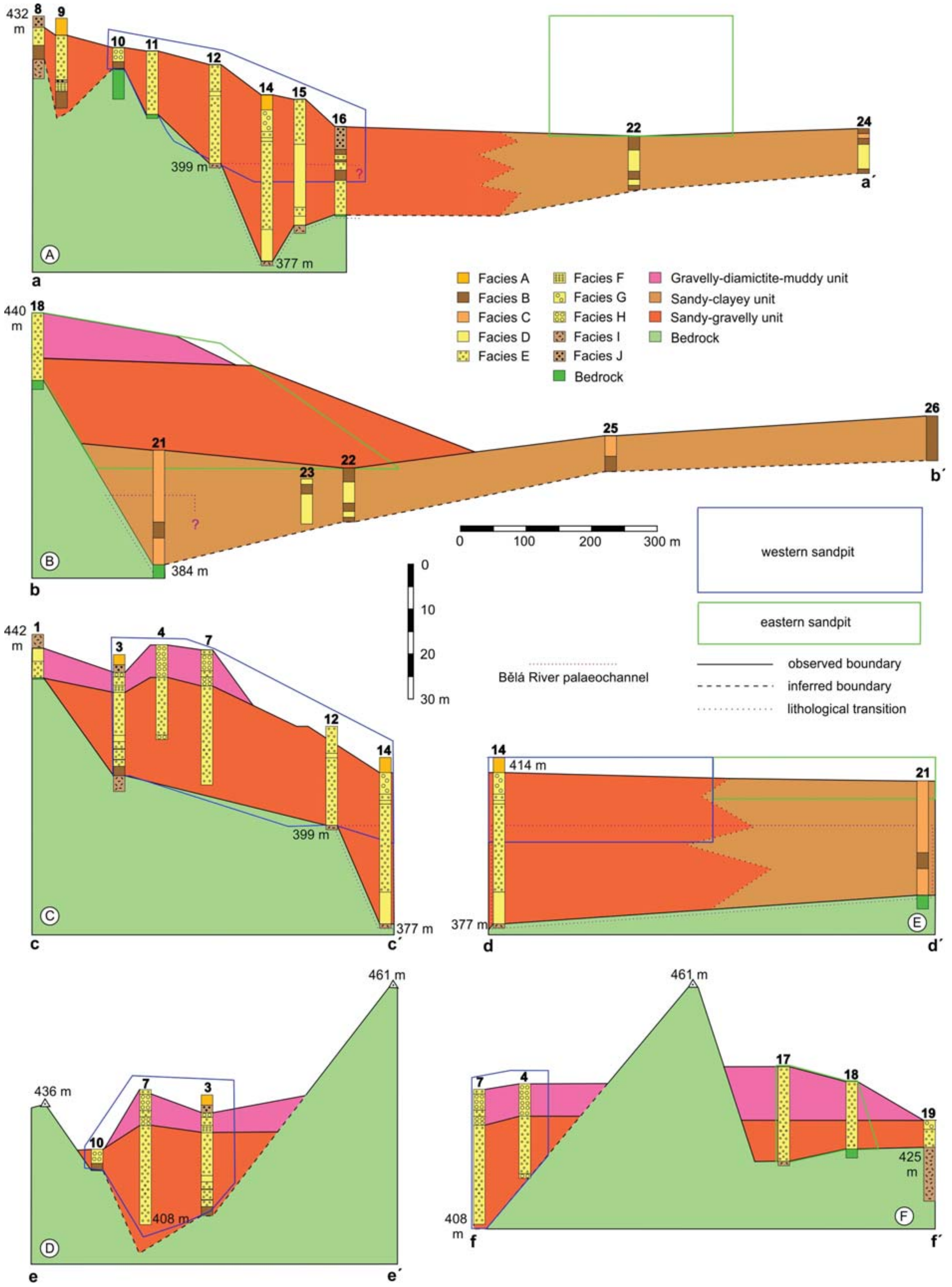
the model, as facies I interchanges mutually with the bedrock and contains angular clasts of bedrock rocks.

The drilling description and model shows the distinct limitation of the accumulation by the slopes of the preglacial landscape. The accumulation lies in a long depression oriented in the SW-NE direction (Text-fig. 11). The upper part of the sedimentary accumulation lies in the slope of this long depression (Text-figs 10A, C). The accumulation is bounded by the hill with the height point 436 m in the west and the hills with height points 461 m and 431 m in the north and northeast (Text-figs 10D, 11). A narrow depression oriented at an angle to the long depression lies between the height point 436 m and Velký Špičák Hill (516 m) on one side and the height point 461 m on the other side (Text-figs 10A, C, D and 11A).

The facies show the following spatial distribution (Text-fig. 10). The fine-grained facies of clay and fine- to medium-sand (facies B, C and D) occur mainly in the lower part of the accumulation and further from the western margin of the depression. The coarser facies of gravely sand, sand and occasionally gravel (facies E and D, less commonly B, F, G and H) occur in the middle to upper part of the accumulation, along the western and northern slopes of the depression. The coarsest facies (mostly bouldery gravel facies H, but also facies E and F and occasionally facies D) occur in the upper part of the accumulation, along the northern margin of the depression.

Three grain-size defined units were defined according to the described spatial distribution of facies: the sandy-clayey unit, the sandy-gravelly unit, and the gravelly-sandy unit. Each of these units is made of facies which correspond spatially and compose large determinable sedimentary bodies (Text-figs 10, 11B).

The sandy-clayey unit is composed of facies B and C. The evident prevalence of the sandy-clayey unit in the eastern part of the long depression infill and in the central part of the present valley (the area of the 422 m elevation) implies that they represent the central part of the valley infill (Text-figs 10A, B, E and 11B).



Text-fig. 10. Geological cross-sections constructed from the drillings documentation. 7-times exaggerated

The sandy-gravelly unit comprises mainly facies E and D and subordinate facies F, G and H. This unit connects the western sandpit, the western part of the long depression infill and the eastern sandpit (Text-figs 10A, B, C and 11B). The sediments of this unit correspond to the sand, gravely sand and gravel with large-scale cross-stratification in the western sandpit according to Gába (1981) and to the large-scale cross-stratified gravely sand and gravel in eastern sandpit according to Prosová (1981) and Cháb *et al.* (2004). However, they also correspond to the sediments from the temporary outcrop described in this paper (Text-figs 7, 8). A granulometric trend from gravelly sand and gravel in the western sandpit towards sand in the eastern sandpit could be observed in the sandy-gravelly unit (with the prevalence of sand in the eastern sandpit according to Gába (1981)).

The sandy-gravelly unit passes laterally into the sandy-clayey unit in the lower part of the accumulation between 377 and 400 m a.s.l. (mainly in the long depression), see Text-figs 10A, E. The upper part of the accumulation (at 400–430 m a.s.l.) in both sandpits is composed of the sandy-gravelly unit. The sandy-gravelly unit rests on the sandy-clayey unit in the eastern sandpit (Text-fig. 10B). The sandy-gravelly unit passes laterally to the sandy-clayey unit closer to the valley centre (elevation point 422 m; Text-fig. 10A, B and 11B).

The gravelly-sandy unit comprises mostly facies H and E and in a subordinate amount facies E and F. The unit was found in the upper part of the western sandpit (430–440 m a.s.l.), see Text-fig. 10 and 11B. It corresponds to the gravel body which has been described by Gába (1981) from the western sandpit.

Muddy facies A occurs predominantly in the upper part of the accumulation, and diamictic facies J in the upper and middle part of the accumulation. The occurrence of these facies is unique and they do not define a continuous body of sediment.

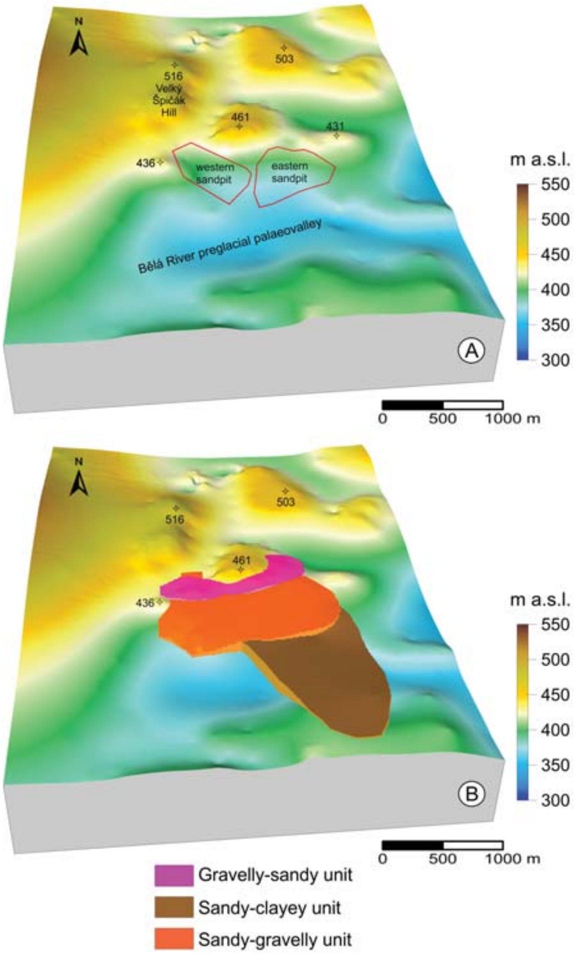
## INTERPRETATION

### The genesis of the sediments in the temporary outcrop

The results of the facies analysis of the sediments in the temporary outcrop shows that they represent the foreset of a coarse-grained Gilbert-type delta (Nemec 1990, Nemec *et al.* 1999, Winsemann *et al.* 2009, Gobo *et al.* 2015).

Facies association FA1 was deposited by high-density turbidity currents with different intensities of deposition and erosion (Cartigny *et al.* 2013, Postma and Cartigny 2014). Facies SGg originated in variable deposition rates, but without any erosion of the deposited layers. Facies SGs and GSs originated by cyclic changes of deposition and erosion on the delta slope. Debris fall happened occasionally (e.g., Gobo *et al.* 2014, 2015). During sedimentation of the facies SGs a local hydraulic jump occurred during erosion of the delta slope. As a result of this, a trough incision and subsequent filling with backset sediments took place (Lang and Winsemann 2013).

Facies association FA2 formed by amalgamation of cohesionless debris flows and debris falls (Sohn *et al.* 1997, Kostic *et al.* 2005, Gobo *et al.* 2014, 2015). Some layers of the Gcs and Go facies coarsen and become thicker downslope and become thinner ups-



Text-fig. 11. A – 3D model of the preglacial relief constructed using the bedrock outcrops and bedrock surfaces and preglacial colluvia reached in drilling documentation. 2-times exaggerated; B – 3D model of preglacial relief and three granulometrically defined units composing the accumulation near Písečná. 2-times exaggerated lope, which corresponds to the shape of the debris fall facies (Colella *et al.* 1987; Nemec 1990). Thick and laterally continuous clast supported coarse-grained accumulations, merging upslope into finer grained and less-sorted sediments originated by amalgamation of individual debris flow layers in the head zone (Nemec 1990). Such a structure is typical of the lower part of facies association FA2, in which the amalgamated facies Gcs and Go pass upslope into alternating layers of facies Gms, Gcs and Go (Text-fig. 8).

Facies association FA3 is represented by the alternation of debris flow and debris fall deposits (facies Gms, Gcs and Go) and high-density turbidity currents. Turbidites developed under changes of conditions of cyclic erosion and deposition on the delta slope (Cartigny *et al.* 2013; Postma and Cartigny 2014). Outsized pebbles and cobbles were incorporated into the turbidites by erosion of previously deposited debris flows and debris fall sediments (Clifton 1984; Postma *et al.* 1988), see Text-figs 7C and white arrows in 8. The erosional effect of the turbidity current on the surface of the previously deposited debris flow and debris fall deposits is demonstrated clearly by imbricated pebbles near the boundary of the sedimentary bodies (black arrows in Text-fig. 7C). Lenticular cobble-pebble clusters of facies Gcs and Go with often distinct upslope fining represent debris fall of large clasts (Postma *et al.* 1988, Nemec 1990). Sediments of subcritical nonstratified turbulent flow occur very rarely in facies association FA3 (Postma and Cartigny 2014).

### The origin of the radarfacies in the GPR profiles

The RF1, RF8 and RF9 radarfacies are interpreted as the surface of the preglacial crystalline basement. The first evidence for this is the course of the bedrock surface at similar altitudes (~377–387 m a.s.l.) in the boreholes along the southwestern margin of the western sandpit (Text-figs 3C, 10C). The second evidence is the abundant presence of angular bedrock debris (amphibolite) in the part of the sandpit through which the north-western segment of the R2 profile runs. The angular debris indicates the presence of bedrock not far below the surface. Bedrock reached in this section of the sandpit was also described by Gába (1981). The third evidence is the bedrock outcrop found directly in the GPR profile track R4, in the places of the surficial course of the radarfacies RF8 reflexes (Text-fig. 3B). The radarfacies RF9 may represent a blocky disintegrated bedrock elevation. Deep located convex-up shapes defined by the RF1 radarfacies in the R1 and R2 profiles represent a rocky elevation.

Other radarfacies may represent the depositional records of diverse sedimentary environments based on the shape and course of the reflexes. Radarfacies RF2 and RF5 are reminiscent of the large-scale cross-bedding of jökulhlaups deposits (Cassidy et al. 2003), the large channels of braided streams (Lunt *et al.* 2004), the eskers (Burke et al. 2008), and the foresets of coarse-grained Gilbert-type deltas (Roberts et al. 2003). Radarfacies RF3 to RF6 resemble the cross-stratification in the channels, bars and dunes of braided rivers (Lunt *et al.* 2004; Smith *et al.* 2005) or the large-scale channels on the surface of subaqueous fan slopes (Winsemann *et al.* 2009). Radarfacies RF 7 represents coarse-grained Gilbert-type delta foresets in cross-section (Winsemann *et al.* 2009, Eilersten *et al.* 2011). Radarfacies R10 represents either glaciofluvial deposits (Beres *et al.* 1995) or subaqueous fan deposits (Winsemann *et al.* 2009). It is possible to interpret radarfacies RF2–RF7 and radarfacies RF10 as large-scale channel infills on the slope of a coarse-grained delta or subaqueous fan due to the interpretation of the sediments in the studied outcrop as a delta foreset or subaqueous fan. The difference in the radarfacies reflexes indicates different cross sections through these infills.

### Preglacial relief and genesis of the sediments in the drilling records

Facies I is interpreted as colluvial sediment. The proofs for that are as follows: the petrography and shape of the clasts (angular clasts from the surrounding bedrock are always present) and the lateral alternation with the bedrock when facies I lies at the base of the sedimentary sequence (Text-figs 10E, F). The facies I lying below the facies with glacial sediments is thus considered preglacial colluvium. For these reasons, the model of preglacial relief was constructed based on the bedrock surface and the surface of the facies I bodies at the base of the sedimentary accumulation (Text-fig. 11A). The long depression below both sandpits represents the margin of the Bělá River palaeovalley. The Bělá River flowed through the area of the present sandpits before the glaciation. The ice sheet margin is documented from the eastern slope of the height point 516 m (Velký Špičák Hill) after Cháb *et al.* (2004). The narrow depression, which is located between the height points 516 m, 436 m and 461 m, enters into the Bělá River palaeovalley from the North and is interpreted as a valley of preglacial origin, which later served as subglacial drainage, through which meltwater and clastic material flowed into the Bělá River palaeovalley.

The architecture of the three units defined by grain size points to a coarse-grained Gilbert-type delta (Postma 1990). The entire accumulation is characterized by two grain-size trends typical of coarse-grained deltas: a vertical coarsening upwards and a proximal-distal fining trend towards the centre of the depression. The gravelly-sandy unit represents a topset. Cobble gravel, gravel and gravelly sand were deposited in shallow braiding channels on the subaerial delta plain (Brodzikowski and van Loon 1991). The sandy-gravelly unit corresponds to the proximal to distal foreset. Such sediments are deposited from debris flows and turbidite flows on the slopes of subaqueous fans and Gilbert-type deltas (Nemec *et al.* 1999; Winsemann *et al.* 2009; Gobo *et al.* 2014, 2015). This interpretation of the sandy-gravelly unit supports the facies character and genesis of the foreset in the temporary outcrop (Text-figs 7, 8), which corresponds to the sandy-gravelly unit according to its position within the whole sequence. The sandy-clayey unit corresponds to the distal foreset and also to the toeset and bottomset of the subaqueous fan and delta. Such sediments are deposited from turbidite flows and from suspensions (Krzyszkowski 1993; Plink-Björklund and Ronnert 1999; Winsemann *et al.* 2004; Gruszka 2007; Eilersten *et al.* 2011). Sediments corresponding granulometrically to the sandy-clayey unit accumulate in substantial thickness in the central parts of narrow mountain glacial lakes, as a result of the incoming of large amounts of material brought by subaqueous fans and deltas (Johnsen and Brennand 2006). The accumulation has a prograding nature, because the sandy-gravelly unit clearly progrades over the sandy-clayey unit (Text-fig. 10B). The occurrence of facies I near the surface of the present landscape in drilling no. 1 in the foothills of Velký Špičák (Text-figs 3C, 10C) is interpreted as postglacial colluvial sediment.

## DISCUSSION

### Previous interpretations of the sedimentary succession

Gába (1981) and Prosová (1981) described the sediments at Písečná as deposited in a proglacial glaciofluvial outwash fan (sandar). Gába (1981) reconstructed the evolution of the depositional environment as follows: the continental ice sheet advanced from North to South along the eastern slope of the Sokol Ridge. Its advance halted above the margin of the Bělá River valley. The material accumulated at the ice sheet front was transported by thawing water further south into the Bělá River valley. A large gravely sandy sedimentary body accumulated by glaciofluvial processes at the valley side. A small lake was located in the axial part of the Bělá River valley, i.e. at the outer part of the glaciofluvial accumulation. Glaciolacustrine silts accumulated in the lake. The ice sheet advanced later into the Bělá River valley and deposited basal till above the glaciofluvial and glaciolacustrine sediments. The ice sheet decay took place without any deposition. Based on its grain-size, the outwash fan near Písečná corresponds closely to the type C end moraine (waterlain deposit-dominated ice-marginal fan) based on the classification of Krzyszkowski and Zieliński (2002).

### The origin of the sedimentary accumulation based on the results presented

A body of > 5 m thick gravel and sand with large-scale cross-stratification (Text-figs 7, 8) has been documented in the section presented in this study. The stratification dip is 20–30°. Subhorizontal or inclined stratification generated by subaerial sheet-flows prevails in gravely-sandy terminoglacial fans (Houmark-Nielsen 1983; Krüger 1997; Zieliński and van Loon 2000; Krzyszkowski 2002; Krzyszkowski and Zieliński 2002; Kjær *et al.* 2004; Pisarska-Jamroży 2006). The inclined stratification has a dip up to 20° and is roughly concordant with the fan surface slope (Krzyszkowski 2002). Large-scale cross-stratification (mostly ~1 m thick) represents a subordinate facies in terminoglacial fans and originates in deep channels during high water discharge (Zieliński and van Loon 1999; Krzyszkowski 2002).

Large-scale cross-stratification with a thickness of several meters originates also in other subaerial environments (Carling 2013). It is mostly represented in the proximal parts of braidplains (Zieliński 1993; Zieliński and van Loon 2003) and subglacial tunnels (Shaw and Gorrell 1991; Brennand 1994; Burke *et al.* 2008). In the proglacial zone, the origin of large-scale cross-stratification is connected with catastrophic floods associated with jökulhlaups (Cassidy et al. 2003; Rushmer 2006), or the sudden outburst of glacier lakes (Carling *et al.* 2002; Smith 2006).

Large-scale cross-stratification of gravel and sand with dips of up to 30° is typical of coarse-grained deltas in diverse positions, e.g. near the fault margins of marine and lake basins (Colella *et al.* 1987; Flores 1990; Sohn and Son 2004; Gobo *et al.* 2015), or in fjords (Nemec *et al.* 1999; Lønne and Nemec 2004; Eilertsen *et al.* 2011). Coarse-grained deltas with large-scale cross-stratification evolved very often in direct connection with glaciers (Brodzikowski and van Loon 1991). They originated in glaciomarine and glaciolacustrine environments, mostly in terminoglacial and proglacial settings (Clemmensen and Houmark-Nielsen 1981; Lønne 1995; Martini 1990; Mastalerz 1990; Nemec *et al.* 1999; Plink-Björklund and Ronnert 1999; Russell and Knudsen 1999; Winsemann et al. 2004, 2009, 2011; Kostic *et al.* 2005; Johnsen and Brennand 2006; Thomas and Chiverrell 2006; Livingstone *et al.* 2010). Terminoglacial subaqueous fans without a subaerial delta plain (Diemer 1988; Lønne 1995; Winsemann *et al.* 2004, 2009; Johnsen and Brennand 2006) with the presence of large-scale cross-stratification evolved beside the deltas. In deep basins, a subaqueous fan and delta could even lie in superposition (Nemec et al. 1999; Plink-Björklund and Ronnert 1999). Subaqueous fans and coarse-grained deltas originated in such morphologically convenient places as the infill of subglacial cavities (Brodzikowski and van Loon 1991; McCabe 1991; Clerc *et al.* 2012).

From this perspective, it is clear that the large-scale cross-stratification at the Písečná site could have evolved in one of the following four ways: I. in a channel incised into the subaerial terminoglacial fan (this would agree with the interpretation of Gába 1981 and Prosová 1981); II. in the deep channels of the proximal part of a braidplain; III. as subaqueous dunes, or a channel infill in subglacial valleys; IV. at the front of a coarse-grained delta, or subaqueous fan.

Option I is not probable for the following reasons. According to Gába (1981) large-scale cross-stratification is the most common type of stratification at the Písečná site. Deposition took place in a setting deep enough for the development of the large-scale cross-strata. However, subhorizontal and inclined (with dips < 20°) stratification, which is the result of shallow sheetflows, predominates in terminoglacial fans according to the above-mentioned studies. Moreover, terminoglacial fans originate on a flat surface gently sloping away of the glacier front (Zieliński 1992; Pisarska-Jamroży 2006). Terminoglacial fans deposited by jökulhlaups originated in the same relief (Russell and Knudsen 1999; Cassidy *et al.* 2003). The melting water could drain from the fans into the landscape and thus the conditions on the fans retain a subaerial character. However, in the case of the Písečná site the deposits prograded into the river valley, which was dammed by the ice sheet at its mouth and mountain ridges on other sides.

Option II is not probable from the following reasons. Braid-plains with deep channels in the proximal zone prograde in wide shallow valleys tens of kilometres away from the glacier (Zieliński and van Loon 2003). Therefore, the morphological basis for the formation of braidplains was completely different from the morphological conditions at the Písečná site. Certain similarity exists between the Písečná site and the sediments of catastrophic floods caused by the sudden outburst of glacier-dammed lakes in a mountain landscape. Large dunes and bars with large-scale cross-stratification originated during these floods in narrow valleys with steep sideslopes (Carling *et al.* 2002; Smith 2006). Nevertheless, lateral fining into sand, silt and clay similar to that seen at the Písečná site is not present in these settings. Tills are not present above the dunes and bars in these settings, which is another difference from the Písečná site.

Option III is not probable from the following reasons. The infills of subglacial valleys incised into the basement (n-channels) and eskers reach lengths of several kilometres with thicknesses of tens of metres. In addition, abrupt lateral fining is not present there. According to Szponar (1986), the ice sheet reached a thickness of up to 200 m in the study area. The origin of a subglacial space with a height of 65 m and the area of 1.5 to 1 km is not to be expected under such a relatively thin ice sheet. A space of these dimensions would be necessary for accumulation of the deposits found near Písečná. The only similarity between the Písečná site and eskers is the presence of tills above the glaciofluvial facies (Russell *et al.* 2007). The esker interpretation is contradicted by two circumstances. Firstly, there is the position of the accumulation in the bedrock depression. Secondly, there is the absence of collapse deformation of the sediments, which is characteristic of eskers (Brennand 1994). A short preglacial subglacial valley developed only between Velký Špičák Hill and the height points 436 m and 461 m. It functioned as a drainage path for water and clastic material into the main depositional area of both sandpits and has been filled during the deposition of the accumulation. The absence of positive sedimentary landforms east of Velký Špičák Hill is further evidence for the water draining through the subglacial drainage incised in the bedrock. The sedimentary infill of a tunnel remains preserved as a positive morphological ridge in case of a drainage tunnel excavated into the glacier (Bennett *et al.* 2007).

The most probable is option IV. The sediments in the temporary outcrop of the western sandpit (Text-figs 7, 8) correspond to the foreset of a coarse-delta and subaqueous fan (Nemec 1990; Nemec *et al.* 1999, Winsemann *et al.* 2009, Gobo *et al.* 2015). Moreover, the relationship of the sediments to the bedrock relief supports this interpretation. The bordering of the accumulation by the sideslope of the Bělá River palaeovalley is equivalent to the bordering of coarse-grained deltas by the slopes of the basin margin (e.g.; Colella 1988; Sohn and Son 2004). The concept of a subaqueous fan/delta requires a lake in the ice sheet dammed valley. This solves the major problem of the interpretation of Gába (1981), who has assumed only a small lake at the subaqueous fan periphery and has not clarified how and where the large amount of melting water discharged from the valley.

The large-scale cross-stratified infill of large channels supported by the GPR survey from the bottom of the accumulation may be considered according to the fan/delta interpretation to be chute infills, which are formed on the slope of the fan, or delta (Diemer 1988; Postma and Cruickshank 1988; Lønne and Mangerud 1991; Lønne 1997; Nemec *et al*. 1999; Winsemann *et al.* 2009).

The interpretation of the Písečná site as a subaqueous fan and/or coarse-grained delta is supported also by the lateral grain-size changes of the sediments. The sandy-gravelly unit (proximal foreset) is limited to the lateral margin of the valley. It is followed by the sandy-clayey unit (distal foreset-bottomset), which extends into the valley centre. The architecture of the fan/coarse-grained delta body corresponds best with the large-scale cross-stratification of gravel and sand in the western and eastern sandpit (at the margin of the valley) and with the lateral transition of the facies from gravel to clay towards the centre of the valley at a distance of max. 1.5 km (Text-fig. 10A, B, 11B).

## Re-interpretation of previous results based on new research

Two superimposed gravel-sand bodies with large-scale cross-stratification are located in the western sandpit according to Gába (1981). The foreset described in present study corresponds to the upper body according to its altitude. A laterally stable tabular body of gravel lies above the upper large-scale cross-stratified body (Gába 1981), see Text-fig. 5. It is characterised by indistinct horizontal and subhorizontal strata of cobbles, pebbles and gravely sand with an alternating matrix supported and clast supported texture (Text-fig. 6). Large clasts are oriented horizontally. Gába (1981) interpreted this gravel as a sediment transitional between glaciofluvial sediments and tills. These sediment facies correspond to the proximal zones of terminoglacial outwash fans or braided rivers (Gustavson 1974; Fraser and Cobb 1982; Miall 1985; Zieliński and van Loon 2000). The tabular body of gravel can be interpreted as the delta topset based on its position directly above the foreset. The upper foreset and topset thus represent a coarse-grained Gilbert-type delta.

The accumulation at Písečná reaches an extraordinary thickness (up to 65 m) within the marginal zone of the continental glaciation in the forefield of the Rychleby Mts. and Zlaté Hory Highlands (Cháb *et al.* 2004; Žáček *et al.* 2004). It is probably not composed of a unique deltaic body, but it represents a superimposed subaqueous fan and coarse-grained Gilbert-type delta, which prograded into a terminoglacial lake. The lower part of the accumulation is not accessible for sedimentological research; therefore, no specific evidence is available for the interpretation of the lower part of the accumulation as a subaqueous fan. However, the vertical transition from a subaqueous fan to a coarse-grained delta due to massive aggradation took place in the deep terminoglacial and proglacial basins of other sites (Nemec *et al.* 1999; Plink-Björklund and Ronnert 1999). Therefore, this development can also be expected at the Písečná site due to the unusually large sediment thickness within the narrow and rather deep mountain valley.

The facies present in the delta plain (massive gravelly streamflood deposits) show that the upper part of the succession represents a terminoglacial delta according to Brodzikowski and van Loon (1991), or a glaciofluvial delta according to Lønne (1995). Based on the classification of McPherson *et al.* (1988) it could be described as a fan delta even though fluvial processes predominated over the delta plain. A channelized nature of the sedimentary architecture is typical of the delta plain of a braid delta (McPherson *et al.* 1988), and this has never been observed in the topset of the studied site at Písečná. Gába (1981) described massive gravel with horizontally bedded cobbles. These sediments form topset relics in the western sandpit (Text-fig. 6). It represents a classical Gilbert-type delta type B according to the Postma (1990) classification. The facies described from the temporary outcrop in the western sandpit proves the processes, which took place on the slope of the coarse-grained Gilbert-type delta. High-density flows with varying degree of erosion and aggradation, cohesionless debris flows, debris falls, and low-density flows point to a glaciofluvial delta (e.g. Mastalerz 1990; Nemec *et al.* 1999; Plink-Björklund and Ronnert 1999; Winsemann *et al.* 2004, 2009; Kostic *et al.* 2005).

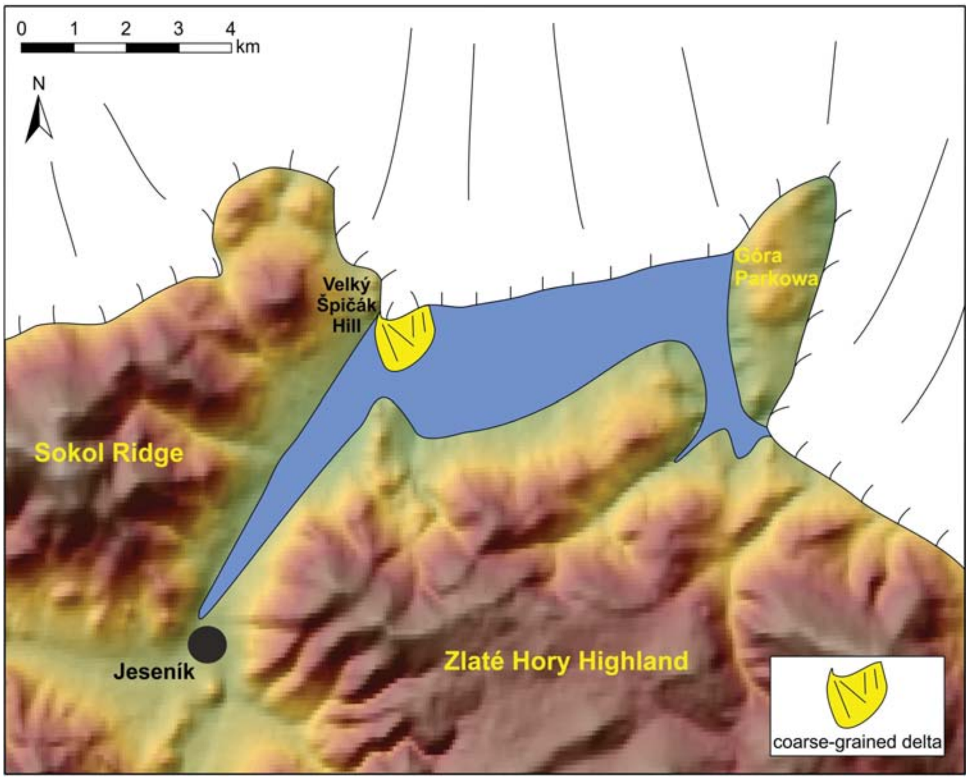
The uppermost part of the sedimentary succession consists of two diamicton layers, which has been interpreted by Gába (1981) as basal till. This interpretation means that the ice sheet advanced again to the South over the delta topset after the deposition of the delta. However, the new literature shows other possible interpretations. The lower diamicton could be classified as a clast-rich sandy diamicton according to the Moncrieff (1989) classification of poorly sorted sediments. It forms thin discontinuous layers, or fills deep erosional troughs. According to these features, it could represent the sediments of sudden catastrophic outbursts in the proximal zone of a subaerial terminoglacial fan according to Zieliński (1992) and Zieliński and van Loon (1999, 2000), or it could represent terminoglacial subaerial tunnel-mouth deposits according to Brodzikowski and van Loon (1991). In both cases, sudden deposition of all fractions occurs in deeply incised channels. It would represent the sediments of episodic outbursts on the degrading ice sheet front in the delta interpretation model. Reworked diamictic material may be present on the delta plains of ice-contact, or terminoglacial deltas (Brodzikowski and van Loon 1991; Lønne 1995). The upper diamicton could be classified as a clast-rich intermediate diamicton according to the Moncrieff (1989) classification. Its position at the end of the depositional sequence, its lithology, lateral continuity, clasts dipping consistently with the slope angle and the thickness increasing towards the valley coincide with features of subaerial terminoglacial flow tills (Brodzikowski and van Loon 1991; Zieliński and van Loon 1996). The absence of thick layers of stratified silt, sand and gravel in till suggests subaerial genesis. Alternating layers of diamictons and stratified sediment are evident in subaqueous flow tills, which were deposited as debris flows in ice-dammed lakes (Ward and Rutter 2000; Evans *et al.* 2012). All potential interpretations assume an ice sheet advance to the South over the delta topset. If the topmost diamicton in the succession was a basal till, the ice sheet melting would occur without the formation of a supraglacial facies. If the topmost diamicton was a flow till, it could represent supraglacial-terminoglacial deposition from a degrading ice sheet front. Facies similar to the upper diamicton are common sediment types of terminoglacial ice-cored moraines (Ewertowski *et al.* 2011).

### The stratigraphic and palaeogeographical position of the accumulation at Písečná

The new interpretation of the Písečná site adds an ice-dammed lake in the Bělá River valley to existing palaeogeographical ideas about the glaciation of this area. The maximum extent of the ice sheet, as well as the stratigraphy of the advance/s in the Bělá River valley remains a still unsolved question. According to Gába (1981), the Bělá River valley was glaciated during the first Saalian glacial and the ice sheet front reached a limit somewhere between Písečná and Jeseník. The studied accumulation at Písečná originated according to Gába (1981) during the advance of the Saalian ice sheet, which has covered the subaerial terminoglacial fan by basal tills. According to Cháb *et al.* (2004) the valley has been glaciated twice, during the first and second Elsterian glacial. During the first advance, the ice sheet filled the whole Bělá River valley to the present Jeseník town (Nývlt *et al.* 2011). The ice sheet front stopped roughly in the area of Písečná during the second advance. Weathered bedrock has been found directly below the studied accumulation in the western sandpit (Gába 1981). Sediments interpreted here as preglacial colluvia have been found beside the bedrock below the studied accumulation in the cores from the drilling database. Sediments corresponding clearly to tills have not been discovered below the gravel, sand and silt. The terminoglacial sediments at Písečná prograded onto a landscape which has either not been glaciated, or where older glacial sediments have been eroded before the younger glaciation. All potential interpretations of the upper diamicton above the delta topset assume an ice sheet advance over the delta. The present state of knowledge does not make it possible to determine more accurately the maximum ice sheet advance position in this area. The thick sedimentary accumulation near Písečná can therefore represent a terminal moraine of the second Elsterian or first Saalian ice sheet. The results obtained in this study could not help to solve the question of the stratigraphical classification of the sediments. It was not a subaerial terminoglacial fan, but a subaqueous terminoglacial fan covered by a coarse-grained Gilbert-type delta. The ice sheet front stagnated above the the Bělá River valley. The till above the topset and small glaciotectonic faults (Gába 1981) document ice sheet front fluctuations. However, the faults could have also originated synsedimentarily.

## NEW DEPOSITIONAL MODEL OF THE PÍSEČNÁ SITE

The ice sheet front halted above the Bělá River palaeovalley and its course was from the eastern slope of Velký Špičák Hill to the east towards Mikulovice town (Text-figs 1B, 12). The ice sheet front east of Mikulovice town probably advanced towards the



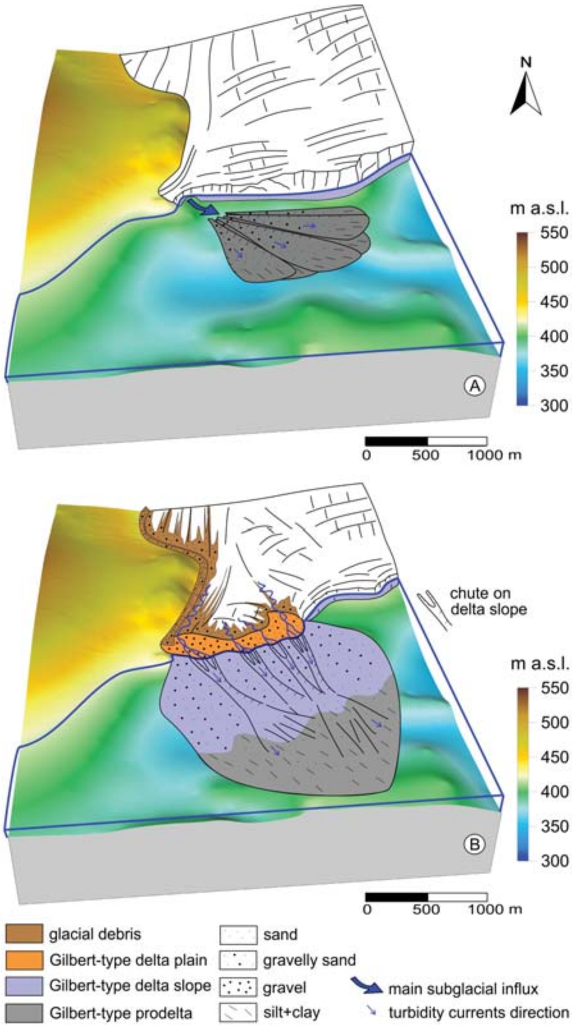
Text-fig. 12. Terminoglacial lake dammed by the ice sheet, Sokol Ridge, Zlaté Hory Highlands and Góra Parkowa. Yellow filled is the ice-contact Gilbert-type delta near Písečná

North-South ridge of Góry Parkowe (543 m a.s.l.) on the territory of Poland.

A terminoglacial lake existed between the ice sheet front, the northern and north-western slope of the Zlaté Hory Highlands and the south-eastern slope of the Sokol Ridge (Text-fig. 12). The lake was filled annually by seasonal water sources: the thawing ice sheet, mountain streams and snow and permafrost thawing from the hillslopes. The lake flooded the Bělá River palaeovalley south of the ice sheet. The lake level was probably controlled by small oscillations of the ice sheet front, when lake drainages could have opened and closed again. Such a drainage could have been located between the ice sheet and the ridge of Góry Parkowe.

The course of the ice sheet margin along the eastern slope of Velký Špičák Hill was North-South on a short segment. A preglacially originated subglacial drainage served as the path of the transported clastic material for the subaqueous fan and coarse-grained delta build-up (Johnsen and Brennand 2006).

The accumulation at Písečná in its initial phase could have developed as a subaqueous fan (Text-fig. 13A). Subaqueous fans represent the oldest part of the sedimentary infill of mountain ice-dammed lakes also at other localities (Johnsen and Brennand 2006). The sediments saturated by hyperpycnal flows draining through the subglacial valley from the NW rotated in the lake flooded by the Bělá River palaeochannel consistently with its orientation, i.e. towards the east. The Bělá River palaeochannel was split by at least two rocky elevations according to the GPR survey. It is possible that the palaeovalley floor was built by a larger number of palaeochannels and one or all of them drained the Bělá River. This would explain the absence of preglacial fluvial gravel in drilling 14 (Text-fig. 10C). The hyperpycnal flows changed their direction according to the local bedrock topography, causing changes in the progradation directions of the sedimentary bodies. The fan deposits lying directly on the bedrock copied its topography. After the filling of the palaeochannel, the sediments further aggraded and prograded to the adjoining lake floor. Every new hyperpycnal flow firstly eroded a chute into the previous sediments, which subsequently was filled by large-scale cross-stratified foresets and cross-stratified dunes (Diemer 1988; Winsemann *et al.* 2009). Distal facies (fine sand, silt and clay) was



Text-fig. 13. A – Initial stage of the development of the sedimentary accumulation at the Písečná site. The subaqueous fan is fed by water and material from the preglacially originating subglacial valley; B – Final stage of the sedimentary accumulation development. Coarse-grained Gilbert-type delta prograded into the lake from the thawing ice sheet front

deposited in the downstream position of the palaeochannel. As deposition took place in a river palaeochannel flooded by the lake, it resembles the fills of channel-like turbidites in a narrow fjord as presented by Lønne and Mangerud (1991) and Lønne (1997). After filling the Bělá River palaeochannel, the aggradation shifted also onto the sideslope of the palaeovalley. Diamicton was described in a sandy-gravelly unit in an altitude of 402–407 m in the drilling nr. 16 (Text-fig. 10A). This diamicton could represent material slipping down from an ice sheet front on the fan slope – i.e. a flow till (Aitken 1995). The diamicton unit corresponds to the altitude of the lower foreset (400–410 m) in the western sandpit outcrop according to Gába (1981), see Text-fig. 5A. The lower foreset could still belong to a subaqueous fan. The sediments started to aggrade also in the supplying drainage at the time of the deposition of the lower foreset. The upper foreset at an altitude of 410–425 m a.s.l. contains only gravel and sand and is overlain by a topset. For this reason, the upper foreset belongs to a coarse-grained Gilbert-type delta (Text-fig. 13B). It is likely that the delta gradually developed from the subaqueous fan when the aggradation reached the lake level (Nemec *et al.* 1999; Plink-Björklund and Ronnert 1999).

The ice sheet front was at the line of Velký Špičák Hill – height points 461 m and 431 m during the formation of the delta. The location and lateral relationship between sandy-gravelly unit and sandy-clayey unit (Text-figs 10, 11), together with the general direction of stratification towards the SSE in the western sandpit (Gába 1981) show the the fan and delta progradation from the NW towards the E, SE and S. The progradation direction towards the SW and SE at the altitude 425 m a.s.l. in the eastern sandpit (Cháb *et al.* 2004) suggests the contribution of material from the area between the height points 461 m and 431 m. The eastern part of the delta prograded generally to the South, i.e. to the centre of the valley at the end of the foreset development. This trend is evidenced by the progradation of the sandy-gravelly unit over the sandy-clayey unit in the eastern sandpit (Text-fig. 10B). The source of water and material could have been subglacial and/or englacial and supraglacial flow.

The depositional conditions of the coarse-grained delta foreset are documented from the temporary section described in this study. The section lies at an altitude of 410–415 m. The five main processes occurred at the delta front: Flow with alternating periods of erosion and deposition (facies SGs and GSs) with occasional scours of slope and backset origin (facies Sb), flow with alternating lower and higher deposition rates (facies SGg), cohesionless debris flows, debris falls (facies Gms, Gcs and Go), and subcritical nonstratified turbulent flow (facies Fl). Cohesionless debris flows and debris falls are the result of the peak high-energetic floods at the delta plain. Gravel and coarse sand were transported as bedload through the main channels of the delta plain towards the channel mouths, where they accumulated. They were later transported by avalanching over the delta slope. Deposits of flows with alternating lower and higher deposition rates originated by sliding of a large amount of predominantly sandy material from the mouth of a lateral channel on the delta plain. The facies with alternation of periods of erosion and deposition were deposited by hyperpycnal flows, which flowed in chutes over the delta slope during the increase, maximum stage and falling of the flood on the delta plain (Prior and Bornhold 1990). Subcritical nonstratified turbulent flows reflect the lowest currents over the delta plain. The absence of thin regular rhythms, but the presence of thicker layers deposited by the above-mentioned processes show that the deposition was mainly influenced by seasonal cyclicity of snow and ice melt, rather than the daily cyclicity (Mastalerz 1990). The foreset is mainly composed of granules, pebbles, cobbles and coarse sand. Fine material (mostly fine sand, silt and clay) bypassing the upper part of delta slope was deposited on the lower delta slope and in the prodelta (Nemec *et al.* 1999). This is how the upper part of the sandy-clayey unit originated. The sequences of sand, silt and clay in the central part of the lake are the result of a considerable lateral contribution of coarse-grained clastic material from lateral inflows into a relatively narrow lake (Johnsen and Brennand 2006). The lake is thus characterised by coarse sedimentation, which could be attributed to a different origin without the palaeogeographical context (Winsemann *et al.* 2007).

The subaerial delta plain prograded from the retreating ice sheet front (Text-fig. 13B). A network of shallow wide channels formed the plain. They developed at an altitude of 430–440 m a.s.l (Text-fig. 5). Gravel sheets and longitudinal bars evolved in these channels. The relatively large thickness of sediments of the delta plain (up to 7 m; Gába 1981) is the result of the contribution of a considerable amount of the material from the fast thawing ice sheet and the lake level rise. Channels filled by clast-rich sandy diamicton occur in the NW corner of western sandpit, i.e. in the place of subglacial drainage, already filled by sediments at that time. It is possible that the ice sheet was most disturbed here by subglacial, englacial and supraglacial streams and streams flowing from the adjacent mountain ridge. The ice sheet was divided into more blocks by these streams. Englacial and supraglacial material released during the degradation of ice blocks slipped into the streams to form hyperconcentrated flows that eroded and subsequently filled the channels.

The maximum depth of the lake could have reached up to ~65 m based on the sedimentary infill (infill base at 377 m a.s.l. in the drilling nr. 14 and the surface at 443 m a.s.l. in the drilling nr. 17, see Text-figs 10C, F). However, it is likely that during the lake development its basin was filled gradually, therefore the real depth was smaller. According to the thickness of the upper foreset (Text-fig. 5A), the water depth during the Gilbert-type delta formation can be estimated at ~20 m.

The deglaciation was then interrupted by a short ice sheet advance over the delta-plain, which resulted in the deposition of basal till, or terminoglacial flow till (Text-fig. 5A). It is not excluded that the present structures and textures of the basal till/terminoglacial flow till have been affected by colluvial processes and aeolian transport of the material during subsequent glacial periods.

The lake finally disappeared after the ice sheet retreat from the mountainside. The water probably drained along the ice sheet towards the NE. The infill of the central part of the lake has been largely removed by subsequent fluvial erosion. The delta near Písečná remained preserved at the periphery of the valley (Text-fig. 1), similarly to a delta in an extinct ice-dammed lake in the Weser Mountains (Winsemann *et al.* 2011). The deltaic part of the accumulation near Písečná lies at high altitude when compared with the altitudinal distribution of the continental glaciation sediments in the forefield of the Rychleby Mts. and Zlate Hory Highlands, as they lie mostly below 400 m a.s.l. It could thus be described as a delta moraine (kame delta) in the context of the whole ice sheet (Hambrey 1995).

## CONCLUSIONS

The accumulation of glacial sediments at the Písečná site has been interpreted as a superimposed lower subaqueous fan and upper coarse-grained Gilbert-type delta. The new interpretation is therefore different from those in the previous literature, according to which it represents a subaerial glaciofluvial outwash fan. A terminoglacial lake occupied the Bělá River valley based on the new interpretation. This was dammed by the ice sheet front in the north and bounded by the slopes of Sokol Ridge, Zlaté Hory Highlands and Góry Parkowe Ridge from other sides. The evolution of the lake, subaqueous fan and delta could not be reconstructed in detail given the present state of the sandpits near Písečná. The lake level reached up to 430 m a.s.l. during the youngest phase of its development, as the subaerial delta plain sediment base lies at this level and rose subsequently during the topset aggradation. A subaqueous fan and delta prograded from the ice sheet margin to the lake.

The sedimentary processes were driven by the preglacial morphology of the bedrock of metamorphic rocks. The direction of the subaqueous fan and partly of the coarse-grained delta progradation copied the course of the Bělá River palaeovalley, which has been filled by the fan and delta sediments. The clastic material drained through the preglacially eroded valley incised in the bedrock at the beginning of the formation of the subaqueous fan and delta. The relationship between the sediments and the preglacial landscape proves that the sedimentary processes in the marginal zone of the ice sheet in this mountainous terrain have primarily been driven by the topography of preglacial landscape.

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