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Chronology of the Late Weichselian glaciation in the Bohemian Forest in Central Europe

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ABSTRACT

A glacial chronology based on in situ-produced ^{10}Be surface exposure dating of moraines in the Bohemian Forest (Central Europe) was established. Eleven exposure ages obtained for moraine boulders in the Prášilské Lake and Laka Lake valleys (Czech Republic) were complemented by ^{10}Be ages from Kleiner Arbersee (Germany) recalculated according to recently calibrated production rates in the Northern Hemisphere. The glacial phases in the Bohemian Forest occurred during the Last Glacial Maximum around 24.1 ± 2.5, 23.6 ± 2.4, 21.8 ± 2.0 and 19.5 ± 2.1 ka. Following phases of local glaciation occurred during the Northern Hemisphere deglaciation period around 16 ka and 14 ka. The last indicated phase may correlate with Older Dryas. The glacial chronology of the Bohemian Forest is in agreement with local glaciation chronologies in the Giant Mts. (Krkonoše Mts.) and the Eastern Alps.

1. Introduction

During the Last Glaciation, Central Europe was a periglacial corridor (Tyráček, 1995) between the Scandinavian Ice Sheet and the Alpine glacier area (Fig. 1A). Evidence of the Last Glacial Maximum (LGM), represented by aeolian sand sheets and loess deposits at lower altitudes (Kasse, 2002; Frechen et al., 2003; Starnberger et al., 2011), is particularly important. There is little data older than 15 ka available for the Bohemian Massif in Central Europe (Pokorný, 2002; Svobodová et al., 2002; Jankovská, 2006; Huber et al., 2009; Engel et al., 2010). In addition to aeolian sediments, dated sequences of glacial landforms have become an important source of information about the LGM in mountain regions, such as the Alps (Ivy-Ochs et al., 2008; Kerschner and Ivy-Ochs, 2008) and the Carpathians (Rinterknecht et al., 2012; Makos et al., in press).

Within the above mentioned periglacial corridor, local glaciers developed in Hercynian mountain regions such as the Vosges (Mercier and Jeser, 2004), the Harz (Rother, 1995), the Giant (Krkonoše) Mountains (Braucher et al., 2006; Carr et al., 2007; Engel et al., 2011) and the Bohemian Forest (Šumava, Bavarian Forest) (Raab and Völkel, 2003; Reuther, 2007; Mentlík et al., 2010) (Fig. 1B). The glaciation of the Bohemian Forest was recognized in the mid-19th century based on a variety of landforms shaped by glaciers (Partsch, 1882; Bayberg, 1886; Rathsburg, 1928, 1932; Preihäusser, 1934). Although a relative glacial chronology of the northwestern Bohemian Forest for the Late Weichselian has been proposed (Mentlík et al., 2010), numerical data for the northern flank of the Bohemian Forest are still unavailable. Additionally, the existing surface exposure ages from the Kleiner Arbersee area (Reuther, 2007) represent moraines in the large cirque only. We suggest that small glaciers in deep cirques at leeward positions could respond more quickly to less significant climate deteriorations. To test these assumptions, we investigated moraine sequences within the Prášilské and Laka valleys.

The objectives of this paper are as follows: (1) to provide local ^{10}Be chronology in the northwestern part of the Bohemian Forest (the Prášilské and Laka Lake valleys), (2) to complement the chronological data from the Kleiner Arbersee valley (the southwestern Bohemian Forest) (Reuther, 2007) to establish a regional ^{10}Be chronology of the Bohemian Forest and (3) to integrate this new

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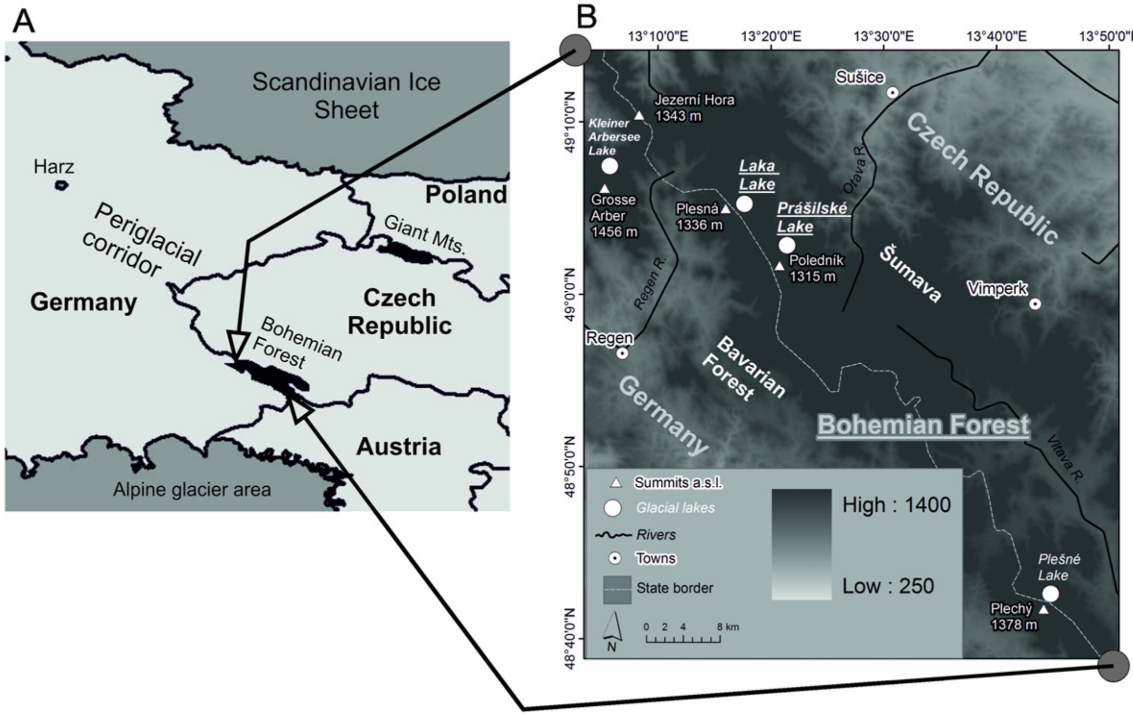

Fig. 1. A: The Bohemian Forest within periglacial corridor in Central Europe. Glaciation limits during the Last Glacial Maximum after Ehlers (Eds.) (2011) (in grey). B: Location of the investigated sites in the Bohemian Forest.

chronology with the available glaciation chronologies along the northeast–southwest transect throughout Central Europe (Giant Mountains – Bohemian Forest – the Alps).

2. Regional settings

2.1. Study area

The Bohemian Forest is located at 48°30′ – 49°20′ N and 12°10′ – 14°20′ E. The highest summits reach over 1400 m a.s.l. at Grosser Arber (1456 m) and Grosser Rachel (1453 m) in the German part of the mountains (Fig. 1B). The highest summits in the Czech region reach over 1300 m a.s.l. (e.g. Plechý, 1378 m, Poledník, 1315 m and Jezerní Hora Mt., 1343 m). The central part of the range with an area of ~670 km^2, consists of the flat, high-elevation terrain of the Šumava Plains, at approximately 1000 m a.s.l. The slightly undulating surface is dissected by tributaries of the Donau (Danube) River (e.g. the Regen, Ilz, Große Mühl Rivers) in the southwest and by the network of the upper Vltava and Otava Rivers on the northeastern flanks. The greatest differences in surface elevation can be found along the incised valleys of major rivers and around the highest summits where cirque and valley glaciers deepened pre-glacial valley heads (Hartvich and Mentlík, 2010).

At present, a transitional Central European climate prevails in the Bohemian Forest, but the overall pattern of temperature and precipitation is strongly affected by local topography. The mean annual temperature ranges from 6.0 °C at 750 m a.s.l. to 1.3 °C at 1300 m a.s.l., and the annual isohyet of 1000 mm coincides with an altitude of 1000 m (Neuhäuslová et al., 2001).

Geomorphological investigation and sampling were conducted in the northwestern part of the Bohemian Forest in two areas with relatively well-preserved moraines (Figs. 2 and 3).

The Prášilské Lake (1079 m a.s.l., 49°04′ N, 13°24′ E) is situated in a stair-shaped cirque on the eastern slopes of Poledník Mountain (1315 m a.s.l.). While crystalline schists surround the lake, the northern part of the cirque consists of granite (Mentlík et al., 2010).

Laka Lake (49°06′ N 13°19′ E; 1096 m a.s.l.) lies in the cirque on the eastern flank of Debrník (Lackenberg) Mountain (1336 m a.s.l.). The bedrock is composed mainly of paragneiss, but a small granodiorite outcrop (300 m long and 150 m wide) occurs in the cirque headwall (Mentlík, 2005).

2.2. Geomorphological evidence of glaciation

Three phases of glaciation were described in the Prášilské valley based on preserved moraines (Fig. 2). These phases are listed as follows, arranged from the relatively oldest and most extensive to the youngest and smallest (Mentlík et al., 2010).

Pras1: the small valley glacier phase, a phase of maximum ice extension (MIE), is represented by the oldest remnants of terminal and lateral moraines. The furthest position of the moraines shows the following glacier maximums: length (2060 m), width (~760 m), thickness (~54 m) and ice surface inclination ~6°.

Pras2: this phase is represented by a significant (up to 12 m high) outer (lake) moraine (Fig. 2) which developed when the whole stair-shaped cirque was occupied by a glacier.

Pras3: during this phase the glacier was restricted to the lower cirque and the inner (lake) moraine (Fig. 2) accumulated.

In the Laka valley, the presence of preserved moraines suggests at least two phases of glaciation (Mentlík, 2005). A lobe-shaped moraine assemblage, with its lowest point at 1045 m a.s.l. (MIE), blocked the valley head upon formation (Fig. 3). The lobe is clearly delimited by the steep slopes (~10 m high) of the outer lateral moraine (Mentlík, 2005). The inner lateral moraine exceeds the surface of the lobe by approximately 4 m along its eastern boundary.

In both valleys, glacial landforms are located along the eastern slopes of high-elevated flat ridges. During glacial episodes, the ridges were free of vegetation cover, forming an efficient deflation surface from which snow was blown to the valley heads at their lee-side. The presence of the high-elevated plateaus on the ridges together with climatic conditions controlled the growth of glaciers (*sensu* Partsch, 1882).

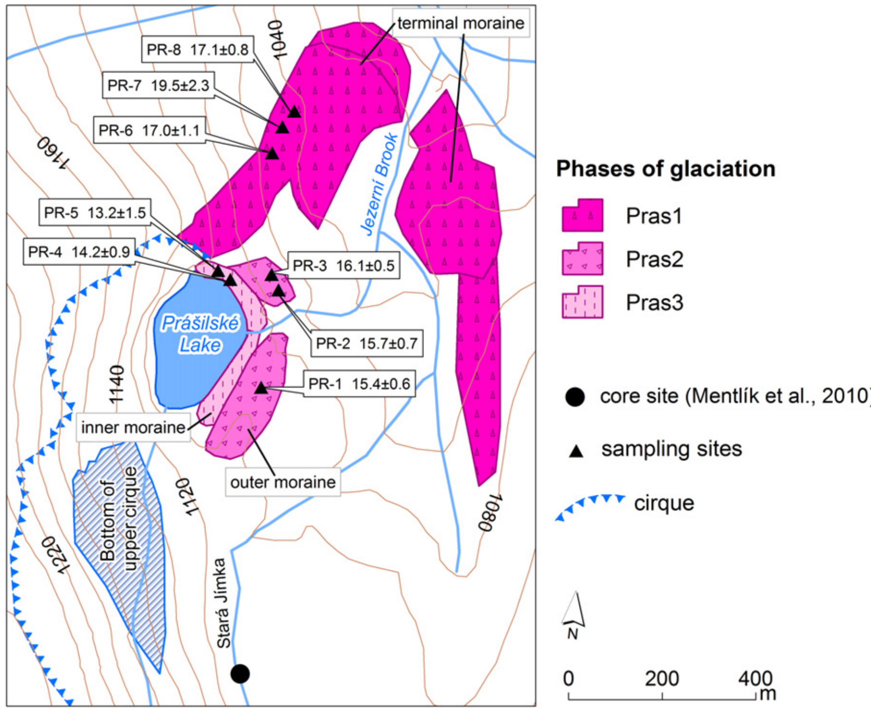

Fig. 2. Geomorphological sketch and location of CRN samples in the Prášilské valley.

3. Methods

3.1. GIS analysis

Digital elevation models (DEMs) of former glaciers were generated following the technique described by Sissons (1974). The models were used to calculate glacier volume and equilibrium line altitudes (ELAs) of the glaciation phases identified in both study areas. The reconstruction of glacier extent was based on field mapping of moraines (Mentlík and Novotná, 2010; Mentlík et al., 2010). The upper headwall limit of ice was estimated by extrapolating the ice surface from geomorphological evidence to a point on the backwall cliff (Hughes, 2010). The presence of ice at the steepest parts of the headwall was excluded using the approach of Sailer et al. (1999).

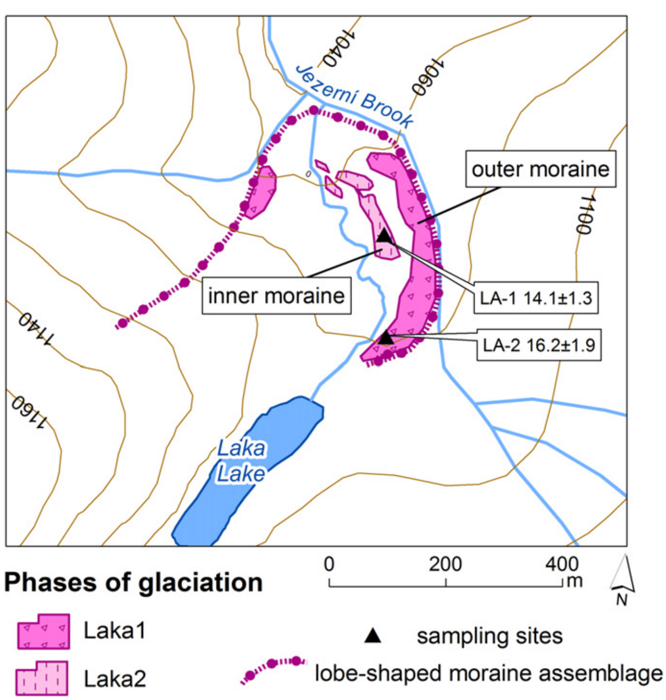

Fig. 3. Geomorphological sketch and location of CRN samples in the Laka valley.

The surfaces of former glaciers were contoured by extrapolating from points at the suggested ice margins. Ice surface contours were drawn as concave in the upper part, convex in the lower part and straight in the middle parts of the former glaciers (Carr and Coleman, 2007; Hughes, 2010). The elevation data were superimposed over current topography (ZABAGED®, 2012), and models of former glaciers were interpolated as a triangulated irregular network (TIN) and a GRID. The ELAs and morphometric characteristics of former glaciers (2D and 3D area, maximum length and volume) were calculated using the maximum elevation of lateral moraines (MELM) and accumulation area ratio (AAR50) methods (Benn and Gemmel, 1997; Benn et al., 2005; Reuther, 2007).

3.2. Surface exposure dating

In the Prášilské valley, we sampled large boulders on the surface of three different moraines (Fig. 2). Three samples were taken from boulders at the flat surface of the terminal moraine (Pras1) and at the ridge of the outer lake moraine (Pras2). Two samples were collected from the inner lake moraine (Pras3). All samples in this area were composed of coarse-grained biotite porphyritic granite (Weinsberg type). Near Laka Lake, the two samples from the ridges of the lateral moraines (Laka1 and Laka2, Fig. 2B) were composed of biotite granodiorite (Laka1 and Laka2). Samples were collected from the upper 3 cm of the rock surfaces using a chisel and hammer. The dip and aspect were measured with a clinometer and compass. The position of each site was recorded with GPS, and the altitude was determined using DEM and topographic maps. The site characteristics are described in Table 1.

The granite samples were crushed, sieved and cleaned with a mixture of HCl and H_2SiF_6. The extraction method for ^{10}Be

Table 1
Sampling sites for ^{10}Be surface exposure dating.

Sample code	Latitude	Longitude	Altitude (m)	Boulder height (m)	Site description
PR-1	49.0752	13.4021	1085	2.0	Crest of outer lake moraine
PR-2	49.0765	13.4019	1079	0.5	Crest of outer lake moraine
PR-3	49.0768	13.4011	1079	1.5	Crest of outer lake moraine
PR-4	49.0766	13.4005	1085	2.5	Crest of inner lake moraine
PR-5	49.0766	13.4004	1083	1.2	Crest of inner lake moraine
PR-6	49.0784	13.4014	1048	4.0	Flat surface of terminal moraine
PR-7	49.0791	13.4020	1042	4.5	Flat surface of terminal moraine
PR-8	49.0794	13.4021	1038	3.0	Flat surface of terminal moraine
LA-1	49.1131	13.3313	1086	0.8	Crest of inner lateral moraine
LA-2	49.1145	13.3303	1090	1.0	Crest of outer lateral moraine

($T_{1/2} = 1.387 \pm 0.012$ Ma) (Chmeleff et al., 2009; Korschinek et al., 2010) involved the isolation and purification of quartz and the elimination of atmospheric ^{10}Be.

A weighted amount (~100 mg) of a 3025 ppm solution of ^{9}Be was added to the decontaminated quartz. Beryllium was subsequently separated from the solution by successive anionic and cationic resin extractions and precipitations. The final precipitates were dried and heated at 800 °C to obtain BeO and then mixed with niobium powder prior to measurement. Measurements were performed at the French AMS National Facility, ASTER, located at the CEREGE in Aix-en-Provence. Beryllium data were calibrated directly against the National Institute of Standards and Technology (NIST) beryllium standard reference material 4325 using an assigned value of $(2.79 \pm 0.03) \cdot 10^{-11}$. Analytical uncertainties (reported as 1 sigma) include uncertainties associated with AMS counting statistics, AMS external error (0.5%) and chemical blank measurement. Long-term measurements of chemically processed blanks yielded ratios in the order of $(3.0 \pm 1.5) \cdot 10^{-15}$ for ^{10}Be. A sea-level, high-latitude (SLHL) spallation production of 4.03 ± 0.18 g^{-1} yr^{-1} was used and scaled for latitude (Stone, 2000) and elevation. This production rate is a weighted mean of recently calibrated production rates in the Northern Hemisphere (northeastern North America (Balco et al., 2009), northern Norway (Fenton et al., 2011), southern Norway (Goehring et al., 2012) and Greenland (Briner et al., 2012)). All individual production rates have been corrected for a ^{10}Be half-life of 1.387 Ma. For the sake of comparison, the same production rates were used for data published by Reuther (2007) as well as previously published exposure ages from the Giant Mountains (part 5.2).

Surface production rates were also corrected for local slope and topographic shielding due to the surrounding morphologies following Dunne et al. (1999). The shielding from snow was estimated according to Reuther (2007) using mean values for snow cover density (0.3 g/cm^3), duration (5 months) and thickness (45 cm) in the study areas. These values were estimated from the data collected at seven weather stations with altitudes ranging from 615 to 1437 m a.s.l. up to 22 km from the study sites, during the period from 1961 to 1990.

Cosmic Ray Exposure (CRE) ages were calculated using the following equation:

$$C_{(x,\varepsilon,t)} = \frac{P_{\text{spall.}}}{\frac{\varepsilon}{\Lambda_n}+\lambda} \cdot e^{-\frac{x}{\Lambda_n}}\left[1-\exp\left\{-t\left(\frac{\varepsilon}{\Lambda_n}+\lambda\right)\right\}\right] + \frac{P_\mu}{\frac{\varepsilon}{\Lambda_\mu}+\lambda} \cdot e^{-\frac{x}{\Lambda_\mu}}\left[1-\exp\left\{-t\left(\frac{\varepsilon}{\Lambda_\mu}+\lambda\right)\right\}\right] \quad (1)$$

where $C_{(x,\varepsilon,t)}$ is the nuclide concentration as a function of depth x (g cm^{-2}), ε is the denudation rate (g cm^{-2} a^{-1}), λ is the radioactive decay constant (a^{-1}), and t is the exposure time (a). P_{spall} and P_μ are the relative production rates due to neutrons and muons, respectively. Λ_n and Λ_μ are the effective apparent attenuation lengths (g cm^{-2}) for neutrons and muons, respectively. The muon scheme follows Braucher et al. (2011). The distribution of exposure ages from single moraines was analysed and the arithmetic mean age was calculated (Ivy-Ochs et al., 2007). If the distribution was not unimodal, the oldest exposure age obtained for a moraine was also taken into account (e.g. Briner et al., 2005).

4. Results

4.1. Area, volume and ELA of glaciers

In the Prášilské valley, the volume and ELAs of former glaciers were determined for three glaciation phases described by Mentlík et al. (2010) (Table 2). At the time of the local MIE (Pras1), the glacier volume was 0.049 km^3, and the ELA was between 1066 m a.s.l. (AAR50) and 1090 m a.s.l. (MELM). During the subsequent phase (Pras2), the ice volume decreased to 8% of that at the MIE and the ELA rose to 1140 m a.s.l. (AAR50). The glacier lost ~89% of the Pras2 ice volume during the ultimate phase of glaciation (Pras3), when the ELA oscillated around the same elevation as in the previous phase.

The position and extent of the outer lateral moraine in the Laka valley indicate an ice volume of 0.014 km^3 during the local MIE, Laka1 (Table 2). During the subsequent phase, the ice volume decreased by approximately 50%. ELAs, from 1145 to 1160 m a.s.l., were similar in both phases of glaciation due to the short advance of glacier termini out of the cirque.

4.2. ^{10}Be surface exposure ages

The exposure ages obtained for eight samples in the Prášilské valley fall into three distinct groups that correspond to existing moraines (Table 3 and Fig. 4). The ages of the three groups indicate deposition of all the preserved moraines during the Late Weichselian glaciation. Three sample sets from the Pras1 and Pras2 moraines yield a mean exposure age of 17.9 ± 1.5 ka and 15.7 ± 0.6 ka, respectively. The mean age of 13.7 ± 1.3 ka was calculated based on two exposure ages obtained on the Pras3 moraine that dams the lake. The sampled boulders from the outer (Laka1) and inner (Laka2) moraines in the Laka valley yield an exposure age of 16.2 ± 1.9 ka and 14.1 ± 1.3 ka, respectively. The within-moraine variability of exposure data is low, with the exception of the oldest moraine Pras1, where the difference in exposure ages exceeds the standard deviation of the ages obtained for the moraine boulders. Possible reasons for the relatively small discrepancy in the exposure ages are considered in Section 5.1.

5. Interpretation and discussion

5.1. Chronology of moraines in the Prášilské and Laka valleys

The obtained exposure ages are consistent within the study area, decreasing with the presumed age of the moraines. An analysis of variance (ANOVA) shows that exposure ages of moraines in the Prášilské valley differ significantly. The F-score implies a slightly larger difference between the terminal moraine Pras1 and the Pras2 moraine ($F = 24.4866$, $p = 0.0003$). However, a significant difference also exists between the moraine Pras2 and the lake moraine Pras3 ($F = 18.1927$, $p = 0.0009$). Although the ANOVA confirms a significant difference in age among the three groups of moraines, the age uncertainties are high (Table 3). Within the dataset, only four samples exhibit uncertainties lower than 5% of

Table 2
Chronological units in the Prášilské and Laka valleys.

Local chronological unit	Description	Lowermost point (m a.s.l.)	Ice surface area (km^2)	Volume of ice		AAR50 (m a.s.l.)
				Absolute (km^3)	% of MIE volume	
Pras1	Flat surface of terminal moraine	997	1.720	0.0490	100	1066
Pras2	Outer lake moraine	1065	0.231	0.0037	7.6	1140
Pras3	Inner lake moraine	1080	0.113	0.0004	0.8	1140
Laka1	Outer ridge	1060	0.751	0.0137	100	1145–1160
Laka2	Inner ridge	1057	0.565	0.0075	54	1145–1160

the relevant exposure age. This fact decreases the potential of the data for correlations, allowing for only cautious comparisons.

The variability in the ^{10}Be ages from Pras1 may be explained either by inheritance of the oldest sampled boulder or by post-deposition changes of the younger sampled boulders. Although pre-exposure of the oldest moraine boulder cannot be fully excluded, the flat appearance of the moraine indicates a substantial lowering of its surface after the glacier retreated. This suggests that moraine boulders probably changed their positions and the age of the samples is underestimated. Therefore, the age from the oldest dated boulder is considered to be closest to the time of moraine formation. A similar approach to interpreting exposure ages from moraines was adopted in a number of studies (e.g. Zreda et al., 1999; Putkonen and Swanson, 2003; Briner et al., 2005). Results from these studies imply that a simple neglecting of individual boulders with exposure ages younger or older than the overall mean is not always correct. Although the arithmetic mean of exposure ages from moraine boulders are often used to determine the timing of moraine deposition, this approach may yield an underestimated age (Phillips et al., 1990; Ivy-Ochs et al., 2007). Moreover, the averaging of exposure ages from a single moraine may obscure the real time of moraine stabilisation as exposure age distributions contain ages of boulders with different depositional histories (e.g. Briner et al., 2005; Reuther, 2007; Engel et al., 2011). Therefore, an average age should be taken as representative only when the set of exposure ages are from a single moraine cluster and overlap within age uncertainties.

Considering that exposure age provides the minimum age for dated surfaces, the moraines in the Prášilské valley deposited around 19.5 ± 2.3 ka, 15.7 ± 0.6 ka and 13.7 ± 1.3 ka.

Within exposure age uncertainties the older and younger moraines in the Laka valley may be correlated with the moraines Pras2 and Pras3 in the Prášilské valley (Fig. 5). The oldest (19.5 ± 2.3 ka) and the mean (17.9 ± 1.5 ka) exposure ages from the Pras1 moraine correspond with the retreat of Northern Hemisphere mountain glaciers at the end of the LGM (Clark et al., 2009). A subsequent advance of local glaciers and stabilisation of the Pras2 (15.7 ± 0.6) and Laka1 (16.2 ± 1.4) moraines coincides with the distinct climate deterioration that occurred around 16.8 ka (Hemming, 2004). Finally, the Pras3 (13.7 ± 1.3 ka) and the Laka2 (14.1 ± 1.1 ka) moraines were deposited in the middle of the Lateglacial. Although the uncertainty of exposure ages obtained for these moraines is relatively high, the timing of their formation tentatively correlates with the Older Dryas (OD) chronozone (Figs. 5 and 6). This cold event is well documented in fossil records in Western and Northern Europe (Lotter et al., 1992; Ammann et al., 1994; Walker, 1995; Peyron et al., 2005).

5.2. Comparison of glaciations in Prášilské, Laka and Kleiner Arbersee valleys

Morphologically significant moraines in the Kleiner Arbersee valley formed during the interval ~25–19 ka, whereas moraines in the Prášilské and Laka valleys were deposited between ~19.5 and ~14.0 ka (Fig. 5).

In the Kleiner Arbersee valley, moraines were deposited in three time spans. The terminal and lateral moraines (WI) formed ~24 ka, the readvance moraine (WII) ~21 ka and the "lake moraine" (WIII and IV) ~19 ka (Table 4). Although the lake moraine is the last dated morphological evidence of glaciation in the surroundings of Kleiner Arbersee, we cannot exclude subsequent glacier readvance in the southern part of the cirque, which is currently filled by the lake.

In comparison with the Kleiner Arbersee valley, it is not possible to distinguish early LGM advances in the surroundings of Prášilské and Laka Lakes. LGM moraines were probably wiped out by the subsequent glacier advance/s and/or incorporated in the Pras1 moraine. According to the results of exposure dating we suggest that the Pras1 moraine represents the final position of the glacier at the end of the LGM (~19 ka). The timing of its deposition coincides with the lake moraine formation in the Kleiner Arbersee.

Variation in the timing of glacial activity in the Kleiner Arbersee and the Prášilské/Laka valleys indicates local variability in the glaciers' response to climate change during LGM and Lateglacial. Differences in cirque dimensions imply substantially smaller glaciers in the Prášilské and Laka valleys than in the Kleiner Arbersee valley.

Table 3
Cosmogenic ^{10}Be surface exposure ages.

Sample valley	Sample	^{10}Be (10^5 atom g^{-1})	Exposure age (ka)	Local chronological unit		
				Oldest age (ka)	Average age (ka)	Name
Prášily	PR-1	1.54 ± 0.06	15.4 ± 0.6	16.1 ± 0.6	15.7 ± 0.6	Pras2
	PR-2	1.57 ± 0.07	15.7 ± 0.7			
	PR-3	1.61 ± 0.06	16.2 ± 0.6			
	PR-4	1.42 ± 0.09	14.2 ± 0.9	14.2 ± 0.9	13.7 ± 1.3	Pras3
	PR-5	1.32 ± 0.15	13.1 ± 1.5			
	PR-6	1.66 ± 0.11	17.1 ± 1.1	19.5 ± 2.3	17.9 ± 1.5	Pras1
	PR-7	1.90 ± 0.22	19.5 ± 2.3			
	PR-8	1.66 ± 0.08	17.1 ± 0.8			
Laka	LA-1	1.42 ± 0.13	14.1 ± 1.3	14.0 ± 1.3		Laka2
	LA-2	1.63 ± 0.19	16.3 ± 1.9	16.2 ± 1.9		Laka1

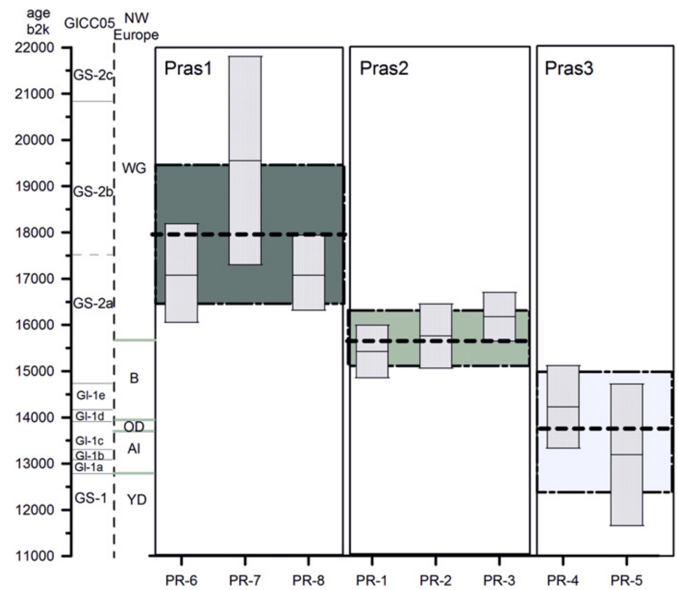

Fig. 4. Exposure ages for particular samples (boxes) and average ages of local chronological units in Prášilské valley (dashed line: average age of moraines formation; dot-and-dash box: *1-σ uncertainty*); GICC05 chronology after Björck et al. (1998), Lowe et al. (2008) and Blockley et al. (2012); Conventional ^{14}C ages of the Lateglacial chronozones (Mangerud et al., 1974) calibrated using OxCal program (Ramsey, 2009; Reimer et al., 2009); WG – Weichselian Glacial, B – Bølling, OD – Older Dryas, Al – Allerød, YD – Younger Dryas.

The volume of Laka ($96.70 \cdot 10^6$ m^3) and Prášily ($11.02 \cdot 10^6$ m^3) cirques is an order of magnitude lower than the volume of the Kleiner Arbersee cirque ($353.75 \cdot 10^6$ m^3). Although the Prášily glacier reached a similar length as the Kleiner Arbersee glacier during the Local Last Glacial Maximum (LLGM), its thickness was just half of it (Mentlík et al., 2010). According to an example described by Hughes (2010) from the Durmitor, glaciers in larger cirques are less favoured by shading and avalanching and are more reliant on direct precipitation on the glacier surface than glaciers in smaller and more enclosed cirques. Thus, any regional rise in temperature or reduction of precipitation is likely to have a greater impact on glaciers in larger cirques. We also suggest that a relatively greater mass of snow is required in larger cirques to reach a sufficient threshold (thickness) for glacier formation (cf. Mangerud et al., 2008). Therefore, a regional rise of temperature or reduction in precipitation exerted a stronger control on glaciers in larger cirques such as Kleiner Arbersee which additionally needed a longer time for their development. By contrast, small glaciers could have a relatively short response time to more immediate (and shorter) climate reversals. This may explain the more significant glacial activity in Kleiner Arbersee valley during the LGM and readvances in smaller cirques in Prášilské/Laka valleys during the shorter cold spells of the Lateglacial.

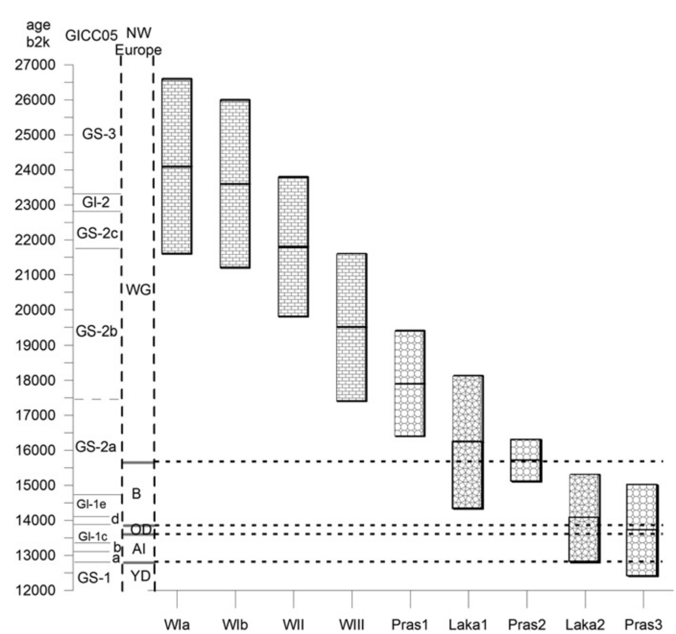

Fig. 5. Average exposure ages of local chronological units in Prášilské, Laka and Kleiner Arbersee valleys; GICC05 chronology after Björck et al. (1998), Lowe et al. (2008) and Blockley et al. (2012); Conventional ^{14}C ages of the Lateglacial chronozones (Mangerud et al., 1974) calibrated using OxCal program (Ramsey, 2009; Reimer et al., 2009); WG – Weichselian Glacial, B – Bølling, OD – Older Dryas, Al – Allerød, YD – Younger Dryas.

The ages obtained for moraines formation imply that glaciation in the Prášilské and Laka valleys finished in the middle of the Lateglacial. This finding is consistent with radiocarbon data from the Kleiner Arbersee, where the basal layer of a peat bog south of the lake at 915 m a.s.l. was dated at 12.8–12.4 cal ka BP (Raab and Völkel, 2003; Reuther, 2007). A similar age (12.6–12.2 cal ka BP) was reported by Mentlík et al. (2010) for organic sediment from the Stará Jímka (Prášilské Lake valley; Fig. 2). Radiocarbon data from both sites suggests that these hollows were ice free during the YD. Glacier development during this period was probably limited by significant dry conditions in Central Europe (Pokorný, 2002).

5.3. Correlation of glaciations in the study area, the Sudetes and the Alps

The LGM glacial events in the Bavarian/Bohemian Forest (phase WI) correlate with glacial activity in the Giant Mts. (the Sudetes), where glaciers terminated below the north-facing cirques and within the troughs on the southern flank. During this cold phase, according to the results of exposure-age dating (Engel et al., 2011), large moraines were formed in the upper Łomnica valley. Glacier advances deposited moraines in the Snowy Cirques and in the upper Labe and Úpa valleys. Although these deposits remain undated, their position and morphology, together with results of relative-age dating (Engel, 2007; Traczyk, 2009; Šebestová, 2011), suggest the deposition of moraines during the same cold phase.

The timing of the lowermost glacial deposits in the Prášilské valley (Pras1) overlaps with the recalculated age for the moraine that dams Kleiner Arbersee Lake (WII) and moraine relics in the upper Labe and Łomnica valleys (Braucher et al., 2006; Engel et al., 2011 and Table 5). The same age may be expected for a few moraines in other parts of the Giant Mts. The readvance phase in the study areas (Pras2 and Laka1) was synchronous with the ice advances in the Łomnica and Łomniczka valleys in the Giant Mountains (Table 5). Moreover, dated roches moutonnées in the Úpa valley (Braucher et al., 2006 and Table 5) and weathering characteristics reported for preserved moraines (Carr et al., 2007) suggest that the uppermost moraine in the Úpa trough was most likely deposited during the same glacial episode.

The terminal phase (Pras3 and Laka2) of the last glaciation in the Bohemian Forest was most likely synchronous with a period of restored glacial activity in the Giant Mountains (Traczyk, 2004). An OD age was suggested for one of the preserved readvance moraines in the Snowy Cirques based on the tentative correlation of moraines with radiocarbon-dated lake sediments deposited in between moraines (Chmal and Traczyk, 1998; Traczyk, 2004). The readvance moraine that dams the Wielki Staw Lake in the eastern Giant Mts.

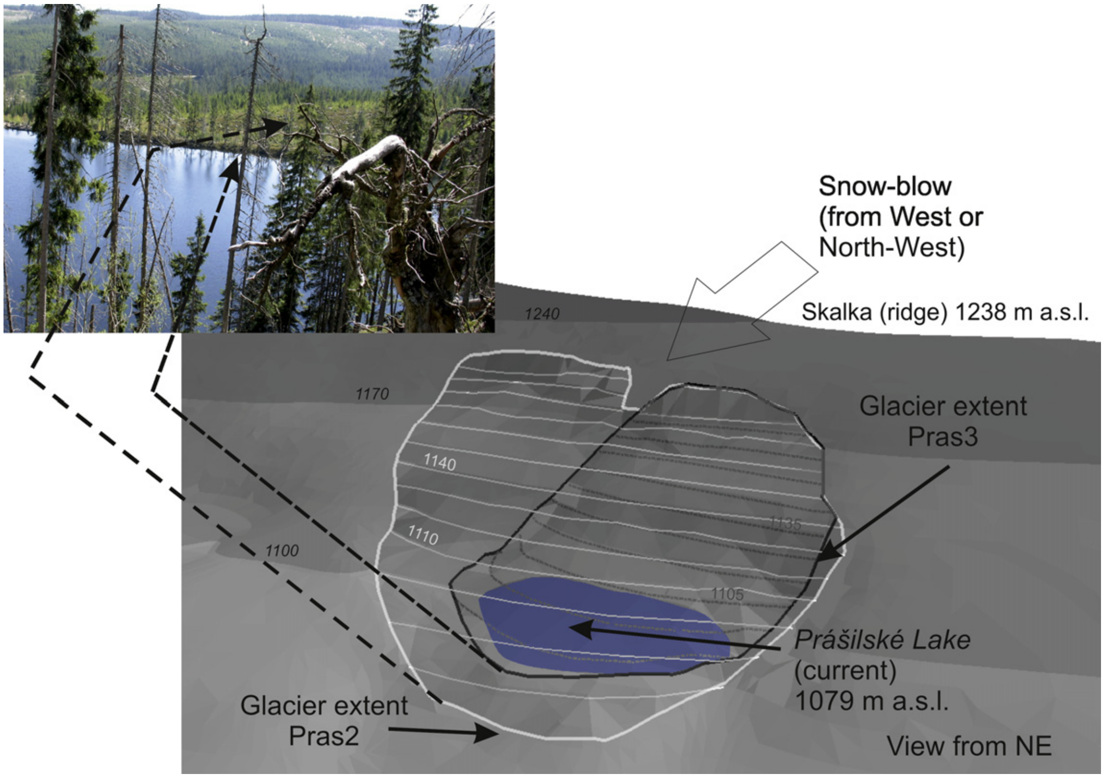

Fig. 6. Extent of glaciers in Prášilské valley during the Pras2 and Pras3 phases.

Table 4
Recalculated ^{10}Be exposure ages for moraines in the Kleiner Arbersee valley. Moraine labels and original exposure ages after Reuther (2007).

Moraine	Original age (ka)	Recalculated age (ka)
WIa	19.1 ± 2.0	24.1 ± 2.5
WIb	18.7 ± 1.9	23.6 ± 2.4
WII	17.3 ± 1.6	21.8 ± 2.0
WIII and WIV	15.5 ± 1.7	19.5 ± 2.1

most likely formed during the same episode as that reported for the nearest older moraine relics (Engel et al., 2011 and Table 5).

Based on the exposure ages presented above, a correlation of the local glacial episodes within the Bohemian Forest with the well-documented chronology of the Last Glacial advances within the Eastern Alps can be proposed. ^{10}Be exposure ages for the oldest preserved moraines in the Bavarian/Bohemian Forest suggest that advances of local glaciers related to the LGM coincide with advances of glaciers in the Eastern Alps (Table 5). The mean exposure age of ~16 ka obtained for older moraine relics in the Laka Valley and for the well-preserved outer lake moraine of Prášilské Lake coincides with the distinct climate deterioration at 17–15.6 ka that resulted in the interruption of afforestation and the Clavadel/Senders readvances of glaciers in the Alps (Monegato et al., 2007; Ivy-Ochs et al., 2008). Finally, the mean age of ~14 ka for the youngest moraines in the study areas (Fig. 6) most likely correlates with the Daun advance related to the OD cooling. Although the short-lived OD event is not well documented in the Eastern Alps (e.g. Huber et al., 2009), it is a significant dramatic event in the Lateglacial records within Central Europe (e.g. Lotter et al., 1992; Friedrich et al., 2001; Litt et al., 2001).

Table 5
Correlation of glacial chronostratigraphies in the Bavarian Forest, the Giant Mountains and the Eastern Alps.

^{10}Be age (ka)	Bavarian Forest[a]	Giant Mts.	Eastern Alps
14.1 ± 1.1	Pras3/Laka2	Śnieżne Kotły Cirques[d]	Daun Phase[f]
16.2 ± 1.2	Pras2/Laka1	Łomnica Cirque, Łomniczka[c]	Clavadel/Sanders[e]
19.5 ± 1.5	WIII[b]/Pras1	Łomnica III[c]	Gschnitz[e]
20–24	WII[b]	Łomnica II and I[c]	LGM[e], Tagliamento paleoglacier[g], Salzach paleoglacier[h]
22–27	WI[b]		Tagliamento paleoglacier[g]

[a] This study.
[b] Reuther (2007).
[c] Engel et al. (2011).
[d] Traczyk (2004).
[e] Ivy-Ochs et al. (2008).
[f] Van Husen (2011).
[g] Monegato et al. (2007).
[h] Starnberger et al. (2011).

6. Conclusions

^{10}Be exposure ages obtained from moraine boulders provide the first quantitative constraints on the timing of glacial episodes over the Late Weichselian in the northern part of the Bohemian Forest. Ten exposure ages from the Prášilské and Laka valleys cluster into three groups. The oldest moraines that formed ~19.5 ka correspond with the onset of Northern Hemisphere deglaciation. A subsequent advance of local glaciers occurred around 15.7 ± 0.6 ka and 16.2 ± 1.4 ka following deterioration of the global climate. Exposure ages of 13.7 ± 1.3 ka and 14.1 ± 1.1 ka indicate the deposition of the youngest moraines in the middle of the Lateglacial.

The correlation of the ^{10}Be ages from the study area with recalculated data from the Kleiner Arbersee valley (Reuther, 2007) provides a comprehensive view of the Late Weichselian glacial chronology in the Bavarian/Bohemian Forest. LGM conditions favoured glacier formation and moraine deposition in the Kleiner Arbersee valley between 24.1 ± 2.5 ka and 19.5 ± 2.1 ka. Subsequent advances of glaciers in smaller cirques (Prášilské and Laka valleys) occurred during the Lateglacial period. The chronology of glaciations in the Bavarian/Bohemian Forest presented herein shows overall agreement with local glacial chronologies of neighbouring mountain regions such as the Sudetes (Giant Mts.) and the Eastern Alps.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quascirev.2013.01.020.

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