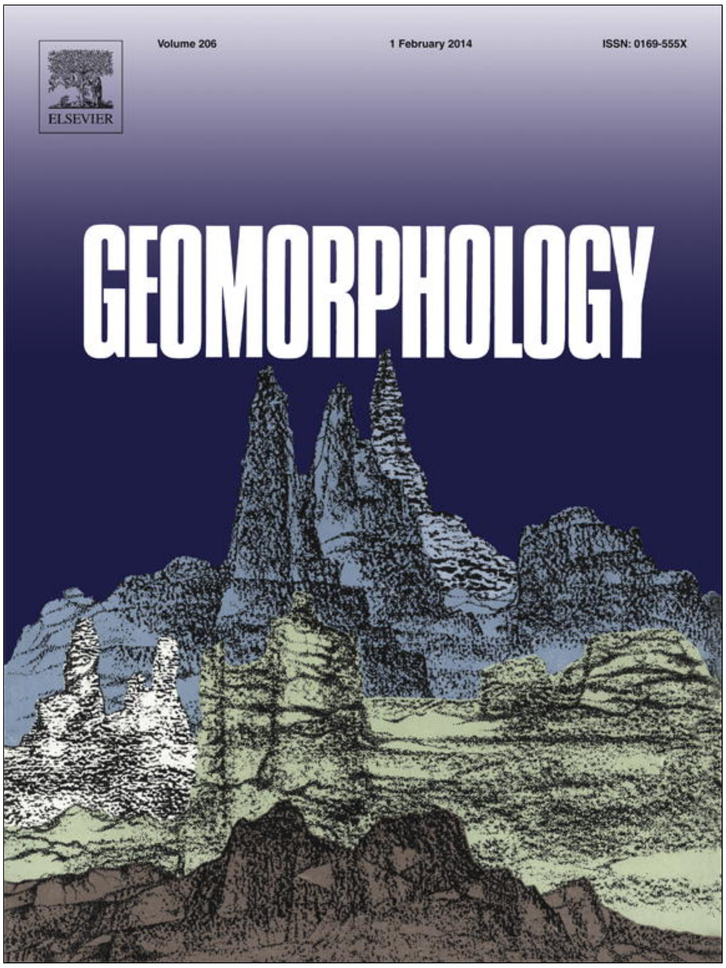
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# [10]Be exposure age chronology of the last glaciation in the Krkonoše Mountains, Central Europe

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ABSTRACT

A new chronology of the last glaciation is established for the Krkonoše (Giant) Mountains, Central Europe, based on in-situ produced $^{10}$Be in moraine boulders. Exposure ages and Schmidt Hammer rebound values obtained for terminal moraines on the northern and southern flank of the mountains suggest that the oldest preserved moraines represent early phases of the Last Glacial Maximum (LGM). Large moraines at the outlet of the Snowy Cirques (Śnieżne Kotły) and in the middle part of the Úpa (Obří důl) trough were deposited around 21 ka while a series of smaller moraines above the LGM deposits represent readvances that occurred no later than $18.1 \pm 0.6$ ka, $15.7 \pm 0.5$ ka, $13.5 \pm 0.5$ ka and $12.9 \pm 0.7$ ka. An exposure age of $13.8 \pm 0.4$ ka obtained for protalus ramparts at the foot of the Úpská jáma Cirque headwall indicates that glaciers advanced only in north- to east-facing cirques during the Lateglacial. The last glacier fluctuation was synchronous with the Younger Dryas cold event. The timing of local glacier advances during the last glacial episode correlates with the late Weichselian glacier phases in the Alps and in the Bavarian/Bohemian Forest.



## 1. Introduction

The Krkonoše (Giant) Mountains belong to Central European Variscan ranges which hosted local mountain glaciations during the Quaternary. Local glaciations of these ranges may provide important palaeoclimatic information for large regions of Central Europe, as mountain glaciers are sensitive indicators of climatic oscillations (e.g. Allen et al., 2008; Heyman et al., 2013). In this respect, the Krkonoše Mountains together with the Vosges and Bavarian/Bohemian Forest (Bayerischer Wald/Šumava Mountains) are important areas with a well-preserved record of glaciation (Engel et al., 2011). However, due to scarce chronological data and relatively limited extent of glacial deposits, glacial chronologies are poorly constrained (Andreoli et al., 2006; Nývlt et al., 2011). Palaeoclimate and landscape changes during the Late Quaternary are relatively well documented in lowland areas around the Krkonoše Mountains where a variety of sediment records exists (Bohncke et al., 2008; Engels et al., 2008; Frechen et al., 1999; Krzyszkowski, 1990; Krzyszkowski and Kuszell, 2007; Kuneš et al., 2007; Mol, 1997; Ralska-Jasiewiczowa et al., 2004; Rybníčková and Rybníček, 1996; Tyráček and Havlíček, 2009). However, less is known about the climate conditions in mountain areas, which generally retain poorer palaeoclimate records. In the Krkonoše Mountains, radiocarbon-dated lake sediments (Wicik, 1986) and peat sequences (Hüttemann and Bortenschlager, 1987; Jankovská, 2004; Skrzypek and Jędrysek, 2005; Speranza et al., 2000; Svobodová, 2004) document landscape evolution and climate fluctuations during the Holocene but significantly less is known about the Lateglacial period (Engel et al., 2010; Jankovská, 2007). Late Weichselian glaciation records therefore present a potentially promising proxy for climatic and environmental changes, largely missing from other sedimentary records.

Since the late 19th century, there have been attempts to identify and date local glacial episodes. A first chronology of local glaciations was proposed by Partsch (1882), who assigned moraines to the last and penultimate glacial periods according to their morphological characteristics and relative position in the landscape. An alternative hypothesis of a single glaciation was proposed two decades later based on geomorphologic criteria (Werth, 1901). However, due to the absence of absolute dating, the timing of glacier advances remained unknown until the end of the 20th century. Initial attempts to constrain the chronology of glaciations were limited to radiocarbon and thermoluminescence (TL) dating of sediments in cirques and moraine depressions. Radiocarbon data indicated minimum ages for the final withdrawal of local glaciers in the Mały Staw Lake ($9450 \pm 210$ $^{14}$C yr BP, Wicik, 1986) and in the upper Labe Valley ($9572 \pm 54$ $^{14}$C yr BP, Engel et al., 2004). TL dating of sediments in moraine depressions below the Snowy Cirques (Śnieżne Kotły) has provided the first chronological indication of pre-late Weichselian glaciation. TL ages of 87–93 ka from two cores suggest that the maximum glacial advance occurred during the early Weichselian or earlier glaciation (Chmal and Traczyk, 1999). A possible

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pre-late Weichselian glacial episode was supported by tentative correlation of till deposits in the Úpa Valley (Carr et al., 2002) and by relative-age and exposure dating of moraines in the pre-existing Labe trough (Braucher et al., 2006; Carr et al., 2007).

The most recent data constrain the timing of the late Weichselian glaciation in the Krkonoše Mountains. The sedimentary record from the Labe Valley indicates that the cirque was ice-free around 27.7 ± 1.5 ka, suggesting the limited extent of the last glaciation within MIS 2 (Engel et al., 2010). $^{10}$Be exposure ages from moraine boulders in the Łomnica and Łomniczka valleys imply the deposition of the oldest preserved moraines in the Last Glacial Maximum (LGM) and subsequent readvances between 17.0 ± 0.5 ka and 13.6 ± 0.9 ka (Engel et al., 2011). The recession of the Labe and Łomnica glaciers terminated no later than 10.8 ± 1.0 cal. ka BP and 11.5 ± 0.3 cal. ka BP, respectively (Chmal and Traczyk, 1998; Engel et al., 2010).

In this paper, we present $^{10}$Be exposure ages for the most complete sequences of moraines in the Snowy Cirques area and in the upper Úpa Valley, central Krkonoše Mountains. We interpret the new ages together with previously published chronological data on local glaciations and we suggest a chronology of the late Weichselian glaciation of the region. The proposed chronology is included into the frame of the Late Quaternary landscape evolution in the Krkonoše Mountains and the timing of local glaciations is compared with existing chronologies in Central Europe.

## 2. Study area

The Krkonoše Mountains are located in a transitional belt between areas dominated by oceanic climate and continental type regimes. The annual precipitation is moderate and increases with altitude from about 800 mm at Kowary weather station (460 m a.s.l.) up to >1500 mm per year in the highest areas of the western part of the Krkonoše Mountains (Głowicki, 2005; Halásová et al., 2007). The mean annual temperature (1961–1990) ranges from 7 °C in foreland areas to 0.4 °C at Sněžka weather station (1602 m a.s.l.), located in the eastern part of the study area (Gramsz et al., 2010; Halásová et al., 2007). Winds are mostly westerly and are responsible for the transport of snow from the summit plateaus to leeward slopes (Jeník, 1961).

The Krkonoše Mountains comprise WNW–ESE oriented parallel ridges which delimit two high-elevated plateaus (1400–1450 m a.s.l.) in the central part of the mountains (Fig. 1). The main Silesian Ridge (1400–1600 m a.s.l.) is ~30 km long and falls northward to the intramontane depression of the Jelenia Góra Basin (350–500 m a.s.l.). The parallel Bohemian Ridge is lower (1300–1550 m a.s.l.) and verges into rounded ridges of N–S orientation that are separated by deep river valleys. The Silesian Ridge and plateau areas are built of Carboniferous granite (~318 Ma; Awdankiewicz et al., 2010) whereas the southern part of the mountains consists of Cambrium to Ordovican metamorphic rocks (Žáčková et al., 2011). The high-elevated plateaus in the Labe and Úpa rivers source areas formed during the Late Cretaceous and the early Palaeogene after the end of a long period of erosion ~75 Ma (Danišík et al., 2010; Migoń, 1997).

Glacial geomorphology dominates the relief of the central part of the Krkonoše Mountains where cirques and troughs are deeply incised into the summit plateaus. The best-developed cirques of Śnieżne Kotły and Łomnica Valley border the northern part of the summit plateaus which have acted as deflation surfaces supplying snow to the glaciers around (Partsch, 1882). Glacial lakes and post-glacial peat bogs occupy the floors of these cirques. The less-developed cirques are distributed along the eastern and southern edges of the plateaus from where glaciers extended into the deeply incised valleys of the Labe and Úpa rivers transforming them into troughs (Sekyra, 1964). In addition to 13 well-defined cirques in the Krkonoše Mountains (Křížek et al., 2012), there are about 30 valley heads where small glaciers could have originated during the Quaternary (Šebesta and Treml, 1976). Two areas with the best-preserved moraine sequences in the Krkonoše Mountains were selected as the study area (Fig. 1). The Snowy Cirques are located in the western part of the mountains and the upper Úpa Valley represents the eastern part of the range.

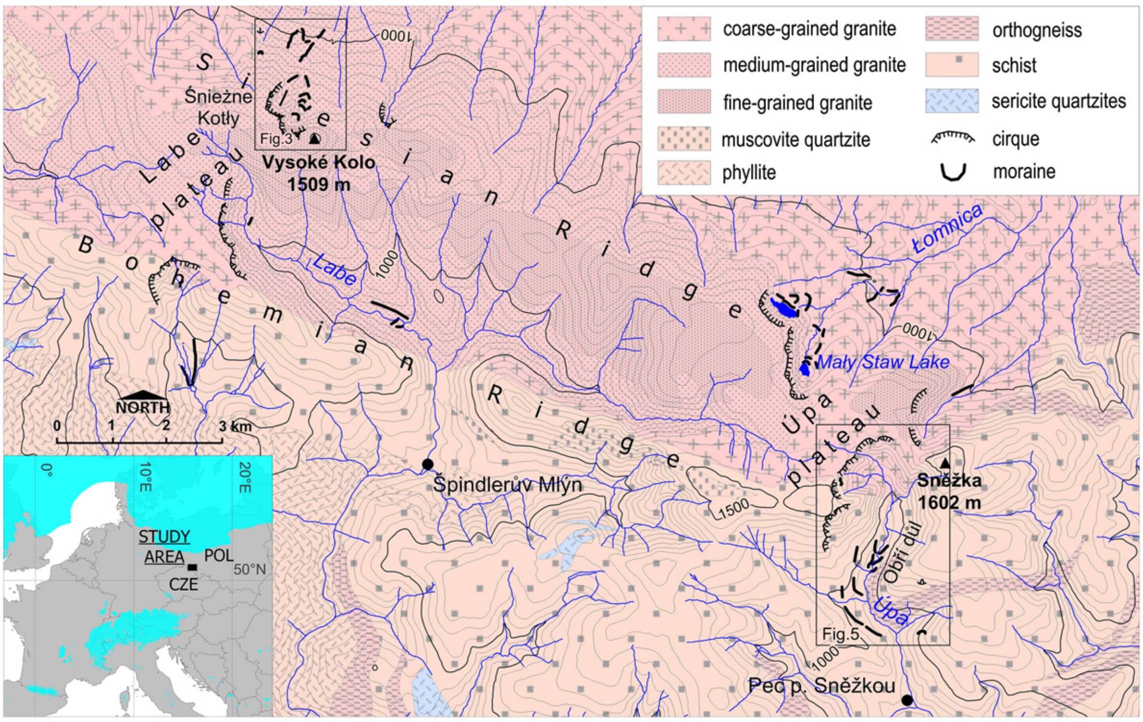


**Fig. 1.** Location of study areas within the Krkonoše Mountains and central Europe (inset). Geology simplified from GeoCR 50 dataset (Czech Geological Survey, 2004) and the Last Glacial Maximum extent of ice sheets (blue areas in the inset) after Ehlers et al. (2011).

### 2.1. Snowy Cirques area

The Wielki Śnieżny Kocioł (WSK) and the Mały Śnieżny Kocioł (MSK) cirques are incised into the northeastern slope of the main ridge of the mountains (Fig. 2A). The cirques have less than 200 m-high rock headwalls (Fig. 2B), which are composed of fine- to medium-grained biotite granite (Traczyk, 2009). The sheer rock headwalls are dissected by frequent ravines from which large talus cones descend to the cirque floor. The flat floor of the WSK cirque (1240–1300 m a.s.l.) is covered by moraine ridges and interleaved depressions, occupied by the Snowy Lakes (Śnieżne Stawki). A relic small rock glacier (Traczyk, 2009) occurs on more inclined and narrower floor of the MSK cirque (1200–1280 m a.s.l.). A major part of the cirques is located above the local timberline (1180–1280 m a.s.l.) where dwarf pine (*Pinus mugo*) dominates (Jeník and Lokvenc, 1962). By contrast, a spruce forest (*Picea excelsa*) covers the forefield of the cirques, including the oldest moraines.

The outermost and thus probably oldest moraines SK-I and SK-II are situated in the forefield of the Snowy Cirques at 930–1120 m a.s.l. (Fig. 3). The moraine complex consists of two terminal moraines with the lowest points at 930 and 960 m a.s.l. The location of the moraines implies the deposition by two individual glacier snouts descending from the MSK and WSK cirques. These terminal moraines are less than 25 m high, and are characterised by steep fronts and flat upper surfaces without characteristic sharp crests. Their morphology shows slightly undulating surfaces with numerous depressions implying vast post-depositional degradation and a potential rotation or shift of moraine boulders. The remnants of lateral moraines are well preserved along the western margin of deglaciated terrain and they can be traced for about 500 m and 750 m up-valley to the mouth of the MSK and WSK cirques, respectively.

The largest moraines SK-III occur in front of the MSK cirque at 1150–1220 m a.s.l. (Fig. 2C). Well-preserved ridges are less than 50 m high and terminate about 500 m laterally from the mouth of the cirque. The left lateral ridge can be traced up-valley for a distance of 250 m to the northern margin of the MSK cirque whereas the right lateral moraine stretches for about 250 m towards the outer rim of the WSK cirque. At the lowest point, the frontal moraine is dissected by the former outflow from the melting glacier. Recent fluvial reworking of the incision is negligible because superficial outflow from the cirque is low. Apart from the trench, only minor signs of post-depositional periglacial or fluvial reworking can be seen on the moraine.

The uppermost moraine SK-VII (1250–1310 m a.s.l.) forms a well-preserved ridge close to the foot of the WSK cirque headwall (Fig. 2B). The moraine is less than 35 m high and only its southeastern part is covered by debris-flow deposits (Migoń et al., 2010). A sequence of three moraine systems can be distinguished in front of the moraine SK-VII (Fig. 2D). The most prominent ridge SK-IV closes the lower part of the cirque floor at 1230–1270 m a.s.l. The moraine is ~30 m high and contains abundant coarse and blocky debris. Between SK-IV and SK-VII moraines there are fragments of two moraine relics (SK-V, SK-VI) which are separated by parallel depressions filled by shallow lakes. Boulders on the surface of the moraine relics are sub-angular to sub-rounded and up to several metres in diameter.

### 2.2. Úpa Valley

The upper Úpa Valley is situated on the lee-side of the high-elevation summit plateau of the Bílá louka Meadow, stretching southward from Sněžka Mountain (1602 m a.s.l.). A sharp upper limit of the Úpská jáma Cirque (Fig. 4A) descends from 1500 m a.s.l. in the western part of the cirque to 1380 m a.s.l. in its northern section. The best-

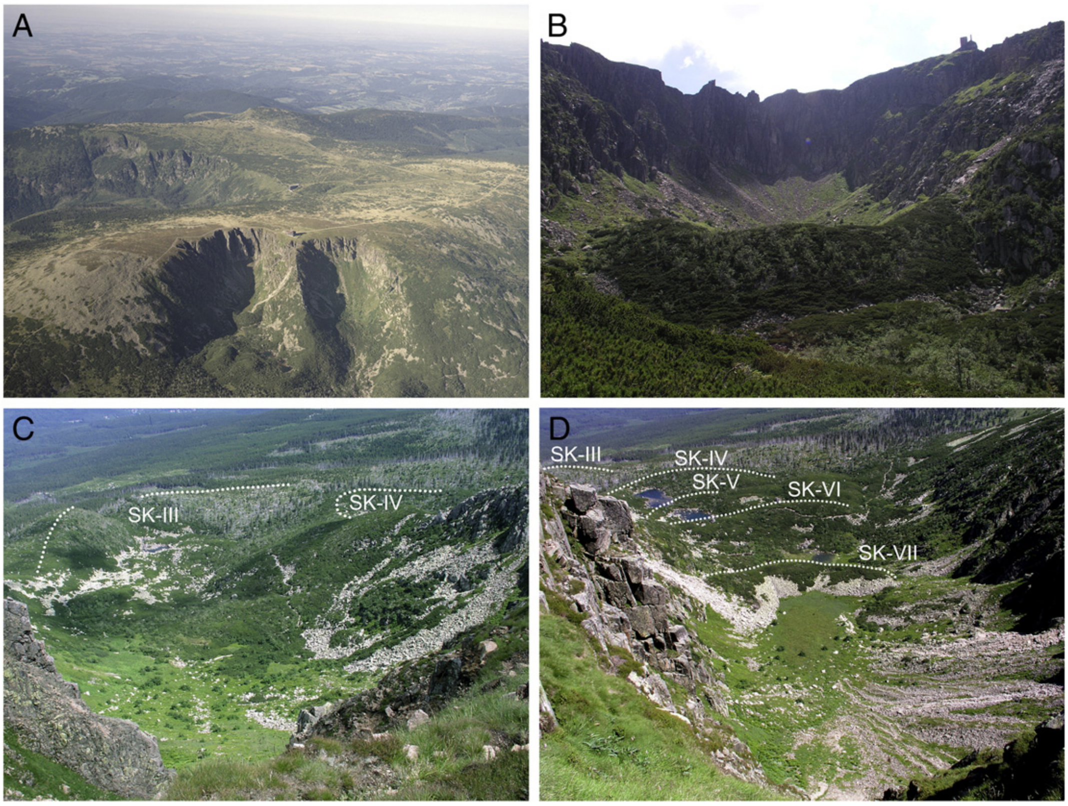


**Fig. 2.** Glacial landforms in the Snowy Cirques area. An overall view from the north (A) illustrates dissection of the high-elevated plateau in the western part of the Krkonoše Mountains dissected by the Snowy Cirques (in front) and the cirque of the upper Labe Valley (left). The Wielki Śnieżny Kocioł Cirque (B) with steep headwall and flat floor is the best developed cirque in the mountains. Note the uppermost moraine at the foot of the cirque headwall. Well-preserved moraine ridges close the mouth of the cirque (C) and cover the cirque floor (D). Photographs: MGGP Aero (A) and Z. Engel.

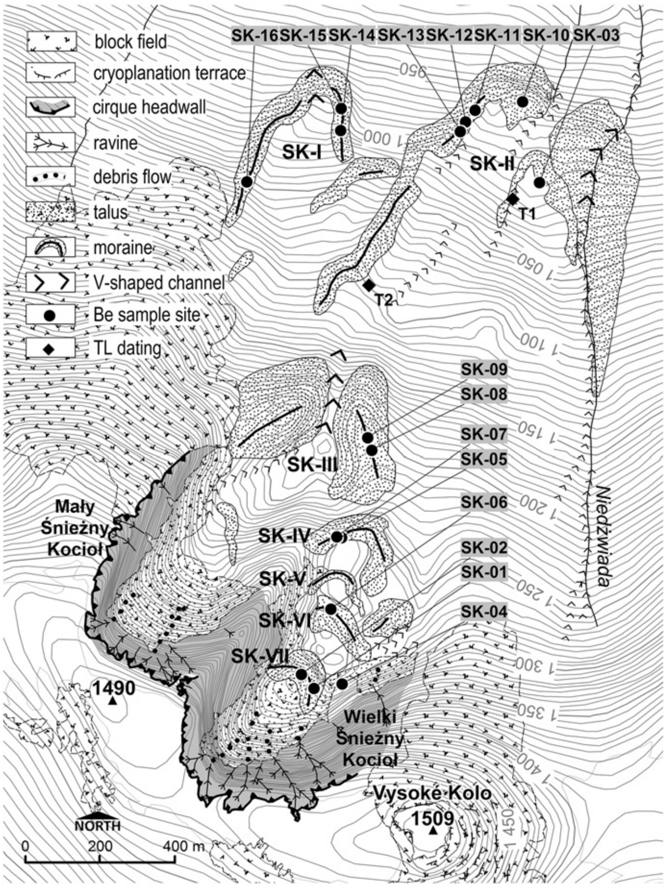


**Fig. 3.** Simplified geomorphologic map of the Snowy Cirque area with moraine locations and sampling sites.

developed cirque headwalls in the western part of the cirque are less than 100 m high but have slopes of greater than 50°. The upper part of the cirque headwall descends to a narrow step at 1300 m a.s.l. which is partly covered by slope deposits and protalus ramparts (Fig. 4B). The cirque floor is located at 1050–1020 m a.s.l. and its transition to a trough has the form of a 60 m high step (Fig. 4C). The cirque is carved in medium-grained porphyritic granite whereas the trough is made up by muscovite mica schist with intercalations of quartzite, chert and gneiss. The Úpa (Obří důl) trough is 3 km long and terminates below the hanging mouth of the Modrý důl Valley. A small glacier probably originated in this tributary valley and as well as in deeply incised hanging cirques in the eastern slope of Studniční hora Mountain (1554 m a.s.l.).

The upper Úpa Valley preserves a sequence of five moraines. Relics of the terminal moraine G-I (825–1020 m a.s.l.) are situated in the lower part of the Úpa trough (Fig. 5) with the lowest point at the confluence of the Růžový potok and Úpa rivers (825 m a.s.l.) The best-preserved moraine ridge rises up the western valley slope towards the mouth of the Modrý důl Valley to 100 m above the floor of the trough. A short section of glacial accumulations on the eastern valley slope is incised and partly covered by alluvial deposits. A sequence of four moraines can be distinguished in the central part of the Úpa trough. The largest moraine G-II occurs above the confluence of the Modrý potok and Úpa rivers (Fig. 4D). The moraine rises from the foot of the western trough slope, extending from 895 to 980 m a.s.l. The last remnants of the lateral ridge can be distinguished below the Velká Studniční jáma Cirque, around 140 m above the trough floor. A lower part of the moraine has been dissected and removed by the Úpa River as have some moraines located higher in the trough. Small remnants of recessional moraines G-III occur above the mouth of the Jestřábí ručej River at 910 m a.s.l. The remnants are ~7 m high and contain very few large boulders on their surface. A sequence of two morphologically pronounced moraine systems can be distinguished behind the moraine G-III. The moraines G-IV and

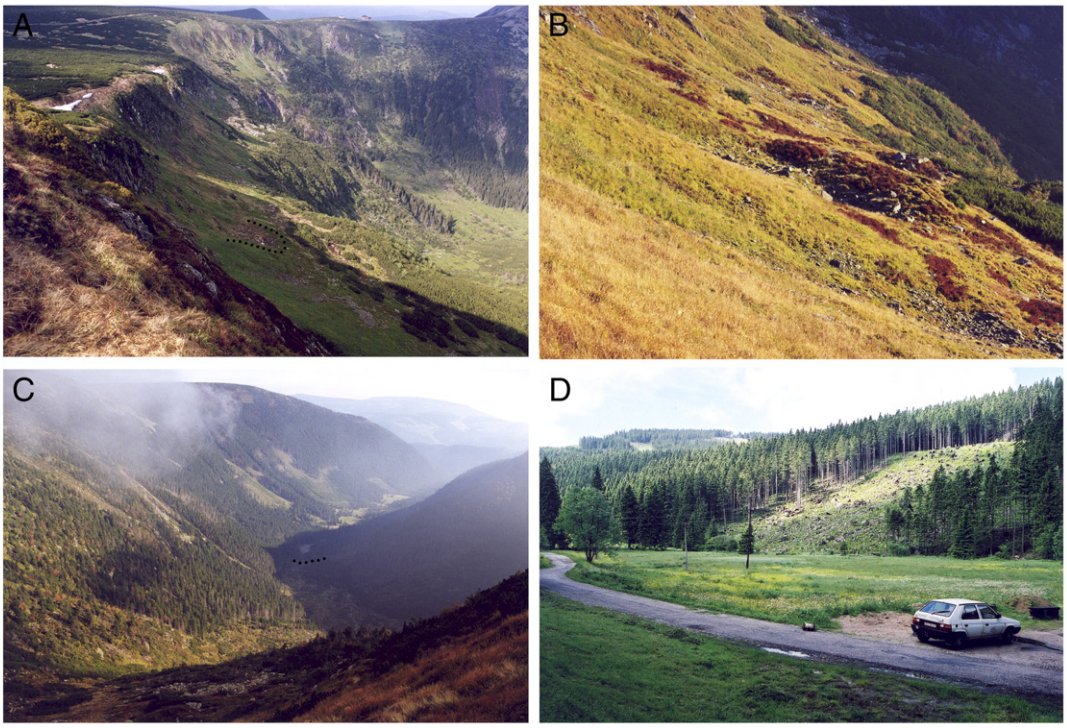


**Fig. 4.** The Úpská jáma Cirque headwall (A) is significantly lower and less-pronounced compared to the headwalls of the Snowy Cirques (see Fig. 2B). A dotted line in the photograph A indicates one of two protalus ramparts sampled for $^{10}$Be exposure dating. Photograph B documents distinct morphology of this protalus. Photograph C shows the Úpa trough where moraines are deposited. A dotted line indicates the location of the step that delimits the cirque floor. The lateral moraine (D, right upper corner) above the confluence of the Úpa and Modrý potok rivers.
Photographs: Z. Engel.

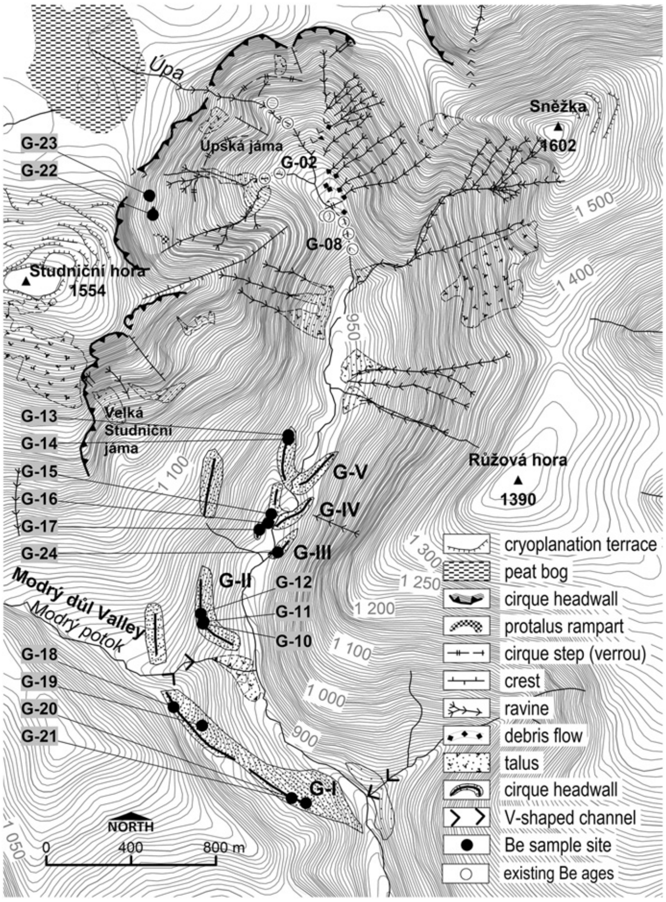


**Fig. 5.** Geomorphologic map of the upper Úpa Valley. The sites G-01 to G-09 indicate the locations of surfaces dated by Braucher et al. (2006) whereas G-10 to G-22 represent sites sampled as a part of this study.

G-V with the lowest points at 915 and 930 m a.s.l. rise up the western and eastern valley slopes. These recessional moraines are ~15 m high, and are characterised by rounded ridges with a limited amount of boulders suitable for exposure dating.

## 3. Methods

### 3.1. Site selection and sampling

$^{10}$Be surface exposure dating is an important tool for the reconstruction of mountain glaciation chronologies and studies that sample morainic boulders have given consistent results (e.g. Ivy-Ochs et al., 2007; Zreda and Phillips, 1995). The sampling of glacially eroded bedrock outcrops can also provide reliable data (Delmas et al., 2008; Gosse et al., 1995; Kelly et al., 2002); however complication can potentially arise from inherited nuclide concentrations (Ivy-Ochs and Kober, 2008). Moreover, bedrock steps and roches moutonnées are generally rare and irregularly distributed in mountain valleys. In this study sampling therefore focuses on morainic boulders, which best represent the timing of glacier advances (Gosse, 2005). Surface exposure dating reflects a complete exposure history of these surfaces and ages obtained may record pre-exposure of boulders, post-glacial degradation of surface or changes of boulder position (Gosse and Phillips, 2001; Hallet and Putkonen, 1994; Ivy-Ochs et al., 2007; Zimmerman et al., 1994). During the sampling, the selection of boulders in their original position is therefore an essential step for obtaining accurate ages. In order to increase the probability that the dated boulders have remained in a stable position, large upright boulders on the surface of moraines have been identified; samples have been collected preferentially from the upper surfaces of upright boulders located on crests of moraine ridges.

In addition, a bedrock surface (SK-04) at the foot of the WSK cirque headwall and protalus ramparts (G-22 and G-23) in the Úpská jáma Cirque were sampled to constrain the timing of glacier recession. All sampled surfaces were composed of medium-grained biotite monzogranite. In order to increase the accuracy of glacial chronology, at least two boulders were sampled for each moraine. While dating of multiple samples does not guarantee that the obtained timing is correct, it increases the probability that the oldest age will coincide with the landform age (Zreda and Phillips, 1995). Following the recommendations presented by Putkonen and Swanson (2003), three to five samples were collected from two moraines with presumably higher ages (SK-I, SK-II, G-I and G-II). Overall, 16 sites (SK-1 to SK-16) were sampled in the Snowy Cirques area and 15 sites (G-10 to G-24) in the Úpa Valley (Figs. 3, 5). Site characteristics and description are given in Table 1.

A Schmidt hammer (SH) was utilised to derive rebound (R) values for moraines that allow assessment of differences in the degree of weathering between the sampled moraines and limited correlation of moraines in the Krkonoše Mts. (Engel et al., 2011). The mean R-value of each moraine was calculated based on 150 SH assays undertaken on embedded granite boulders. 25 hammer impacts taken on horizontal surface of six boulders were processed following Moon's (1984) guidelines. The mean R-values from six boulders were averaged and the resulting value was taken as representative for each moraine. Analysis of variance (ANOVA) was used to determine whether any differences exist in mean R-value among groups of moraines. The significance of a relationship was tested by F test with p-level 0.05.

### 3.2. Sample preparation and data treatment

The granite samples were crushed, sieved and cleaned with a mixture of HCl and $H_2SiF_6$. The extraction method for $^{10}$Be ($T_{1/2} = 1.387 \pm 0.012$ Ma) (Chmeleff et al., 2010; Korschinek et al., 2010) involves isolation and purification of quartz and elimination of atmospheric $^{10}$Be. A weighed amount (~0.1 g) 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 extraction and precipitation. The final precipitates were dried and heated at 800 °C to obtain BeO and finally mixed with niobium powder prior to measurements, which were performed at the French Accelerator Mass Spectrometry (AMS) National Facility. Beryllium data were calibrated directly against the National Institute of Standards and Technology beryllium standard reference material 4325 by using an assigned value of $(2.79 \pm 0.03) \cdot 10^{-11}$. Age uncertainties include AMS internal variability (<0.5%), an external AMS uncertainty of 0.5% (Arnold et al., 2010), blank correction and 1 sigma uncertainties. Long-term measurements of chemically processed blanks yield ratios in the order of $(3.0 \pm 1.5) \cdot 10^{-15}$ for $^{10}$Be. A sea-level, high-latitude spallation production of $4.03 \pm 0.18$ at$\cdot$g$^{-1}\cdot$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 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 related to a $^{10}$Be half-life of 1.387 Ma.

Surface production rates were also corrected for local slope and topographic shielding due to surrounding terrain following Dunne et al. (1999). The shielding from snow was estimated according to Gosse and Phillips (2001) and Reuther (2007) using average snow density of 0.3 g$\cdot$cm$^{-3}$, the mean thickness and duration of snow cover in the study area. These values were estimated from data collected during the years 1961–1990 at nine weather stations in the Krkonoše Mountains (445–1410 m a.s.l.) and from detailed measurements of snow cover in valley heads (Głowicki, 1977; Kwiatkowski and Lucerski, 1979).

**Table 1**
Sampling sites and $^{10}$Be surface exposure ages from the Snowy Cirques and Úpa Valley.

| Sample | Altitude (m) | Boulder height (m) | Surface dip/ aspect (°) | Sample thickness (cm) | Topographic shielding factor | Snow cover depth/ duration (cm/month) | Total shielding factor | Production rate (at$^{-1}$ g$^{-1}$ yr$^{-1}$) | $^{10}$Be concentration (at$^{-1}$ g$^{-1}$) | $^{10}$Be uncertainty | $^{10}$Be age (yr) | Analytical uncertainty (±yr) | Total uncertainty (±yr) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SK-01 | 1283 | 1.4 | Horizontal | 3 | 0.98584 | 151/6 | 0.85623 | 10.807 | 137,094 | 9209 | 12,652 | 850 | 1139 |
| SK-02 | 1273 | 1.4 | Horizontal | 3 | 0.98700 | 155/6 | 0.85449 | 10.700 | 140,016 | 5851 | 13,052 | 545 | 954 |
| SK-03 | 1000 | 3.0 | Horizontal | 3 | 0.99969 | 128/5 | 0.90231 | 9.059 | 177,097 | 8405 | 19,511 | 926 | 1493 |
| SK-04 | 1254 | –[a] | 17/350 | 3 | 0.97989 | 160/6 | 0.84494 | 10.421 | 135,268 | 5177 | 12,945 | 495 | 921 |
| SK-05 | 1240 | 3.0 | Horizontal | 3 | 0.99698 | 163/5 | 0.85763 | 10.460 | 132,817 | 21,003 | 12,662 | 2002 | 2142 |
| SK-06 | 1253 | 6.0 | Horizontal | 3 | 0.99552 | 160/6 | 0.85842 | 10.579 | 143,556 | 4861 | 13,535 | 458 | 933 |
| SK-07 | 1245 | 2.0 | 2/355 | 3 | 0.99887 | 162/6 | 0.85994 | 10.531 | 191,279 | 6658 | 18,138 | 631 | 1258 |
| SK-08 | 1208 | 1.0 | 10/15 | 1 | 0.99932 | 165/6 | 0.85828 | 10.268 | 219,197 | 7064 | 21,193 | 687 | 1455 |
| SK-09 | 1207 | 1.5 | Horizontal | 1 | 0.99948 | 165/6 | 0.85841 | 10.261 | 216,294 | 6294 | 20,927 | 613 | 1406 |
| SK-10 | 986 | 1.2 | Horizontal | 3 | 0.99971 | 127/5 | 0.90294 | 8.962 | 173,162 | 6179 | 19,283 | 688 | 1346 |
| SK-11 | 982 | 1.8 | Horizontal | 3 | 0.99969 | 127/6 | 0.87171 | 8.623 | 136,806 | 4969 | 15,820 | 575 | 1110 |
| SK-12 | 993 | 1.4 | Horizontal | 2 | 0.99853 | 128/6 | 0.86997 | 8.682 | 132,487 | 7647 | 15,213 | 878 | 1267 |
| SK-13 | 998 | 1.5 | Horizontal | 2 | 0.99964 | 128/6 | 0.87094 | 8.728 | 130,880 | 7012 | 14,950 | 801 | 1203 |
| SK-14 | 1007 | 1.6 | Horizontal | 2 | 0.99941 | 128/6 | 0.87074 | 8.792 | 145,909 | 6221 | 16,552 | 706 | 1218 |
| SK-15 | 1001 | 1.4 | 10/60 | 2 | 0.99964 | 128/6 | 0.87094 | 8.754 | 169,423 | 5964 | 19,316 | 680 | 1344 |
| SK-16 | 1055 | 1.5 | Horizontal | 2 | 0.99921 | 130/6 | 0.86914 | 9.128 | 189,970 | 9354 | 20,782 | 1023 | 1613 |
| G-10 | 947 | 3.2 | Horizontal | 3 | 0.99894 | 126/5 | 0.89030 | 8.554 | 126,852 | 8314 | 14,780 | 969 | 1313 |
| G-11 | 951 | 1.8 | Horizontal | 3 | 0.99870 | 126/5 | 0.89030 | 8.583 | 151,575 | 17,018 | 17,615 | 1978 | 2242 |
| G-12 | 961 | 2.6 | 10/355 | 3 | 0.99780 | 126/5 | 0.88941 | 8.645 | 123,628 | 8073 | 14,252 | 931 | 1264 |
| G-13 | 971 | 2.0 | 17/90 | 2 | 0.99582 | 127/5 | 0.88549 | 8.677 | 130,270 | 4251 | 14,965 | 488 | 1022 |
| G-14 | 966 | 1.2 | Horizontal | 4 | 0.99582 | 127/5 | 0.88549 | 8.643 | 135,878 | 4211 | 15,674 | 486 | 1058 |
| G-15 | 940 | 1.8 | Horizontal | 4 | 0.99348 | 126/5 | 0.88400 | 8.442 | 123,407 | 4498 | 14,569 | 531 | 1023 |
| G-16 | 932 | 1.5 | Horizontal | 3 | 0.99416 | 125/5 | 0.88521 | 8.400 | 153,404 | 5505 | 18,218 | 654 | 1274 |
| G-17 | 927 | 2.5 | 7/95 | 3 | 0.99487 | 126/5 | 0.88524 | 8.506 | 161,780 | 5428 | 18,978 | 738 | 1512 |
| G-18 | 987 | 1.0 | Horizontal | 4 | 0.99748 | 127/5 | 0.88696 | 8.812 | 144,672 | 4448 | 16,374 | 503 | 1104 |
| G-19 | 974 | 3.5 | Horizontal | 3 | 0.99905 | 127/5 | 0.88835 | 8.725 | 165,054 | 5480 | 18,877 | 627 | 1294 |
| G-20 | 914 | 1.6 | Horizontal | 3 | 0.99915 | 125/5 | 0.88965 | 8.317 | 123,199 | 9521 | 14,762 | 1141 | 1444 |
| G-21 | 906 | 1.8 | 15/110 | 3 | 0.99917 | 124/5 | 0.89026 | 8.267 | 138,368 | 4779 | 16,689 | 576 | 1155 |
| G-22 | 1353 | 1.5 | Horizontal | 3 | 0.97873 | 109/6 | 0.86634 | 11.552 | 162,649 | 5222 | 14,049 | 451 | 956 |
| G-23 | 1365 | 0.9 | Horizontal | 2 | 0.99244 | 102/6 | 0.88369 | 11.898 | 162,025 | 4946 | 13,588 | 415 | 915 |
| G-24 | 925 | 2.7 | Horizontal | 3 | 0.99246 | 122/5 | 0.88549 | 7.783 | 129,504 | 4203 | 16,585 | 571 | 1201 |

[a] Bedrock outcrop at the foot of the WSK cirque headwall.

Cosmic Rays Exposure ages were calculated using the equation:

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

where $C(x, \varepsilon, t)$ is the nuclide concentration as a function of depth $x$ ($\text{g}\cdot\text{cm}^{-2}$), $\varepsilon$ the denudation rate ($\text{g}\cdot\text{cm}^{-2}\cdot\text{a}^{-1}$), $\lambda$ the radioactive decay constant ($\text{a}^{-1}$), and $t$ the exposure time (a). $P_{\text{spall}}$, and $P_\mu$ are the relative production rates due to neutrons and muons, respectively. $\Lambda_n$, $\Lambda_\mu$ are the effective apparent attenuation lengths ($\text{g}\cdot\text{cm}^{-2}$), for neutrons and muons, respectively. The muon scheme follows Braucher et al. (2011).

### 3.3. Surface exposure ages interpretation

The set of exposure ages from single moraines was processed along with general interpretation strategies (0Ivy-Ochs et al., 2007; Phillips et al., 1990). It was taken into account, that a mean exposure age of boulders differs from the timing of moraine deposition and age distributions tend to tail to younger age (Phillips et al., 1990; Zreda and Phillips, 1995). Therefore, a distribution of exposure ages obtained from a single moraine in the study area was expected with respect to its modality and age range. When boulder ages cluster and overlap within one-sigma deviation of the oldest age then average age was calculated and taken as representative for moraine. An average was used instead of error-weighted mean that implies misleading robustness of ages (Ivy-Ochs et al., 2007). In most cases, age distributions for a single moraine were not unimodal and the oldest exposure ages obtained were interpreted to represent the timing of deposition. The possible effect of pre-exposure was also considered using exposure ages and SH testing. The inheritance could be indicated by the discrepancy between measured R-values and exposure ages or by apparently higher ages compared with adjacent moraines.

As deposits of some glacial advances are mostly missing at a given location (Gibbons et al., 1984; Zreda and Phillips, 1995), the timing of a moraine sequence may be interpreted as a first approximation of the local glaciation chronology. In order to constrain the timing of glaciations in the Krkonoše Mountains, chronologies from both study areas were interpreted to represent major intervals of deposition. Finally, the proposed glacial chronology was compared with the Central European context.

## 4. Results

### 4.1. Chronology of moraines in the Snowy Cirques area

The SH R-values are strongly consistent within the area, decreasing with presumed age of moraines (Fig. 6). The mean R-values measured on the moraine SK-I (25.4 ± 1.4 to 32.4 ± 4.4) and SK-II (27.5 ± 2.6 to 35.5 ± 2.6) are significantly lower (F (1;10) = 59.478, p < 0.001) than mean R-values obtained for moraines located higher-up in the cirque area (33.0 ± 5.6 to 44.3 ± 4.6). Among moraine belts in the cirque, there is no significant difference in the mean R-values with the exception of the uppermost moraine SK-VII. The mean R-values obtained for boulders on this moraine (40.8 ± 5.3 to 44.3 ± 4.6) are significantly higher (F (1;10) = 6.593, p = 0.028) than values calculated for the moraine SK-VI (36.9 ± 3.0 to 42.0 ± 4.2).

Despite the observed R-values, the variability of exposure ages is high within the same moraine, with exceptions of the moraine SK-VII and SK-III. Samples SK-01 (12.7 ± 0.9 ka) and SK-02 (13.1 ± 0.5 ka) give the mean age of 12.9 ± 0.7 ka for the moraine SK-VII. Samples SK-08 (21.2 ± 0.7 ka) and SK-09 (20.9 ± 0.6 ka) from the moraine

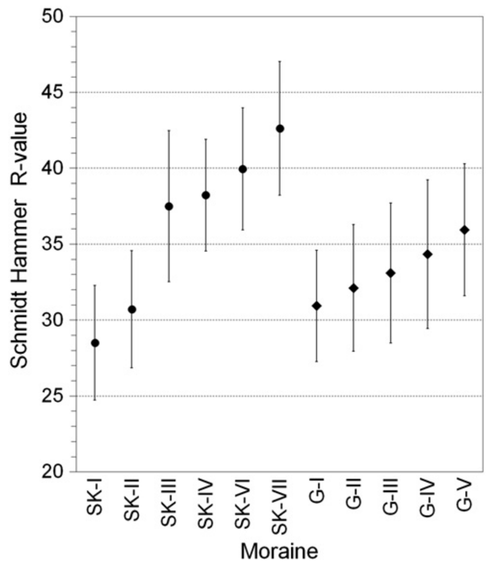


**Fig. 6.** Mean R-values for moraines in the Snowy Cirque area (circles) and Úpa Valley (diamonds).

SK-III exhibit a good agreement for both R-values and exposure ages but the high R-values should be linked with young exposure ages or vice versa but this is not what is observed (Table 2). The variability in $^{10}$Be ages from other moraines exceeds one-sigma deviation of the oldest boulder age and only the oldest ages are taken as representative for these moraines.

The set of exposure ages shows reasonable consistency in chronology of moraines except for the moraine SK-III. The mean (21.1 ± 0.7 ka) and oldest (21.2 ± 0.7 ka) age of this moraine are greater than the oldest age (SK-03: 19.5 ± 0.9 ka) obtained for apparently older moraine SK-II and are roughly the same as the oldest sample SK-16 (20.8 ± 1.0 ka) from the moraine SK-I (Fig. 7). This may be explained either by pre-exposure of sampled boulders on moraine SK-III or by underestimation of ages obtained for the moraines SK-I and SK-II. Possible reasons are considered in Section 5.1.

### 4.2. Chronology of moraines in the Úpa Valley

The SH data presented in Table 2 indicate that the degree of weathering of moraine boulders increase with presumed age of moraines. The mean R-value increases from 30.9 ± 3.7 for the terminal moraine G-I to 35.9 ± 4.3 for moraines G-V located in the upper part of the trough (Fig. 6). The mean R-values for all moraine belts are well within standard deviations of the whole dataset and there is no significant difference in the degree of weathering among moraines. This may be attributed to relatively narrow time span during which moraines were deposited. The mean R-value of 37.1 ± 3.4 was obtained for protalus ramparts located at the foot of the Úpská jáma Cirque headwall at 1350–1365 m a.s.l.

Exposure ages show reasonable within-site consistency only for protalus ramparts. The exposure age for G-22 (14.0 ± 0.5 ka) is only slightly lower than the sample G-23 (13.6 ± 0.4 ka) and well within standard deviation of the oldest age. Therefore, the mean exposure age of 13.8 ± 0.4 ka is assigned to protalus ramparts. The variability in $^{10}$Be age from moraine boulders exceeds one-sigma deviation of the oldest age for all moraines and the oldest boulder ages are taken as representative for these moraines.

Within exposure age uncertainties, the timing of moraine deposition is consistent. However, samples from the terminal moraine G-I show comparable or lower age than samples from apparently younger moraine G-III (Table 2). As the age for the moraine G-III is consistent with the chronology of moraines higher-up in the valley (Fig. 8), the oldest

**Table 2**
$^{10}$Be surface exposure ages from the Snowy Cirques and Úpa Valley.

| Sample | $^{10}$Be age (yr) | $^{10}$Be age uncertainty (±yr) | Moraine/sampled surface | Minimum altitude (m a.s.l.) | R-value | Oldest age (ka) | Mean age (ka) |
|---|---|---|---|---|---|---|---|
| SK-14 | 16,552 | 706 | SK-I[a] | 960 | 28.5 ± 3.8 | 20.8 ± 1.0 | 18.9 ± 0.8 |
| SK-15 | 19,316 | 680 | | | | | |
| SK-16 | 20,782 | 1023 | | | | | |
| SK-03 | 19,511 | 926 | SK-II | 930 | 30.7 ± 3.9 | 19.5 ± 0.9 | 17.0 ± 0.8 |
| SK-10 | 19,283 | 688 | | | | | |
| SK-11 | 15,820 | 575 | | | | | |
| SK-12 | 15,213 | 878 | | | | | |
| SK-13 | 14,950 | 801 | | | | | |
| SK-08 | 21,193 | 687 | SK-III | 1150 | 37.5 ± 5.0 | 21.2 ± 0.7 | 21.1 ± 0.7 |
| SK-09 | 20,927 | 613 | | | | | |
| SK-05 | 12,662 | 2002 | SK-IV | 1230 | 38.2 ± 3.7 | 18.1 ± 0.6 | 15.4 ± 1.8 |
| SK-07 | 18,138 | 631 | | | | | |
| SK-06 | 13,535 | 458 | SK-VI | 1240 | 40.0 ± 4.0 | 13.5 ± 0.5 | 13.5 ± 0.5 |
| SK-04 | 12,945 | 495 | Roche moutonnée | 1254 | 42.8 ± 2.8 | 13.0 ± 0.5 | 13.0 ± 0.5 |
| SK-01 | 12,652 | 850 | SK-VII | 1250 | 42.7 ± 4.4 | 13.1 ± 0.5 | 12.9 ± 0.7 |
| SK-02 | 13,052 | 545 | | | | | |
| G-18 | 16,374 | 503 | G-I | 825 | 30.9 ± 3.7 | 18.9 ± 0.6 | 16.7 ± 0.8 |
| G-19 | 18,877 | 627 | | | | | |
| G-20 | 14,762 | 1141 | | | | | |
| G-21 | 16,689 | 576 | | | | | |
| G-10 | 14,780 | 969 | G-II | 895 | 32.1 ± 4.2 | 17.6 ± 2.0 | 15.5 ± 1.3 |
| G-11 | 17,615 | 1978 | | | | | |
| G-12 | 14,252 | 931 | | | | | |
| G-17 | 18,978 | 738 | G-III | 910 | 33.1 ± 4.6 | 19.0 ± 0.7 | 17.8 ± 0.7 |
| G-24 | 16,585 | 571 | | | | | |
| G-15 | 14,569 | 531 | G-IV | 915 | 34.3 ± 4.9 | 18.2 ± 0.7 | 16.4 ± 0.6 |
| G-16 | 18,218 | 654 | | | | | |
| G-13 | 14,965 | 488 | G-V | 930 | 35.9 ± 4.3 | 15.7 ± 0.5 | 15.3 ± 0.5 |
| G-14 | 15,674 | 486 | | | | | |
| G-22 | 14,049 | 451 | Protalus rampart | 1345 | 37.1 ± 3.4 | 14.0 ± 0.5 | 13.8 ± 0.4 |
| G-23 | 13,588 | 415 | | | | | |

[a] A moraine deposited by the MSK glacier.

age obtained for the moraine G-I seems to be underestimated. An inaccurate age of the sample G-11 (17.6 ± 2.0 ka) which represents the moraine G-II is consistent with other dated moraines only due to large $^{10}$Be uncertainty.

*4.3. Correlative potential of moraines*

The potential of dated moraines for correlations is limited by different position and geomorphology of the two study areas. The response of glaciers to climate changes probably differed between these sites, leading to discrepancies in the timing of moraine deposition. Moreover, the less precise timing of moraines below the Snowy Cirques and in the lower part of the Úpa trough decreases the potential of relevant exposure data for correlations. Exposure ages obtained for the oldest moraines in both study areas overlap within $^{10}$Be age uncertainties, allowing for tentative comparisons only. By contrast, a synchronous origin is observed for the moraines SK-IV and G-IV (18.1–18.2 ka) and for the moraine SK-VI and protalus ramparts (13.5–13.8 ka) in the Úpská jáma Cirque. A missing equivalent for the moraine G-V (15.7 ka) may be attributed to incomplete sampling in the WSK cirque, where samples were collected only from well-preserved moraines. It is probable that the deposition of undated moraine relics SK-V located between the moraines SK-IV (18.1 ka) and SK-VI (13.5 ka) on the bottom of the WSK cirque (Fig. 7) was coincident with the origin of the youngest moraine in the Úpa trough. The uppermost moraines SK-VI (~13.5 ka) and SK-VII (13 ka) in the WSK cirque lack its equivalent in the Úpa Valley, presumably due to unfavourable conditions for glacier development at east- to south-facing cirque slopes during the Lateglacial.

Although none of the two study areas contains dated deposits of all glacial events, the succession of moraines in both areas preserves the best available record for correlation of the Weichselian glaciation in the Krkonoše Mountains. The Snowy Cirques foreland represents more favourable area for reconstructions of older glacial events than the Úpa Valley where trough-confined moraines have been affected by concentrated runoff. Results of exposure dating presented in Table 3 show that some moraines in the study area correlate well with glacial deposits at other locations within the range. Coincident ages of younger moraine belts within study areas as well as their correlation with well-preserved moraines in the Labe, Łomnica and Łomniczka valleys suggest a synchronous development of glaciers throughout the Krkonoše Mountains. The strongest correlation is observed for moraines dated to 19–17 and 15–13 ka.

## 5. Discussion

*5.1. Early phases of the last glaciation history*

The oldest terminal moraines that were deposited in early phases (K-I and K-II) of the last glaciation are located 2 to 4 km below the cirques. In the northern flank of the mountains glaciers descended from the Snowy Cirques to the terminal moraine SK-I at 960 m a.s.l. This relates to the largest extent of the palaeoglacier and is marked by lower and more restricted moraine ridges than the subsequent moraine SK-II that terminates at 930 m a.s.l. The same situation occurred in the eastern part of the mountains where the Łomnica glacier deposited less distinctive moraines first and higher ridges subsequently (Traczyk, 1989). The forefield of the Łomnica cirques is similar to the Snowy Cirque area allowing the spread of glaciers over slightly undulated slopes without large pre-glacial incisions (Fig. 8). By contrast, characteristic valley glaciers confined to incised valleys, existed in the southern flank of the mountains. Extensive glaciers descended the upper Labe and Úpa valleys, where they formed terminal moraines.

Exposure ages obtained for the oldest moraines in the Snowy Cirques and in the Úpa Valley overlap within age uncertainties with $^{10}$Be ages which represent consecutive moraines SK-III and G-III. However, the position and morphology of the oldest moraines suggest, that there should be more prominent difference in the timing of moraines. As exposure ages obtained for the moraines SK-III and G-III are

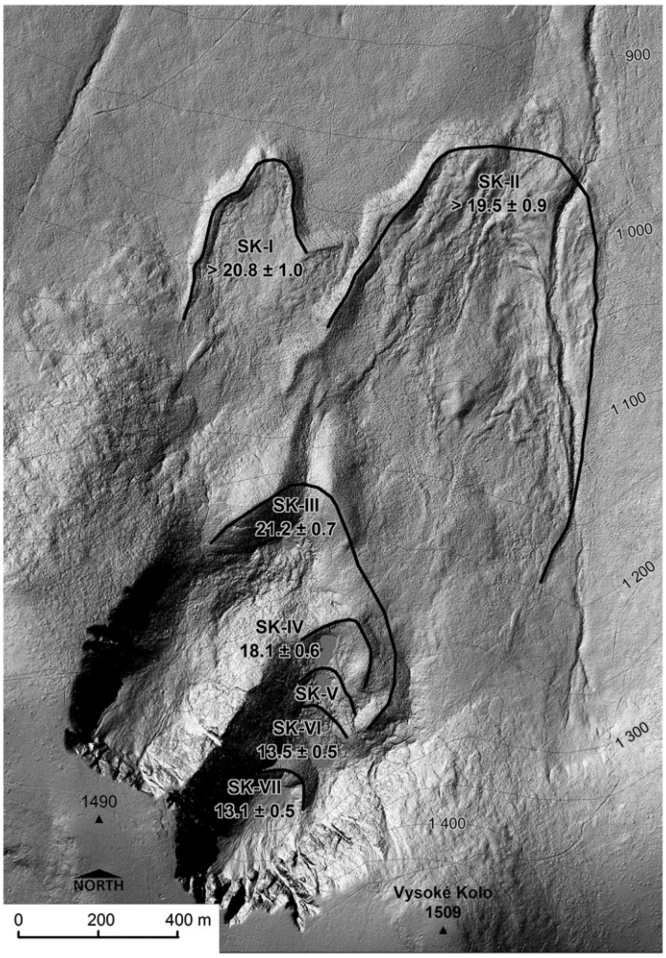


**Fig. 7.** $^{10}$Be exposure ages for moraines in the Snowy Cirques.

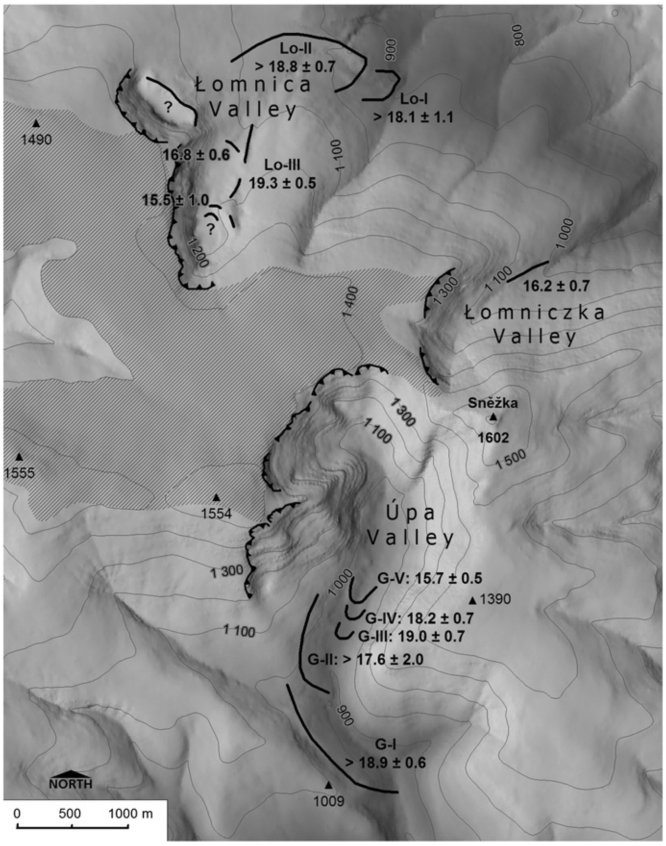


**Fig. 8.** $^{10}$Be exposure ages for moraines in the Úpa, Łomnica and Łomniczka valleys, the eastern Krkonoše Mountains. Oblique hatching indicates high-elevated deflation area from which snow was blown to cirques on the leeward side of the plateau.

consistent with the timing of younger moraines, ages of the two oldest moraines seem to be underestimated. Moreover, the age underestimation of the moraines is apparent from the SH data measured on moraine boulders. The decrease of mean R-values towards lower elevation implies that boulders in the oldest moraines are more weathered than moraine boulders located higher in the study areas. The difference is more pronounced in the Snowy Cirque area where mean R-values obtained for boulders on moraines SK-I and SK-II are significantly lower than values for moraine boulders located in the cirque (Fig. 9). This indicates a time lag between the deposition of the two moraine groups, implying the origin of the oldest moraines before 21–19 ka. On the other hand, R-values obtained for the oldest moraines are higher than R-value (27.3) reported for a bedrock surface in the western Krkonoše Mountains that yields exposure age of 36.5 $\pm$ 2.1 ka (Engel, 2007; Table 3). The comparison of R-values and $^{10}$Be exposure ages within the mountains suggests that the oldest preserved moraines in the Snowy Cirques and in the Úpa Valley originated between ~36 and 21 ka.

The lower ages of the oldest moraines may be attributed to post-depositional changes of the sampled boulders and/or to the combined effect of vegetation and snow cover shielding. Exposure age of boulders can be modified due to the degradation of moraines, thawing of dead ice, frost-heave, rotation, weathering or erosion of a boulder (e.g. Ivy-Ochs et al., 2007; Putkonen and Swanson, 2003; Zreda and Phillips, 1995). All these spatially diversified processes affect boulders on the moraine surface at various rate yielding different exposure histories. The effect of post-deposition changes on exposure age of moraine boulders in the Krkonoše Mountains was reported from the Łomnica Valley, where the terminal moraine was reworked by gravitational mass-movement and frost weathering, yielding lower exposure ages than those obtained for the nearest consecutive moraine (Engel et al., 2011). Within the study area, a Holocene variation of the alpine treeline position and related changes in vegetation cover (Treml et al., 2008) may have reduced the production rate and contributed to the underestimation of exposure ages. Moreover, local montane forest prolongs the duration of the snow cover by 20–40% (Kwiatkowski and Lucerski, 1979) increasing the snow-shielding effect. Considering that the vegetation cover changes the production rate by 2.5 to 4% (Kubik et al., 1998; Plug et al., 2007) and the effect of snow shielding decreases the apparent age by less than 12% (Benson et al., 2004; Favilli et al., 2009), the minimum exposure age for the two oldest moraines in the study area (SK-I: 24 ka, SK-II: 23 ka, G-I: 22 ka, G-II: 21 ka) would be higher than exposure ages for the nearest consecutive moraines SK-III and G-III.

Within the limits of available data, it appears that the oldest moraines in the study area represent positions of glaciers related to the LGM (sensu Clark et al., 2009). This view contradicts the chronology proposed by Chmal and Traczyk (1999) which attributes the oldest moraines below the Snowy Cirques to the penultimate (Saalian) glaciation. However, this assumption was based on the TL dating of water-laid sediments which often yields an overestimated age (e.g. Aitken, 1998). This is probably the case of the reported TL ages (89 $\pm$ 13 ka) which differ substantially from the radiocarbon age of 5320 $\pm$ 50 years BP (Chmal and Traczyk, 1999) obtained for the overlaying organic sediments.

### *5.2. Recession of glaciers*

The transition from the LGM to the present interglacial is characterised by an overall recession of local glaciers interrupted by a series of

**Table 3**
Summary of published chronological data related to Quaternary glaciations in the Krkonoše Mountains.

| Reference | Dating method | Sample site | Lab. code | Age (years)[a] | Interpretation | Area |
|---|---|---|---|---|---|---|
| Wicik (1986) | Conventional $^{14}C$ | Lake sediment | Hv-11978 | 11245–10229 | Local glacier decay | Mały Staw Lake |
| Hüttemann and Bortenschlager (1987) | Conventional $^{14}C$ | Peat | VRI-621 | 8930–8029 | Initiation of mire development on high-elevated plateau areas | Labe Plateau |
| Chmal and Traczyk (1998) | Conventional $^{14}C$ | Lake sediment | Gd-4926 | 12371–10810 | Ice-free cirque | Snowy Cirques |
| Chmal and Traczyk (1999) | TL | Lake sediment | Lub-635 | 93000 ± 14000 | Local glacier retreat | Snowy Cirques |
| | | | Lub-636 | 87000 ± 13000 | | |
| | | | Lub-637 | 89000 ± 13000 | | |
| Engel et al. (2004) | AMS $^{14}C$ | Lake sediment | Erl-6184 | 11133–10720 | Ice-free cirque | Labe Valley |
| Braucher et al. (2006) | $^{10}Be$ exposure-age | Tor | L-21 | 36468 ± 2064 | Deglaciation of southern edge of high-elevated plateau area | Labe Plateau |
| | | Ploughing block | L-12 | 29728 ± 1679 | Deglaciation of central part of high-elevated plateau area | Labe Plateau |
| | | Moraine boulder | L-19 | 18734 ± 1457 | Moraine deposition in trough | Labe Valley |
| | | Cirque threshold | G-08 | 16483 ± 2168 | Glacier retreat from trough to cirque | Úpa Valley |
| | | Cirque floor | G-02 | 13298 ± 1502 | Deglaciation of cirque floor | Úpa Valley |
| Engel et al. (2010) | OSL | Fluvial sediment | Shfd06135 | 27680 ± 1510 | Ice-free cirque | Labe Valley |
| | AMS $^{14}C$ | Lake sediment | Erl-11402 | 30974–30227 | | |
| Engel et al. (2011) | $^{10}Be$ exposure-age | Moraine boulder | Lo-3 | 19319 ± 506 | Moraine deposition | Łomnica Valley |
| | | | Lo-4 | 16782 ± 594 | | |
| | | | Lo-2 | 15496 ± 999 | | |
| | | Moraine boulder | Lk-1 | 18144 ± 1058 | Moraine deposition in trough | Łomniczka Valley |

[a] $^{14}C$ ages are calibrated using the IntCal09 data set (Reimer et al., 2009), $^{10}Be$ ages are recalculated using the procedure described in the current paper.

readvances. The time when glaciers in the Krkonoše Mountains began to retreat from their LGM positions remains undated. However, the first readvance (K-III; Fig. 10) terminated no later than ~19 ka, when glaciers deposited large moraines in front of the north-facing cirques and in the middle part of troughs on the southern flank of the mountains. In the study area, valley glaciers deposited moraines near the outlet of the Snowy Cirques (21.2 ± 0.7 ka) and in the Úpa trough at 910 m a.s.l. The exposure age of 19.0 ± 0.7 ka obtained from moraine relics in the Úpa Valley correlates well with exposure age estimate (19.3 ± 0.5 ka) calculated for the largest lateral moraine in the Łomnica Valley (Engel et al., 2011; Table 3). Moreover, the only well-preserved moraine in the Labe (Labský důl) trough dated by Braucher et al. (2006) probably deposited during the same phase (Table 3).

The subsequent readvance (K-IV) of glaciers in the study area occurred around 18 ka (Fig. 10). In the Snowy Cirques area, glacier deposited morphologically distinct moraine SK-IV at the mouth of the WSK cirque. The exposure age of 18.1 ± 0.6 ka that represents this moraine correlates well with exposure age of 18.2 ± 0.7 ka obtained for the moraine G-IV that terminates at 915 m a.s.l. in the Úpa Valley. The last readvance phase (K-V) before the onset of the Bølling warm interval

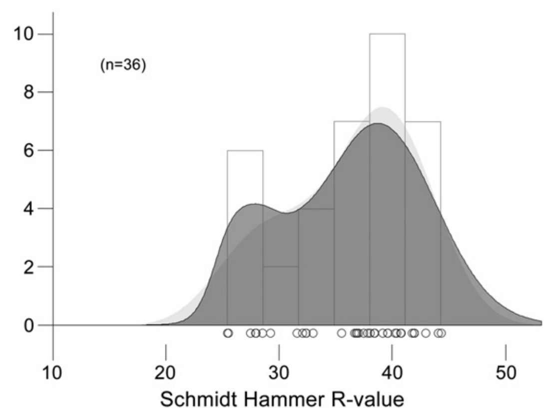


**Fig. 9.** The probability distribution of R-values measured on moraines in the Snowy Cirques. Dark and light grey shaded areas: Probability Density Plot and Kernel Density Estimation, respectively (Vermeesch, 2012). Grey rectangles: conventional histograms. Open circles: individual SH data.

dates back to ~16 ka (Fig. 10). At this time, short valley glaciers deposited the uppermost preserved moraine in the Úpa trough (15.7 ± 0.5 ka) and in the Łomniczka Valley (16.2 ± 0.7 ka, Fig. 8). In the Łomnica Valley, glacier snout terminated at the mouth of the cirque as indicated by exposure age of 15.5 ± 1.0 ka obtained from moraine relics at 1160 m a.s.l. (Engel et al., 2011, Table 3). The same phase of origin may be tentatively suggested for relics of the moraine SK-V located between the two Snowy Lakes in the WSK cirque, based on exposure ages of 18.1 ± 0.6 ka and 13.5 ± 0.5 ka obtained for the previous and subsequent moraines, respectively.

### 5.3. Lateglacial advances

A prominent warming at the onset of the Lateglacial (14.7–11.7 ka) caused rapid environmental changes in the Krkonoše Mountains including permafrost degradation, glacier recession and tundra vegetation establishment (Czudek, 2005; Jankovská, 2007). As a response to increased precipitation and melting of ground ice, intense fluvial erosion dissected periglacial deposits and alluvial fans (Chmal and Traczyk, 1998). The beginning of organic accumulation started in the lower parts of the Western Sudetes Mountains around 13.7 ka, following maximum erosional dissection in Bølling time (Chmal and Traczyk, 1998; Rybníčková and Rybníček, 1996). In plateau areas of the Krkonoše Mountains above 1300 m a.s.l. mountain tundra prevailed (Jankovská, 2007).

Retreat of glaciers back into cirques during the Lateglacial was interrupted by a series of smaller glacier advances K-VI and K-VII (Fig. 10). As a response to a short-lived cold phase (GI-1d, ~14.1–13.9 ka), glacier readvanced in the WSK cirque depositing the moraine SK-VI behind the Snowy Lakes. Exposure age of 13.5 ± 0.5 ka obtained for the moraine supports a tentative hypothesis of its Older Dryas age (Traczyk, 2004). During the same cold phase the moraine that dams Mały Staw Lake in the Łomnica cirque was probably deposited. This is indicated by exposure age of the youngest dated moraine in the cirque (Engel et al., 2011; Table 3). In south-facing cirques, only permanent snowfields existed, as suggested by exposure ages of 13.6 ± 0.4 ka and 14.0 ± 0.5 ka obtained on protalus ramparts in the upper part of the Úpská jáma Cirque.

There is an apparent response of glaciers in the Snowy Cirques to the initial cooling during the YD (GS-1, 12.9–11.7 ka). The readvance (K-VII)

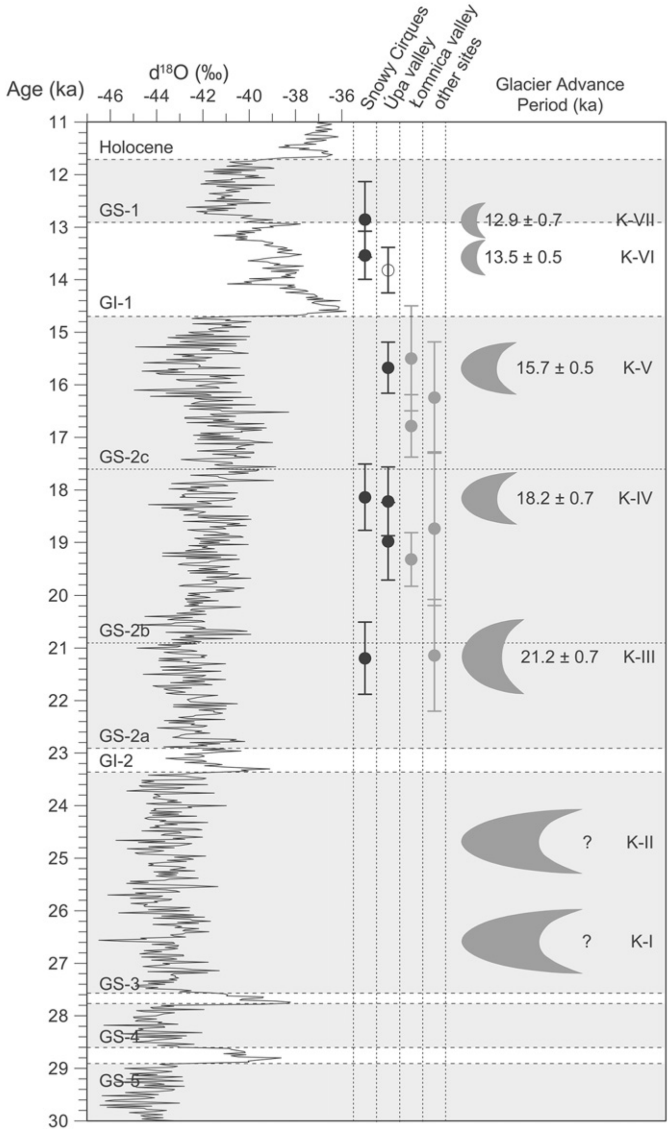


**Fig. 10.** Chronology of the last glaciation in the Krkonoše Mountains based on $^{10}$Be exposure ages from the Snowy Cirques and the Úpa Valley (black circles). Unfilled circle show the mean exposure age obtained for protalus ramparts in the Úpská jáma Cirque and grey circles show exposure ages for moraines in the Labe, Łomnica and Łomniczka valleys. The timing of glacier advances is shown on the right-hand side of the figure back to 21 ka, while poorly constrained earlier advances are indicated by question marks. The time scale is based on the GICC05 data for the NGRIP ice core (Andersen et al., 2006; Rasmussen et al., 2006).

related to this cold event led to the deposition of the youngest moraine relics in the WSK cirque (SK-VII: 12.9 ± 0.7 ka). Apart from the Snowy Cirques, glaciers probably readvanced in the Łomnica Valley as evidenced by occurrence of moraine-like accumulation in the western part of the Mały Staw Lake basin (Choiński, 2003). Another small glacier probably existed in the upper Labe Valley as indicated by a sedimentary sequence in the cirque related to proglacial environment (Engel et al., 2010). South-facing cirques, more exposed to sunlight, probably remained glacier-free, as indicated by the exposure ages from the Úpská jáma Cirque floor (Braucher et al., 2006; Fig. 10 and Table 3) and from protalus ramparts (13.8 ± 0.4 ka). Limited glaciation in the south-facing cirques suggests that temperature conditions related to different slope orientation could represent limiting factor for glacier initiation during the Lateglacial. This situation contradicts conditions during the full-glacial when snow deflation and leeward position of cirques controlled the rise and distribution of glaciers (Migoń, 1999). Unfavourable conditions for more extensive glaciation in the Lateglacial correspond with milder palaeotemperatures and minor cold oscillations in Central Europe compared to the pre-Lateglacial time (e.g. Ilyashuk et al., 2009).

### *5.4. Chronology of late Weichselian glaciations in the context of palaeoenvironmental conditions within Central Europe*

Exposure ages and the SH data obtained for the oldest moraines in the study area indicate that the early phase (K-I and K-II) of local mountain glaciation occurred during the LGM. The absence of pre-late Weichselian moraines suggest, that local glaciation was more extensive during the OIS 2 than in possible earlier phases of the (pre-)Weichselian glacial. This is in agreement with the evolution of glaciations in the Vosges (Mercier and Jeser, 2004), Jura (Buoncristiani and Campy, 2011) and Alps (van Husen, 2011). By contrast, more extensive glaciation related to early and/or middle Weichselian cold events were suggested for the Bavarian Forest (Reuther, 2007) and Tatra Mountains (Baumgart-Kotarba and Kotarba, 2001). According to the sedimentary record in the Labe Valley, an ice-free environment started to change towards glaciated cirque after 27.7 ± 1.5 ka (Table 3). Local glaciers could have been near their maximum extent at the interval when glaciers in the Alps reached their LGM position, but direct correlation is missing. The optically stimulated luminescence (OSL) and radiocarbon-based alpine geochronology suggest that this happened between ~26.5–25 ka and 21–20 ka (Ivy-Ochs et al., 2004; Monegato et al., 2007; Starnberger et al., 2011; van Husen, 2011), which is in agreement with Greenland GS-3 (27.5–23.3 ka) and GS-2c (22.9–20.9 ka; Lowe et al., 2008) and with the period of the LGM sea-level lowstand (26–21 ka; Peltier and Fairbanks, 2006). Coincident exposure ages were reported for the terminal moraine below Kleiner Arbersee Lake in the Bavarian Forest (Reuther et al., 2011) that is located between the Krkonoše Mountains and Eastern Alps. LGM advance in the Tatra Mountains (Northern Carpathians) was dated 23–20 ka using cosmogenic $^{36}$Cl dating (Baumgart-Kotarba and Kotarba, 2001; Makos et al., 2012).

During the LGM, the Scandinavian ice sheet advanced to the southern Wielkopolska Lowland (Leszno/Brandenburg Phase, 24–19 ka) leaving 150 km-wide ice-free corridor between the southern ice-sheet limit and the Krkonoše Mountains (Marks, 2011). Air temperature in the corridor and in southern forelands of the mountains was at least 4.5–7 °C lower then at present (Corcho Alvarado et al., 2011; Zuber et al., 2004). In the Krkonoše Mountains, mean annual air temperature was estimated at −8 °C to −10 °C (Chmal and Traczyk, 1993). Under these conditions, continuous permafrost as much as 250 m thick may have occurred in the mountains (Czudek, 2005). The summer thawing of permafrost was limited to the uppermost layer 1–3 m deep (Jahn, 1977). During the LGM, the deposition of loess started in the forelands whereas isolated patches of loess-like deposits formed in the mountains (Issmer, 1999; Traczyk and Migoń, 2000). Periglacial environment dominated the mountains where landforms such as tors, blockfields, nivation hollows and solifluction mantles developed (Leśniewicz, 1996; Martini, 1970; Traczyk and Migoń, 2000). The late Weichselian age was tentatively suggested for slope cover deposits, rock glaciers and cryoplanation terraces, though formation of these landforms already initiated in preceding glacial phases (Chmal and Traczyk, 1993; Jahn, 1969).

The first readvance (K-III; 21–19 ka) of glaciers in the study area after the LGM reflects transition of cold episode GS-2c (22.9–20.9 ka) to warmer episode GS-2b (20.9–17.6 ka; De Jong et al., 2009). By this time, the Scandinavian ice sheet extended to central Poland (Poznań/Frankfurt Phase, ~19 ka) and northeastern Germany (Heine et al., 2009), depositing erratic material about 200 km north of the Krkonoše Mountains (Marks, 2011). A rapid recession of alpine glaciers that started at 21–20 ka (Ivy-Ochs et al., 2004; Pellegrini et al., 2005) slowed down and glacier readvances (Bühl and Steinach Stadials) after the LGM occurred around 19 ka in the Alps (Kerschner, 2009; van Husen, 1997).

At the same time, local glaciers readvanced in the Bavarian Forest (Mentlík et al., 2013).

The second readvance (K-IV; ~18 ka) of glaciers in the study area occurred during the transition from warmer episode GS-2b (20.9–17.6 ka) to colder episode GS-2a (17.6–14.7 ka; De Jong et al., 2009). Dry conditions and unstable climate with strong short-term fluctuations prevailed in Central Europe during this episode (Huber et al., 2010; Kerschner et al., 1999); July air temperatures ranged from 13 °C to 15 °C in sites above 500 m (Renssen and Isarin, 2001). The distinct climate deterioration resulted in glacier readvances in the Alps (Gschnitz Stadial; Ivy-Ochs et al., 2008) and Tatra Mountains (Baumgart-Kotarba and Kotarba, 2001; Makos et al., 2012) around 17.5 ka.

The last readvance phase (K-V; ~16 ka) before the onset of the Bølling warm interval could correspond with glacier advances in the Bohemian Forest dated at 16.2 ± 1.4 ka (Mentlík et al., 2013) and with the Clavadel/Senders Stadial (>16 ka; Ivy-Ochs et al., 2008) in the Alps. In southern Bohemia, around 200 km southwards from the Krkonoše Mountains, the climate was cold around 16 ka with maximum July temperatures of 10–11 °C (Pokorný, 2002). Palaeoecological and sedimentary records from eastern alpine forelands indicate a subsequent climatic warming and expansion of lowland forests after 16 ka (Doppler et al., 2011; Vescovi et al., 2007). More than 250 km northwards from the Krkonoše Mountains, the Scandinavian ice sheet readvanced and deposited hummocky moraines in the Pomerania Lakeland around 15.8 ka (Kramarska, 1998; Rinterknecht et al., 2005). The climate was cold and the vegetation treeless in the northern Poland at that time (Wacnik, 2009). After 14.6 ± 0.3 ka the ice sheet margin started to retreat from the Pomeranian Phase position (Rinterknecht et al., 2006).

The initial Lateglacial glacier readvance (K-VI; ~14 ka) is in agreement with a phase of increased snow accumulation, solifluction and frost weathering that was related to the cold and dry conditions of the Older Dryas in the Krkonoše Mountains (Traczyk, 2004). This cold oscillation has also been recognised in numerous radiocarbon-dated fossil records in Central Europe (e.g. Bešta et al., 2009; Bos, 2001; Böttger et al., 1998; Friedrich et al., 2001; Gasiorowski and Kupryjanowicz, 2009; Lauterbach et al., 2011; Leroy et al., 2000; Litt et al., 2001; Lotter et al., 1992). At the Swiss Plateau, it was recorded as the Aegelsee Oscillation and dated at ~13.9 cal. ka BP (Lotter et al., 1992). Although the short-lived Older Dryas (GI-1d) belongs to the most dramatic events in the Lateglacial records within Central Europe (Bešta et al., 2009), it is not well documented in the lower parts of the Alps (Daun Phase; van Husen, 2011). However, exposure ages indicate readvances of glaciers around 14 ka in the Bohemian Forest (Mentlík et al., 2013).

The most recent phase (K-VII; ~13 ka) of the glaciation in the Krkonoše Mountains correlates with glacier advances in the Alps (Egesen-max Stadial, 12.2 ± 1.0 ka; Ivy-Ochs et al., 2009) and Carpathian Mountains (Baumgart-Kotarba and Kotarba, 2001; Rinterknecht et al., 2011) related to the early GS-1 (YD) cold event in Greenland (Walker et al., 1999). In Central Europe, the cooling is represented by a marked decrease in the $\delta^{18}O$ of lake sediments (Böttger et al., 1998; Lauterbach et al., 2011; Lotter et al., 1992; Schwander et al., 2000), rapid environmental changes (Ammann et al., 2000; Bos, 2001; Brauer et al., 1999; Goslar et al., 1999; Ilyashuk et al., 2009; Leroy et al., 2000; Litt et al., 2001, 2003; Magny, 2001; Pokorný and Jankovská, 2000; Schaub et al., 2008; Wennrich et al., 2005) and alpine glacier advances (Ivy-Ochs et al., 2009). During the coldest phase of the YD the mean July air temperature was estimated around 13 °C in northern Poland (Wacnik, 2009) and 12 °C in southern Bohemia (Pokorný, 2002). In the Krkonoše Mountains, the cooling generated permafrost aggradation, glacier readvance and periglacial environment expansion (Czudek, 2005; Traczyk, 2004). A phase of enhanced formation of patterned grounds, protalus ramparts, solifluction lobes and rock glaciers was attributed to the YD (Traczyk, 2004; Traczyk and Migoń, 2000). In addition, a phase of frequent gravity-driven geomorphic events was proposed for the paraglacial period (Migoń, 2008), which occurred after the local glacier retreat at the Lateglacial/Holocene transition. A mountain tundra with a very rare vegetation cover spread over the central part of the mountains at that time (Jankovská, 2007).

## 6. Conclusions

$^{10}$Be exposure ages obtained from moraines in the Snowy Cirques area and in the Úpa Valley have revealed a chronology of the last glaciation in the Krkonoše Mountains. The most recent glacial episode began after the termination of an ice-free period around 27.7 ± 1.5 ka (Engel et al., 2010) and lasted until the YD. The precise timing of the initial phase of glaciation remains unclear because exposure ages obtained for the oldest moraines in the study area are underestimated. Considering spatially diversified shielding effect of vegetation and snow cover on production rate (Benson et al., 2004; Favilli et al., 2009; Kubik et al., 1998), exposure age estimates of 24–21 ka for the oldest moraines fall within the LGM. Subsequent recession of local glaciation was interrupted by glacier readvances around 19, 18, 16, 14 and 13 ka. The timing of these events correlates with glacier advances in the Alps (e.g. Ivy-Ochs et al., 2009) and Bavarian/Bohemian Forest (Mentlík et al., 2013; Reuther et al., 2011). Our findings suggest, that local glaciation in the Krkonoše Mountains was possibly more extensive during the LGM than in earlier phases of the Weichselian glacial. This suggestion is in agreement with the evolution of glaciations in the Vosges (Mercier and Jeser, 2004), Jura (Buoncristiani and Campy, 2011) and Alps (van Husen, 2011), but contradicts the early and/or middle Weichselian timing of the most extensive glaciation in the Bavarian Forest (Reuther, 2007) and Tatra Mountains (Baumgart-Kotarba and Kotarba, 2001).

The position and size of moraines indicate that only small cirque glaciers existed during the Lateglacial in the Krkonoše Mountains. The evidence of the last glacier oscillation in the Snowy Cirques shows remarkable similarities with that of the Łomnica glacier in the eastern part of the mountains. The mean age of 12.9 ± 0.7 ka for the youngest moraine in the Snowy Cirques, the age constraints of the uppermost moraine in the Łomnica Valley and the position of these moraines close to cirque headwall show that the last glacier oscillation occurred during the early GS-1 cold event (YD). The lack of moraines in a similar position in south-facing cirques and the exposure age of 13.8 ± 0.4 ka for protalus ramparts at the foot of the Úpská jáma Cirque headwall indicate that the last glacier advance occurred in more sheltered north- to east-facing cirques only. The asymmetric pattern of glaciation suggests that temperature conditions related to different slope aspect controlled glacier advances during the Lateglacial. Age and position of the youngest moraines confirm the decay of local glaciers during the Lateglacial/Holocene transition which was indicated by chronological data from the Labe, Łomnica and Úpa valleys.

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