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^{10}Be exposure age chronology of the last glaciation of the Roháčská Valley in the Western Tatra Mountains, central Europe

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ABSTRACT

^{10}Be exposure ages from moraines and bedrock sites in the Roháčská Valley provide chronology of the last glaciation in the largest valley of the Western Tatra Mts., the Western Carpathians. The minimum apparent exposure age of 19.4 ± 2.1 ka obtained for the oldest sampled boulder and the mean age of 18.0 ± 0.8 ka calculated for the terminal moraine indicate that the oldest preserved moraine was probably deposited at the time of the global Last Glacial Maximum (LGM). The age of this moraine coincides with the termination of the maximum glacier expansion in other central European ranges, including the adjacent High Tatra Mts. and the Alps. The equilibrium line altitude (ELA) of the LGM glacier in the Roháčská Valley, estimated at 1400–1410 m a.s.l., was 50–80 m lower than in the eastern part of the range, indicating a positive ELA gradient from west to east among the north-facing glaciers in the Tatra Mts. Lateglacial glacier expansion occurred no later than 13.4 ± 0.5 ka and 11.9 ± 0.5 ka, as indicated by the mean exposure ages calculated for re-advance moraines. This timing is consistent with the exposure age chronology of the last Lateglacial re-advance in the High Tatra Mts., Alps and lower mountain ranges in central Europe. The ELA in the Roháčská Valley estimated at 1690–1770 m a.s.l. in this period was located 130–300 m lower than in the north-facing valleys in the High Tatra Mts. ^{10}Be exposure ages obtained for a rock glacier constrains the timing of this landform stabilization in the Salatínska Valley and provides the first chronological evidence for the Lateglacial activity of rock glaciers in the Carpathians.

1. Introduction

Reconstructions of the past glacier variability are among the most useful records of paleoclimate changes during the Quaternary. In mountain regions, glacier history is often the primary proxy for climate during glacial periods. Mountain glaciers are a particularly important paleoclimate proxy for two reasons. First, glaciers are the key climate indicators, retreating and advancing in response to changes in the glacier mass balance, which is mainly determined by snow accumulation (precipitation) and glacier melt (air temperature) over a year (e.g. Winkler et al., 2010). Second, geomorphic evidence of glacier advances such as ice marginal landforms, polished bedrock surfaces and trimlines is the only well-preserved palaeoclimate proxy for glacial periods in many mountain systems, which generally retain poor sedimentary records. Glacier history is considered a reliable indicator of climate changes in those ranges, where glacier deposits are widespread and confidently dated.

Despite the wide application of cosmogenic nuclide dating in the field of glacial geology over the past three decades (Ivy-Ochs et al., 2014), the chronology of glaciations remains poorly constrained in many mountain regions. A large data set of exposure ages on glacial deposits exists from the Andes (e.g. Rodbell et al., 2009 and references therein; Fernández and Mark, 2016), the Cordilleras in the western U.S. (Balco, 2011; Rood et al., 2011; Young et al., 2011), High Asia (Chevallier et al., 2011; Heyman, 2014; Owen and Dortch, 2014) and Scandinavia (Hughes et al., 2016; Stroeven et al., 2016), but other ranges are yet underexplored. Limited chronological data are available for the Carpathians, the largest mountain region in mainland Europe. The glaciation history of this range has been an object of glacial studies since the mid-19th century when Zejszner (1856) recognized the existence of former glaciers in the Tatra Mts. (Fig. 1, inset), the Western Carpathians. There were a number of geomorphological investigations

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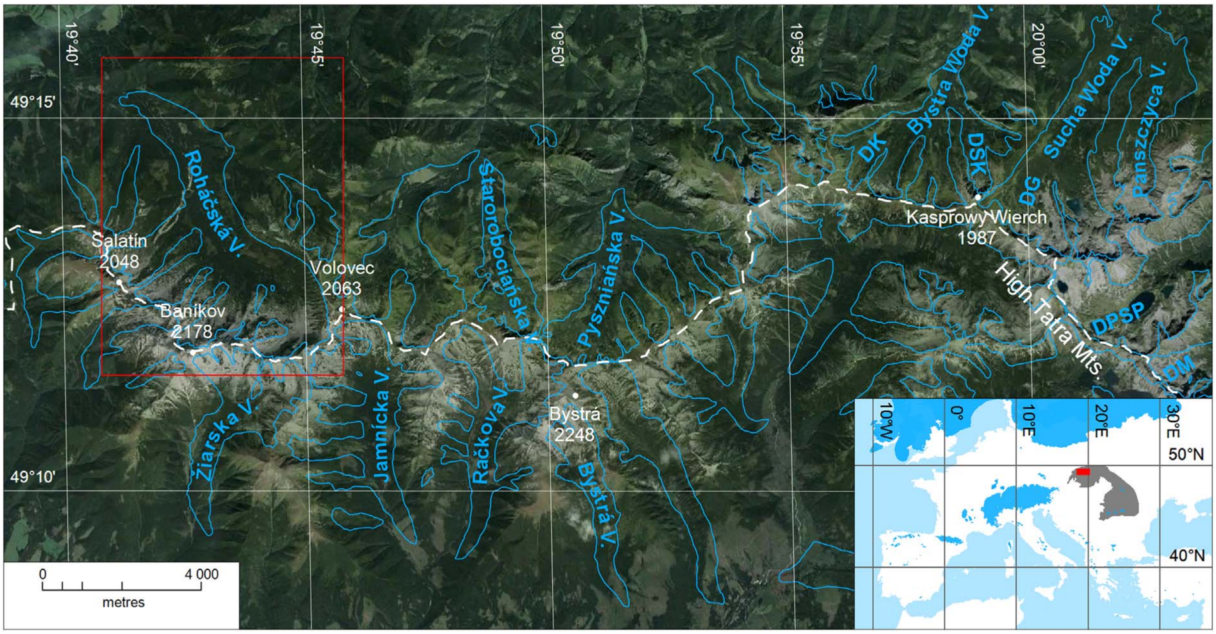

Fig. 1. Overview of the Western Tatra Mts. range and its position in the Carpathians of central Europe (grey shade, inset map). The LGM extent of glaciers in the Tatra Mts. and central Europe (blue shades, inset map) is after Zasadni and Kłapyta (2014) and Ehlers et al. (2011), respectively. The valleys cited in the paper are indicated by full names or abbreviations (DK: Kondratowa, DSK: Sucha Kasprowa, DG: Gąsienicowa, DPSP: Pięciu Stawów Polskich Valley, DM: Za Mnichem). A red box indicates the outline of Figs. 2 and 6 and a dashed line marks the water divide. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of the glacial landscape within the Carpathians during the next decades (e.g. Sawicki, 1911; Lukniš, 1964; Sîrcu, 1964), but no chronological evidence was reported from this region until the beginning of the 21st century (Reuther et al., 2007; Urdea and Reuther, 2009; Rinterknecht et al., 2012; Kuhlemann et al., 2013; Gheorghiu et al., 2015; Ruszkiczay-Rüdiger et al., 2016).

The Tatra Mts. have been the most extensively glaciated part of the Carpathians during the Quaternary. The large extent of local glaciations resulted from high topography of the range (the maximum elevation of 2655 m a.s.l.) and their location in the north-western part of the Carpathians exposed to humid air masses moving in from the Atlantic Ocean. A number of cirque and valley glaciers formed along the divide (Zasadni and Kłapyta, 2014) leaving a strong erosional imprint on the landscape. The strong geomorphological evidence left by former ice masses makes the Tatra Mts. a primary focus of palaeoglaciological research in the Carpathians. In this region, the first reconstructions of the spatial extent of local glaciers were achieved (Partsch, 1882; Dénes, 1902) and different palaeoglacial histories have been suggested (Dénes, 1902; de Martonne, 1911; Partsch, 1923; Romer, 1929).

The number and likely age of Quaternary glaciations in the Tatra Mts. were initially assessed based on geomorphologic criteria (Halicki, 1930; Lukniš, 1959; Klimaszewski, 1960) or weathering characteristics of moraine material (Lukniš, 1973). Krupiński (1984) and Baumgart-Kotarba and Kotarba (1993, 1995, 1997) published the first radiocarbon data from moraine-dammed lakes, providing minimum age constraints on the termination of the last glaciation. Further progress was made when glacier advances were constrained in selected valleys using thermoluminescence (Prószyńska-Bordas et al., 1988; Butrym et al., 1990; Lindner et al., 1990, 1993; Lindner, 1994) and optically stimulated luminescence techniques (Baumgart-Kotarba and Kotarba, 2001). Exposure-age dating applied to glacial landforms since the end of 1990s allowed for reconstruction of the glaciation history in selected sites within the range (Dzierżek et al., 1999; Baumgart-Kotarba and Kotarba, 2001; Dzierżek, 2009; Makos et al., 2013a, 2013b, 2014; Engel et al., 2015). Makos et al. (2016) published the first exposure ages from the Kondratowa, Sucha Kasprowa and Bystra Woda valleys in the Western Tatra Mts. (Fig. 1).

In this paper, we present new ^{10}Be exposure ages for moraines, rock glaciers and a bedrock surface in the Roháčská Valley, the largest area of Quaternary glaciation in the Western Tatra Mts. We thus establish a new glaciation chronology for the valley spanning the LGM and Lateglacial. We compare the derived chronology with published chronological data on local glaciations in both the Western and High Tatra Mts. and we interpret our findings with respect to the results of the recent paleoclimate studies from the Carpathians and Alps.

2. Study area

The Western Tatra Mts. (49°08′–49°17′ N, 19°34′–20°00′ E) are a 30 km-long and 16 km-wide range in the northernmost part of the Carpathians. The range extends between 790 and 2248 m a.s.l. (Bystrá Mountain; Fig. 1). The range extends from the western part of the High Tatra Mts., the highest part of the Carpathians. The southern part of the range is built of Proterozoic gneisses, schist and amphibolite while the main ridge consists of polygenetic Variscan granitoids (Jurewicz, 2007). The crystalline basement is overlain by Mesozoic sedimentary sequences which consist of an autochthonous sedimentary cover, the High-Tatric and Krížna nappes in the western and northern part of the range (Putiš, 1992). In the topographic sense the Tatra Mts. emerged due to a Miocene rotational uplift that resulted in an asymmetric horst structure of the massif (Králiková et al., 2014). The massif is deeply incised by glacial valleys and cirques with headwalls up to 600 m high (Křížek and Mida, 2013), displaying the most pronounced glacial morphology within the Carpathians. However, glacierization at present only consists of glacierets or firn-ice patches below north-facing rock walls (Gądek, 2008).

The climate in the Western Tatra Mts. is transitional between maritime and continental influences. The range represents an orographic barrier to air masses moving in from the Atlantic Ocean, which results in higher precipitation on the northern flank compared to the southern slopes (Konček et al., 1974). Mean annual precipitation generally increases with altitude from 900 to 960 mm at the southern foothills (Vido et al., 2015) up to ∼1800 mm at Kasprowy Wierch summit (1991 m a.s.l.; Żmudzka, 2011). The number of days with snow cover varies from 110 to 120 per year for the foothills to about 220 days at 2000 m a.s.l. (Niedźwiedź et al., 2014) and the mean snow depth

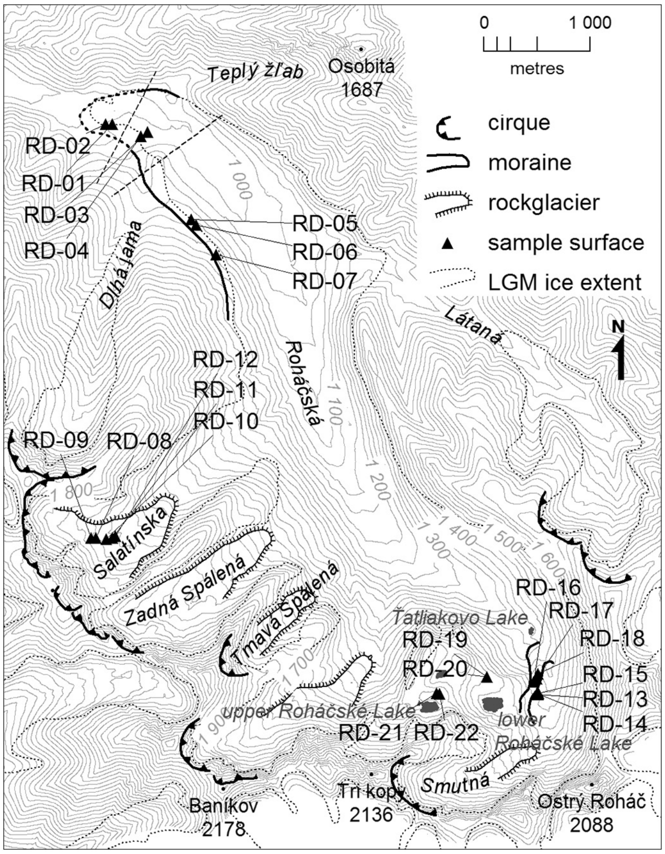

Fig. 2. Location of the sample sites in the Roháčská Valley, the Western Tatra Mountains. Dashed lines near terminal moraine mark the position of cross-profiles depicted in Fig. 5. The LGM extent of glaciers is after Zasadni and Kłapyta (2014).

increases from 20 to 25 cm at the southern foothill to 65 cm in the summit zone (Kočický, 1996). Mean annual air temperature ranges from 6 to 8 °C for the foothills to −1 °C for the highest areas (Niedźwiedź et al., 2014). The climatic snow line has been estimated at 2500–2600 m a.s.l. with a ~200 m lower altitude on the northern slopes compared to the southern flank (Zasadni and Kłapyta, 2009). Prevailing westerly winds at the base of the range are modified by rugged topography and local mountain circulation patterns frequently occur. Local valley circulation patterns occur mainly in summer, whereas cold *bora*-type winds and relatively warm and dry *foehn*-type winds occur in winter (Niedźwiedź, 1992).

The Roháčská Valley is the longest valley of the Western Tatra Mts. It is located in the western part of the range on the northern slope of the main ridge (Fig. 1). The valley has an asymmetric pattern with nine left-side tributary valleys incised in the main ridge and only two right-side valleys (Fig. 2). Bedrock on the left side of the NW-trending valley consists of biotite granodiorite-tonalite to muscovite-biotite granodiorite, while the right-side tributary valleys consist mainly of porphyritic granitoid and leucogranite (Nemčok et al., 1994). The left-side valleys that join the main trough as hanging valleys (Figs. 3 and 4) represent the most-pronounced glacial landscape within the Western Tatra Mts. Well-developed cirques form the upper part of these valleys above 1650–1700 m a.s.l. Talus cones cover the lower sections of the headwalls enclosing cirque floors filled with extensive rock glaciers (Fig. 4). The rock glaciers extend along 0.8–1.4 km long sections of the hanging valleys descending to 1470–1570 m a.s.l. The hanging valleys terminate 170–240 m above the bottom of the main trough. Slope deposits and moraines cover the major part of the trough surface, while fluvial deposits are limited to a narrow belt along the Studený potok Brook.

The Roháčská Valley preserves a sequence of three morphologically pronounced moraine groups. The relics of a terminal moraine are situated in the lower part of the trough (970 m a.s.l.) near the mouth of the Dlhá jama Valley (Fig. 2). The lower part of the terminal moraine is degraded as indicated by low rounded ridges on the southern side of the Studený potok Brook between ~980 and 1000 m a.s.l. (Fig. 5). A well-preserved part of the terminal moraine ascends the left valley slope from the mouth of the Dlhá jama Valley towards SE. The crest of the moraine is 1.1 km long and extends to 1150 m a.s.l. The last remnants of the lateral moraine can be distinguished at the mouth of the Salatínska Valley, around 230 m above the trough floor. A set of two morphologically pronounced moraine systems occurs in the upper part of the trough at the mouth of the Smutná Valley. The larger moraine rises from the trough floor above Ťatliakovo Lake, extending from 1380 to 1540 m a.s.l. The smaller moraine with a well-preserved crest starts at 1440 m a.s.l. and ascends the valley slope up to 1530 m a.s.l. The moraines are ~30 and 15 m high, respectively, and consist of large boulders. The lower parts of these moraines were removed by fluvial processes during the deglaciation. Apart from three distinct moraine groups denuded relics of glacial deposits can be distinguished at 1360 m a.s.l. near Ťatliakovo Lake and between 1570 and 1600 m a.s.l. north of the lower Roháčské Lake (Fig. 3).

3. Methods

3.1. Rock surface sampling

Samples for ^{10}Be analysis were collected mostly from boulders on moraines, which best represent the timing of glacier advances and past climatic fluctuations (e.g. Kerschner and Ivy-Ochs, 2008). Only large upright boulders situated on moraine crests were sampled to increase the probability of sampling surfaces in their original positions. Following Putkonen and Swanson (2003), at least three boulders were sampled on each landform (except for the relics of glacial deposits near lower Roháčské Lake where only two suitable boulders were found) to minimize the impact of a sample with an anomalous exposure history, though five samples collected is currently preferred as a minimum to derive a robust chronology (Dortch et al., 2013). The samples were collected preferentially from boulders higher than 1 m with the aim of reducing the possibility of the post-depositional exhumation of boulders and avoiding the effects of snow and vegetation cover (e.g. Heyman et al., 2011). The center portion of the predominantly slightly dipping top surfaces of the boulders was sampled to minimize edge effects (Gosse and Phillips, 2001) and effects of neutron loss (Masarik and Weiler, 2003). The samples were collected using a chisel and a hammer; the samples were taken from the sampled surface to a depth of 2 to 7 cm. The dip/orientation of the sampled surfaces were measured with a clinometer and a compass and their location/altitude was determined with GPS. All the sampled surfaces were composed of biotite to muscovite-biotite granodiorite.

Overall, 13 boulders were sampled on moraines in the trough, three boulder samples were collected around Roháčská Lakes and five from a rock glacier in the Salatínska Valley. Boulders on the terminal moraine (RD-05 to RD-07), the re-advance moraine above Ťatliakovo Lake (RD-16 to RD-18) and the uppermost re-advance moraine (RD-13 to RD-15) were sampled to constrain the timing of local glaciation maximum and subsequent glacier re-advances. Four boulder samples (RD-01 to RD-04) from rounded ridges in front of the terminal moraine (Fig. 5) represent the time when the moraine was breached and two boulders (RD-19 and RD-20) from moraine relics near the lower Roháčské Lake allow to determine the timing of post-LGM glacier re-advance or standstill in a compound cirque. Only one boulder sample (RD-21) was obtained from the dam of the upper Roháčské Lake as the number of preserved boulders suitable for sampling precluded the collection of more samples. An additional sample (RD-22) was extracted from the bedrock dam surface to constrain the timing of this boulder. These two samples are expected to determine the timing of the initial glacier recession in the high-elevated ridge area. In addition, five boulders were sampled on

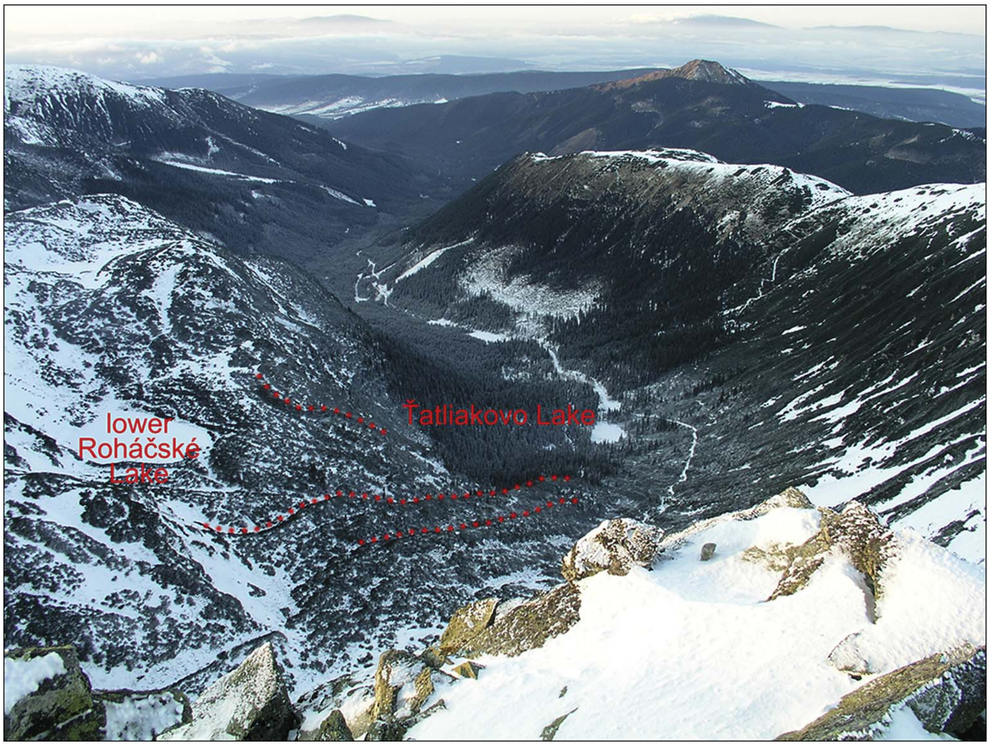

Fig. 3. The view of the Roháčská Valley from SE from Volovec summit. Red dots show the moraine ridges in the upper part of the main trough below the mouth of the Smutná Valley (Fig. 2). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the surface of a rock glacier in the Salatínska Valley (RD-08 to RD-12). The sample site locations are shown in Fig. 2, and the site characteristics are given in Table 1.

3.2. Sample preparation and data treatment

The samples were crushed, sieved and cleaned with a mixture of HCl and H_2SiF_6. The extraction method for ^{10}Be (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 the measurements, which were performed at the French Accelerator Mass Spectrometry (AMS) National Facility ASTER (CEREGE, Aix en Provence). The 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 1σ uncertainties. The $^{10}Be/^{9}Be$ measured blank ratio associated to the samples presented in this paper is $5.79 \cdot 10^{-16}$ that is 136 times lower than the minimum sample ratio. A sea-level, high-latitude spallation production of 4.01 ± 0.18 at·g^{-1}·yr^{-1} (Borchers et al., 2016) was used and scaled

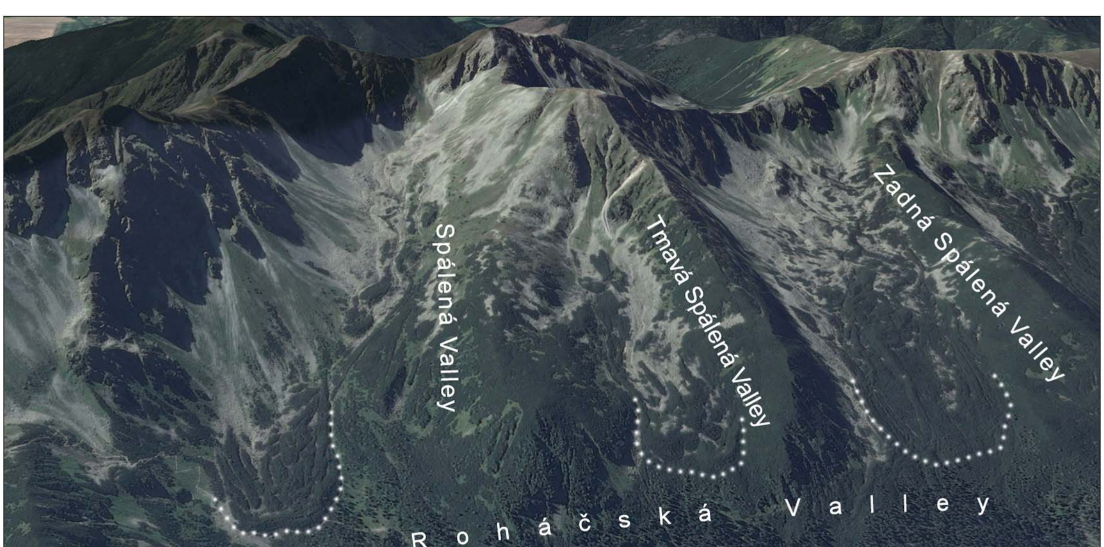

Fig. 4. Hanging valleys filled with rock glaciers at the south-western side of the Roháčská Valley. White dots mark the terminal area of rock glaciers.

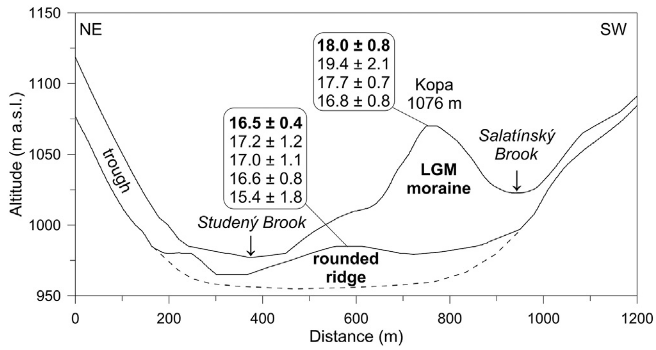

Fig. 5. Morphology of the lower section of the Roháčská valley. The position of cross profiles is shown in Fig. 2. 3 × vertical exaggeration.

for latitude (Stone, 2000) and elevation. The surface production rates were also corrected for the local slope and topographic shielding due to the surrounding terrain following Dunne et al. (1999). Shielding from snow was estimated according to Gosse and Phillips (2001) using an average snow density of 0.3 g·cm^{-3} and an estimated snow thickness and duration at sample sites. These values were derived from the mean thickness and duration of snow cover during the years 1960/61–1989/90 at nine weather stations (725–1991 m a.s.l.) in the Tatra Mts. (Kočický, 1996).

Cosmic Rays Exposure ages were calculated using the equation:

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

where $C(x, \varepsilon, t)$ is the nuclide concentration as a function of depth x (g.cm^{-2}), ε the denudation rate (g.cm^{-2}.a^{-1}), λ the radioactive decay constant (a^{-1}), and t the exposure time (a). P_{spall} and P_μ are the relative production rates due to neutrons and muons, respectively. Λ_n, 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 multiple exposure ages obtained for a given moraine or rock glacier was examined using the chi-square (χ^2) test in accordance with the guidelines recommended by Ward and Wilson (1978). The 95% critical value for χ^2 with n–1 degrees of freedom was calculated and compared with the theoretical value. If the calculated value was lower than the theoretical one, all ages were used to calculate the mean exposure age. Alternatively, outliers with the largest calculated χ^2 value were successively excluded from further consideration until the distribution passes χ^2 test (see Supplementary Table S1). The final datasets were used to calculate arithmetic and error-weighted mean exposure ages for a given moraine and rock glacier. The arithmetic mean exposure age with associated uncertainties was taken as depositional age of the three moraines and a rock glacier (e.g. Ivy-Ochs et al., 2007). However, the exposure age of the oldest boulder was also considered during the interpretation as mean exposure ages represent the minimum age of the sampling site exposure (e.g. Briner et al., 2005). The reduced chi-squared (χ^2_R) statistic and a standard deviation (SD) to arithmetic mean exposure age ratio was applied on groups of exposure ages from dated landforms to approximate scatter in the data. Following the procedure presented by Blomdin et al. (2016), groups of samples from individual landforms were classified as well-, moderately- or poorly-clustered.

The exposure ages with 1σ uncertainty are reported in the ^{10}Be time scale. The analytical uncertainties were taken into account when the ages were compared between the study sites and with previous exposure-age data reported from the Tatra Mts. Total uncertainties were used to compare the exposure ages with radiocarbon and luminescence data. The total uncertainty includes the analytical uncertainty and 4.5% maximum uncertainty associated with the production rate.

3.3. Glacier reconstruction

The reconstruction of former glacier extent was based on the delimitation of ice marginal landforms (moraines and trimlines), polished bedrock surfaces and blockfields (suggested to be located above the trimeline) at the divide between the Smutná and Roháčská valleys. The landforms were identified and mapped in the field and verified using the existing 5 m grid digital elevation models (EUROSENCE®). Glacier termini and lateral parts of former glaciers were delimited based on terminal moraines, lateral moraine ridges and their relics in valley slopes. The maximum glaciation is represented by terminal moraine and left lateral moraine and the ice surface was assumed in the matching altitude at the opposite (right) trough slope. This approach was also applied on other markers of glacier extent, including re-advance moraines. The trimline in the trough and in lower parts of the hanging valleys was identified as an upper limit of glacially abraded and over-steepened trough shoulders. Similarly, the trimline in cirques was delimited as the upper edge of the headwall over-steepening below a rugged rock terrain. This approach was introduced by Zasadni and Kłapyta (2014) in the High Tatra Mts. In headwall sections, where the trimline is not preserved due to the post-glacial slope transformation (Pánek et al., 2016), the upper limit of former glaciers was placed according to adjacent landforms or at the point where slopes steepen to over 60° (e.g. Meierding, 1982).

The surfaces of former glaciers were contoured by extrapolating from points at the suggested ice margins (Mentlík et al., 2013). Ice surface contours were drawn as convex in the upper, concave in the lower and straight in the middle part of the modelled glaciers (Carr and Coleman, 2007). The modelled former glacier surfaces were superimposed over the current topography and used for the approximately evaluation of differences in ice volume between identified glaciations phases. Volume of postglacial valleys infill was neglected. The models of former glaciers were used to calculate the glacier area, the volume and ELAs for three glaciation phases.

The approximate ELAs were determined from geomorphological evidence using the median elevation of glacier (MEG) and toe-to-headwall ratio (THAR) methods (Benn and Evans, 2010). The first approach generally overestimates ELA but gives good results for small glaciers with regular shape (Porter, 1975), i.e. for glaciers that descended from the Smutná Valley during post-LGM re-advances. The THAR method is approximative too as a ratio differs regionally. We used a value of 0.4 which was reported as the most appropriate for mid-latitude mountain glaciers in Europe (Dahl and Nesje, 1992) and North America (Meierding, 1982). The traditional methods were used to determine ELAs for the sake of comparison with other previously glaciated areas in central Europe. More reliable ELA values were calculated using the steady-state AAR ($ssAAR_0$) method (Kern and László, 2010). The values of $ssAAR_0$ calculated from the logarithmic equation ($ssAAR_0 = 0.0648{*}\ln S + 0.483$ where S represents the area of former glacier; Kern and László, 2010) were compared with paleo-ELAs from the High Tatra Mts. recently determined based on the $ssAAR_0$ method (Makos et al., 2013a, 2013b, 2014; Engel et al., 2015).

4. Results

4.1. Exposure ages

The exposure age estimates are consistent within the area, decreasing with the presumed age of sampled moraines (Fig. 6). Moreover, only one age obtained for the sampled rock glacier was indicated as an outlier and excluded from further consideration based on the results of χ^2 analysis (Table 2). The exposure ages from the dated landforms are

Table 1
Sample sites characteristics and ^{10}Be surface exposure ages from the study area.

Sample	Altitude (m a.s.l.)	Boulder length/width/height (m)*	Surface aspect/dip (°)	Sample thickness (cm)	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	Counts	^{10}Be Age (yr)	Analytical uncertainty (± yr)	Total uncertainty (± yr)
RD-01	997	4.8/4.7/2.6	horizontal	4.0	22/4	0.99	9.44	162,995	11,701	205	17,221	1236	1618
RD-02	995	2.4/1.8/1.4	325/7	5.0	21/4	0.99	9.35	144,247	16,857	84	15,381	1797	2025
RD-03	1013	2.9/2.0/0.9	horizontal	7.0	22/4	0.99	9.32	158,654	10,616	231	16,969	1135	1532
RD-04	1022	3.7/3.3/1.7	horizontal	4.0	23/4	0.98	9.63	159,937	7668	465	16,565	794	1280
RD-05	1086	3.7/2.7/1.2	horizontal	4.0	25/5	0.98	10.09	169,806	7922	493	16,792	783	1284
RD-06	1103	2.3/1.5/0.9	horizontal	2.0	26/5	0.98	10.39	201,583	21,977	108	19,362	2111	2415
RD-07	1150	1.9/1.9/0.9	315/4	4.0	28/5	0.98	10.60	188,055	6943	823	17,701	654	1256
RD-08	1654	2.7/1.4/1.7	100/11	2.7	49/6	0.95	15.41	176,412	7453	648	11,423	483	844
RD-09	1655	5.2/2.7/2.4	310/5	3.5	49/6	0.95	15.32	187,752	8930	473	12,231	582	942
RD-10	1651	2.5/2.0/1.2	255/3	4.0	49/6	0.95	15.24	201,578	10,962	358	13,204	718	1075
RD-11	1637	3.5/2.1/1.9	295/17	4.0	48/6	0.95	15.10	196,221	9802	426	12,969	648	1019
RD-12	1636	2.5/2.3/2.6	20/16	2.0	48/6	0.95	15.35	206,684	7955	750	13,442	517	965
RD-13	1508	6.9/4.8/3.1	195/14	5.0	43/6	0.95	13.58	162,878	6313	758	11,964	464	861
RD-14	1517	2.8/0.9/2.1	180/7	4.0	43/6	0.95	13.78	174,808	8155	493	12,657	590	968
RD-15	1509	3.0/1.9/1.6	horizontal	3.0	43/6	0.95	13.81	153,052	7521	535	11,053	543	863
RD-16	1479	7.1/5.0/4.2	75/8	4.5	42/6	0.96	13.36	183,561	8273	531	13,704	618	1035
RD-17	1482	3.2/2.1/2.1	140/6	5.0	42/6	0.96	13.32	186,879	8545	553	13,993	640	1063
RD-18	1476	2.9/2.1/2.0	horizontal	4.0	42/6	0.96	13.39	165,966	6415	743	12,366	478	889
RD-19	1594	2.4/1.6/1.4	horizontal	4.5	46/6	0.96	14.51	200,964	13,447	231	13,819	925	1248
RD-20	1594	2.0/1.1/0.5	207/15	4.0	46/6	0.96	14.66	214,411	10,475	521	14,603	713	1137
RD-21	1735	1.5/1.5/0.9	270/10	6.0	52/7	0.94	15.81	263,704	11,048	631	16,658	698	1228
RD-22	1735	–	252/4	5.0	52/7	0.94	16.04	257,382	8199	1154	16,030	511	1098

* Blank field marks bedrock site.

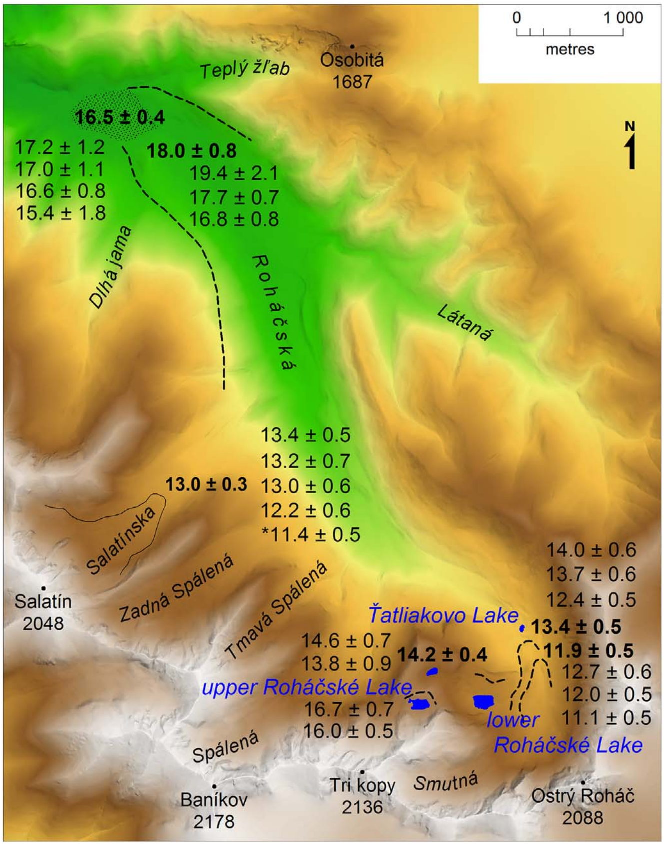

Fig. 6. Exposure ages for sampled surfaces (Table 1) and arithmetic mean exposure ages (bold; Table 2) for the dated landforms. Dashed and solid lines indicate outer limit of moraines and sampled rock glacier, respectively, a dotted area represents a degraded part of the terminal moraine. An asterisk indicates exposure ages removed from the dataset based on (χ^2) test.

well-clustered except for moderately clustered boulder ages (RD-16 to RD-18) obtained for the re-advance moraine above Ťatliakovo Lake (Table 2).

Three samples (RD-05 to RD-07) collected from the terminal moraine range from 19.4 ± 2.1 to 16.8 ± 0.8 ka and yield the arithmetic mean age of 18.0 ± 0.8 ka (Table 2). Four samples (RD-01 to RD-04) from the lowered part of the terminal moraine have a mean age of 16.5 ± 0.4 ka. Two samples (RD-19 and RD-20) collected on the surface of the denuded accumulation near lower Roháčské Lake yield the mean age of 14.2 ± 0.4 ka and slightly younger mean age of 13.4 ± 0.5 ka was obtained for three boulders (RD-16 to RD-18) from the re-advance moraine above Ťatliakovo Lake. Three exposure ages from the last re-advance moraine at the mouth of the Smutná Valley (RD-13 to RD-15) have the mean age of 11.9 ± 0.5 ka.

Sample RD-22 extracted from a glacially modified bedrock dam of upper Roháčské Lake at 1719 m a.s.l. yields the minimum apparent age of 16.0 ± 0.5 ka. The age is consistent with the exposure age of 16.7 ± 0.7 ka obtained for a boulder (RD-21) on the bedrock surface.

A rock glacier in the Salatínska Valley is represented by five boulder samples (RD-08 to RD-12). Although the exposure ages obtained for these boulders were moderately clustered, the most deviating age of 11.4 ± 0.5 ka (RD-08) was identified as an outlier using χ^2 analysis and removed from the dataset. The four remaining samples then yield a mean exposure age of 13.0 ± 0.3 ka (Table 2).

4.2. Extent and ELA of former glaciers

The extent and ELAs of former glaciers in the Roháčská Valley were determined for the period of the maximum glacier expansion and for two re-advances (Table 3 and Fig. 7). The maximum glaciation extended over cirques and hanging valleys from which tributary glaciers descended in the main trough. The main LGM valley glacier was nearly 9 km long and had an area of 14.4 km^2. The ELA was estimated at 1400 and 1410 m a.s.l. for the local LGM based on AAR$_0$ and THAR methods, respectively. The MEG approach yields much higher value (1520 m a.s.l.) implying the ELA over-estimation, which was reported for irregular glaciers (Carrivick and Brewer, 2004). During the penultimate re-advance (~13.4 ka), the glacier descended to the upper part of the trough reaching the length and surface area of 2.4 km and 0.9 km^2, respectively. The ELA was estimated at 1670–1760 m a.s.l. The position of the youngest moraine indicates a slightly lower length (2.2 km) and surface area (0.6 km^2) of the glacier during the last re-advance (~11.9 ka) when the ELA was probably located between 1690 and 1770 m a.s.l.

5. Interpretation and discussion

5.1. Glaciation chronology in the study area

The terminal moraine in the lower part of the trough represents the local LGM as indicated by the arithmetic mean age of 18.0 ± 0.8 ka (n = 3) and the minimum apparent exposure age of 19.4 ± 2.1 ka for the oldest sampled boulder (Figs. 6 and 8A). The mean age is younger than the peak of the global LGM (26.5–19 ka; Clark et al., 2009) and the timing of the LGM in the High Tatra Mts. (~26–20 ka; Engel et al., 2015; Makos, 2015). The younger age may result from low number of sampled boulders (e.g. Dortch et al., 2013) or from scattering due to a post-depositional movement or shielding of the sampled boulders (e.g. Balco, 2011). The exposure ages from the terminal moraine are the only chronological evidence of an LGM glacier expansion in the Western Tatra Mts. because the attempt by Makos et al. (2016) to date the terminal moraine in the Bystra Woda Valley (Fig. 1) yielded apparent ages of 10.0 ± 0.6 to 16.1 ± 0.6 ka that are younger than the Lateglacial moraines in the upper reaches of this valley.

The timing of the initial phase of glacier recession after the local LGM remains unclear. However, the degradation of the terminal moraine occurred around 17 ka as indicated by the maximum (17.2 ± 1.2 ka), arithmetic (16.5 ± 0.4 ka; n = 4) and error-weighted mean (16.7 ± 0.5 ka; n = 4) exposure ages from rounded ridges in front of the moraine (Figs. 5 and 6; Table 2). The retreat of glaciers and related degradation of the moraine falls within the period of post-LGM climate warming and deglaciation in the High Tatra Mts. that lasted until 18–17 ka (Makos et al., 2013a). The period of overall glacier recession in the study area is also constrained by the exposure ages from the upper Roháčské Lake dam. The exposure age of 16.7 ± 0.7 ka obtained for a boulder at 1735 m a.s.l. indicates that a small niche glacier filled the depression holding the lake during this phase. The boulder age is consistent with the exposure age of 16.0 ± 0.5 ka obtained for the adjacent bedrock. These ages imply that glaciers in hanging valleys and valley-side depressions were probably separated from the glacier in the trough during this phase.

The post-LGM recession of glaciers was interrupted by a glacier stagnation or minor re-advance that probably occurred somewhere between 16 and 15 ka. Exposure ages of 14.6 ± 0.7 and 13.8 ± 0.9 ka obtained for the denuded relics of glacial deposits near the lower Roháčské Lake probably underestimate the true depositional age of the landform as a result of its post-depositional lowering and possible boulder exhumation (e.g. Applegate et al., 2012). The absence of prominent moraine ridge, the hummocky appearance and low height of these deposits indicate oscillations of the ice margin. The course of this landform and a similar hummocky appearance of deposits that dams Ťatliakovo Lake imply glacier stagnation in larger section of the valley or re-advance to the upper part of the trough. The exposure data from the landform overlap with exposure ages from re-advance moraines in the nearby Kondratowa Valley (Makos et al., 2016) and tentatively match the timing of "inner" moraines at Morskie Oko

Table 2
^{10}Be surface exposure ages from sampled landforms in the Roháčská Valley.

Phase	Landform	Minimum altitude (m a.s.l.)	Number of samples/sample code	Critical χ^2	95% χ^2	χ^2_R	SD to arithmetic mean exposure age (%)	Age clustering (class)	Weighted Mean Age ± Analytical Uncertainty (kyr)	Arithmetic Mean Age ± Analytical Uncertainty (kyr)	Maximum Age ± Analytical Uncertainty (kyr)
LGM	Terminal moraine	970	3/RD-05 to RD-07	5.99	2.79	1.4	7	A	17.4 ± 0.5	18.0 ± 0.8	19.4 ± 2.1
Glacier retreat	Lowered moraine	950	4/RD-01 to RD-04	7.81	0.87	0.3	5	A	16.7 ± 0.5	16.5 ± 0.4	17.2 ± 1.2
	Moraine boulder	1735	1/RD-21	–	–	–	–	–	–	–	*16.7 ± 0.7
	Bedrock dam	1735	1/RD-22	–	–	–	–	–	–	–	*16.0 ± 0.5
Re-advance I	Moraine boulder	~1370	2/RD-19 to RD-20	3.84	0.48	0.5	4	A	14.3 ± 0.6	14.2 ± 0.4	14.6 ± 0.7
Re-advance II	Lateral moraine	1380	3/RD-16 to RD-18	5.99	5.59	2.8	7	B	13.2 ± 0.3	13.4 ± 0.5	14.0 ± 0.6
	Rock glacier	1510	5/RD-08 to RD-12	9.49	10.17	2.5	7	B	–	–	–
			4/RD-09 to RD-12	7.81	2.55	0.9	4	A	13.0 ± 0.3	13.0 ± 0.3	13.4 ± 0.5
Re-advance III	Lateral moraine	1440	3/RD-13 to RD-15	5.99	4.09	2.0	7	A	11.9 ± 0.3	11.9 ± 0.5	12.7 ± 0.6

* Age refers to one sample and should be treated as the minimum exposure age.

Table 3
Morphological characteristics of former glaciers and ELAs in the study area.

^{10}Be age chronology (ka)	Minimum altitude (m a.s.l.)	Surface area (km^2)	Volume		ELA (m a.s.l)		
			(km^3)	% of LGM	MEG	THAR	ssAAR$_0$ (ratio)
~18.0 (LGM)	970	14.4	0.7	100	1520	1410	1400 (0.65)
~13.4	1380	0.9	0.04	6	1730	1670	1760 (0.45)
~11.9	1440	0.6	0.02	3	1750	1690	1770 (0.45)

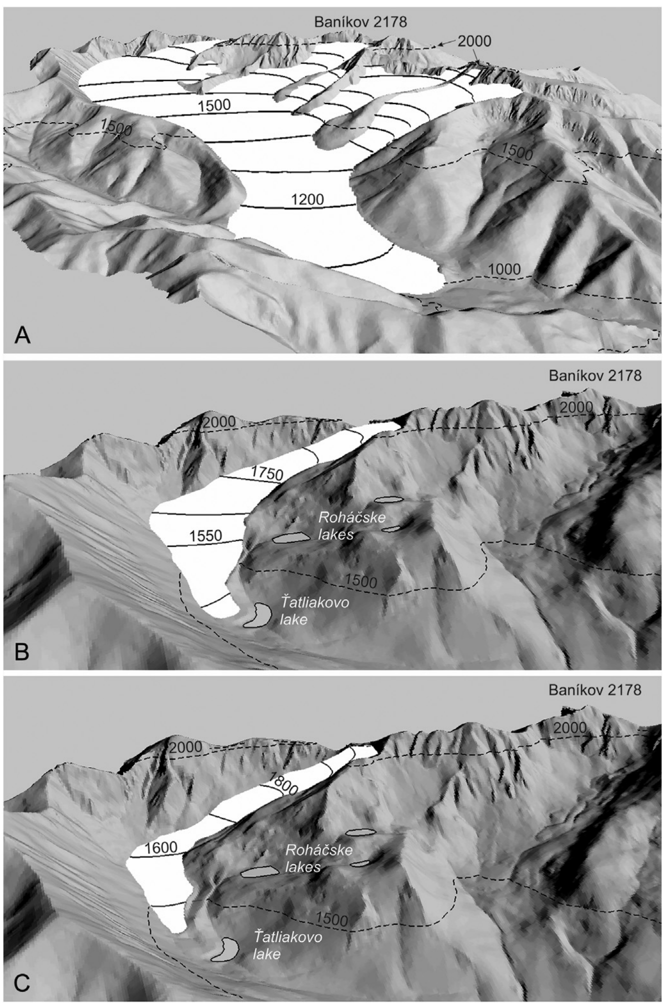

Fig. 7. Reconstruction of the glacier extent in the study area around 18.0 ka (A), 13.4 ka (B) and 11.9 ka (C). All views from NW. No vertical exaggeration.

(Dzierżek, 2009) and Štrbské Lakes (Makos et al., 2014) in the High Tatra Mts. (Fig. 8B).

The next re-advance of glaciers in the study area occurred no later than 13.4 ± 0.5 ka (n = 3) and resulted in the deposition of a well-preserved lateral moraine above Ťatliakovo Lake (Figs. 3 and 6). Around the same time, the stabilization of rock glaciers started in adjacent hanging valleys as indicated by the oldest (13.4 ± 0.5 ka) and mean (13.0 ± 0.3 ka; n = 4) exposure age from the rock glacier in the Salatínska Valley (Fig. 6). The exposure-age data from the rock glacier represent the first chronological evidence of this landform activity in the Carpathians. The timing of the glacier expansion around 13.4 ± 0.5 ka (n = 3) overlaps with the mean exposure age of 14.0 ± 0.7 ka reported by Makos et al. (2016) from the terminolateral moraine in the Sucha Kasprowa Valley in the Western Tatra Mts. (Fig. 8C). Moreover, ^{36}Cl exposure-age data published by Dzierżek (2009) and Makos et al. (2013b) indicate an equivalent glacier re-advance in the High Tatra Mts. (Fig. 8C).

The final glacier re-advance in the study area occurred around 12 ka. The glacier in the Smutná Valley descended to a similar position that was attained during the previous re-advance depositing moraines 200 m behind the older ridges (Figs. 6 and 7). The mean exposure age of 11.9 ± 0.5 ka (n = 3) obtained for the last set of moraines in the study area overlaps with the timing of the re-advance moraines in the Pięciu Stawów Polskich (~12 ka; Dzierżek, 2009) and Za Mnichem (12.5 ± 0.6 ka; Makos et al., 2013b) valleys in the High Tatra Mts. (Fig. 8D). The timing of this re-advance is also constrained by calibrated (INTCAL13; Reimer et al., 2013) radiocarbon data that delimit the minimum age of re-advance moraines that dam Zielony Staw Gąsienicowy (11.6 ± 0.3 cal. ka BP for sample Gd-1446) and Kurtkowiec (11.9 ± 0.4 cal. ka BP, Gd-9151) lakes in the Gąsienicowa Valley (Baumgart-Kotarba and Kotarba, 2001).

5.2. Regional conditions for mountain glaciations in central Europe

The timing of the terminal moraine and the absence of older moraines in the study area indicate that the largest expansion of glaciers probably occurred during Marine Isotope Stage 2 (MIS 2; Rasmussen et al., 2014). This is in agreement with the evolution of local glaciations within central European ranges (e.g. Ehlers et al., 2011) including the High Tatra Mts. (Makos et al., 2013a). The sedimentary evidence from the Western Tatra Mts. forelands indicates the repeated presence of glaciers during the Middle Pleistocene glacial periods (Lindner et al., 2003 and references therein; Marks, 2011). The inferred presence of small glaciers in low-elevated ranges (< 1200 m a.s.l.) between the Fennoscandian ice sheet and the Alps (Feldmann, 2002; Engel et al., 2017) prior the Weichselian glacial supports this view. However, the lack of old moraines precludes the assessment of extent and chronology of former glaciations within the Western Tatra Mts.

The position of the moraines in the Roháčská Valley and the established exposure age chronology indicate that glacier termini remained behind the mountain front during the local LGM. A similar position of terminal moraines can be seen in other valleys within the Western Tatra Mts. (Zasadni and Kłapyta, 2014). A different situation occurred in the nearby High Tatra Mts. where glaciers descended from troughs depositing large moraine complexes at the foot of mountain flanks (Lukniš, 1973). The largest valley glaciers on the southern flank spread over the forefield area of this range and eventually coalesced with adjacent glaciers (e.g. Zasadni and Kłapyta, 2014). The contrasting pattern of glaciers confined to incised valleys in the Western Tatra Mts. and more extensive LGM glaciation with piedmont glacier lobes along the High Tatra Mts. implies different preconditions of these ranges for the development of local glaciations. The smaller extent of glaciers probably reflects lower elevation of the western part of the massif. The influence of the mountain topography together with elevation-related warmer conditions in the Western Tatra Mts. on glaciers was more significant than orographically conditioned higher precipitation in this windward part of the Tatra massif.

The maximum advance of the glaciers in the study area reflects on the climate cooling of the Northern Hemisphere at the end of the last glacial cycle. The minimum apparent exposure ages indicate that the local glaciation reached its maximum extent close to the global LGM when glaciers re-advanced close to their LGM position in the Alps (Wirsig et al., 2016 and references therein) and other ranges within central Europe (Engel et al., 2015 and references therein). However, the timing of the maximum glaciation in the Western Tatra Mts. is based on three exposure ages only and the possibility of underestimation of the depositional age of the terminal moraine cannot be excluded. The poorly constrained stagnation or expansion of the glaciers in the study area between 16 and 15 ka tentatively correlates with glacier advances

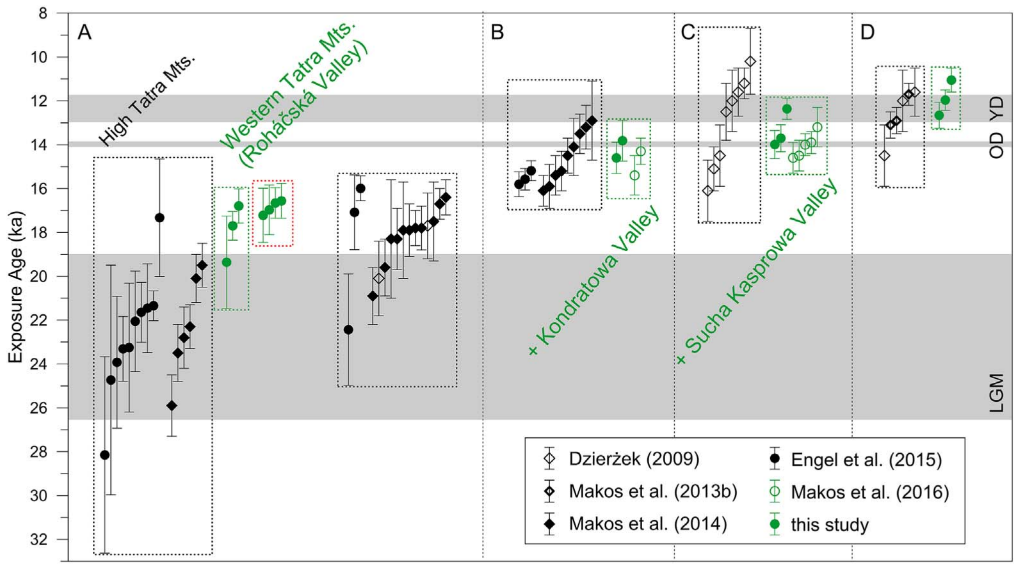

Fig. 8. The exposure age chronology of the last glaciation in the Western (green symbols) and High (black) Tatra Mts. Circles and diamonds show individual ^{10}Be and ^{36}Cl ages, respectively. The timing of the glacier advances (dotted rectangles) from the local LGM (panel A) to the YD (panel D) is based on the arithmetic mean ages with total uncertainties calculated for the exposure-age data from individual moraines. Outlier exposure ages identified in the dataset from the study area and the Kondratowa Valley (Makos et al., 2016) based on χ^2 analysis were not included in the plot. Red rectangle indicates exposure ages from the denuded terminal part of the LGM moraine and a probable period of landform degradation. The timing of the Younger and Older Dryas is after Rasmussen et al. (2014). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in the Alps (during the Daun stadial probably) and the High Tatra Mts. that occurred prior to the onset of the Bølling warm period (Heiri et al., 2014; Engel et al., 2015). The deposits formed during this glacier advance are denuded and hardly preserved, which is also the case of the alpine moraines related to this period (Ivy-Ochs, 2015). The next re-advance that culminated around 13.4 ka coincides with the timing of initial glacier re-advance in the Alps during the Egesen stadial (~13.5 ka; Ivy-Ochs, 2015) and could be tentatively related with climate fluctuations of the Older Dryas (OD) cold period. The last re-advance around 11.9 ka probably reflects climate cooling during the Younger Dryas (YD). The extreme conditions of this period led to formation of glaciers in many mountain regions within Europe including low-elevated ranges (e.g. Rinterknecht et al., 2012; Engel et al., 2014; Mercier, 2014). In the Alps, the YD cold oscillation resulted in repeated glacier advances and deposition of morphologically pronounced moraines (Ivy-Ochs et al., 2009).

The difference between the local LGM ELA estimated for the Roháčská Valley (1400–1410 m a.s.l.) and the ELA values reported by Makos et al. (2014, 2016) for the Bystra (1480 m a.s.l.) and Sucha Woda valleys (1460 m a.s.l.) in the eastern part of the range (Fig. 1) indicates the west-east ELA gradient of 50–80 m. This gradient along the northern flank of the Tatra massif is consistent with a low gradient of ~50 m reported for south-facing glaciers in the eastern part of the Tatra Mts. (Makos et al., 2014). During the YD, the west-east ELA gradient increased as indicated by the difference of 130–300 m between the ELA in the Roháčská Valley (1690–1770 m a.s.l.) and ELA of north-facing YD glaciers in the Pięciu Stawów Polskich Valley (1900 m a.s.l.; Makos et al., 2013a), Szpiglasowy cirque (1980 m a.s.l.; Zasadni and Kłapyta, 2016) and Za Mnichem Valley (1990 m a.s.l.; Makos et al., 2013b) in the High Tatra Mts.

Although the ^{10}Be exposure ages were obtained from the most complete moraine sequence within the range, the obtained dataset is too limited to permit establishing a precise chronology of glaciations since the local LGM. The range of total uncertainties related with the exposure ages is mostly an order of magnitude greater than the duration of Lateglacial cold oscillations (e.g. Rasmussen et al., 2014), which makes difficult to correlate moraines in the study area with climate signal. Moreover, the mean exposure ages of the sampled moraines may be underestimated and the preserved sequence of moraines incomplete. In the absence of chronological data for moraines in other valleys (apart from the catchment area of the Bystra Woda Valley) within the range, any attempt at correlating local glacier advances with the central European event stratigraphy is tentative. Therefore, further dating studies are required to provide chronological evidence that may be used to examine the timing of mountain glaciation in the Western Tatra Mts. and to compare the chronology with the wider European context.

6. Conclusions

The exposure ages obtained in the Roháčská Valley indicate that the moraines preserved in this valley were formed during the last glacial cycle (MIS 2). The terminal moraine in the lower part of the valley represents the local LGM while other moraine ridges preserved in the valley reflect glacier re-advances during the Lateglacial period. The arithmetic mean of 18.0 ± 0.8 ka (n = 3) calculated for the terminal moraine as well as the minimum apparent exposure age of 19.4 ± 2.1 ka obtained for the oldest sampled moraine boulder constrain the deposition of the lowermost preserved moraines close to the global LGM. The timing of the maximum glacier expansion coincides with the termination of the LGM glaciation period in the High Tatra Mts., the Alps and lower ranges in central Europe (Engel et al., 2015; Makos, 2015; Wirsig et al., 2016). The local LGM ELA estimated at 1400–1410 m a.s.l. was located about 50–80 m lower than in the Bystra and Sucha Woda valleys (Makos et al., 2014, 2016) in the eastern part of the range. The observed difference indicates a positive west-east ELA gradient of north-facing glaciers in the Tatra Mts.

The initial post-LGM glacier stagnation or expansion occurred between 16 and 14.6 ka and the subsequent Lateglacial re-advances no later than 13.4 ± 0.5 ka (n = 3) and 11.9 ± 0.5 ka (n = 3). The oldest re-advance is poorly documented in the study area but tentatively overlaps with ^{10}Be and ^{36}Cl dated moraines in the Western (Kondratowa Valley) and High Tatra Mts. (Makos et al., 2014 and 2016; Engel et al., 2015). The penultimate glacier expansion in the Roháčská Valley (13.4 ± 0.5 ka; n = 3) is broadly synchronous with the stabilization of rock glaciers in the Salatínska Valley and with the glacier re-advance in the Sucha Kasprowa Valley in the Western Tatra Mts. (Makos et al., 2016). This re-advance is also in accordance with ^{36}Cl exposure ages reported for moraines in the High Tatra Mts. (Dzierżek, 2009; Makos et al., 2013b) which is also the case of the youngest (11.9 ± 0.5 ka; n = 3) moraine in the study area that probably reflects climate cooling during the YD interval. The YD ELA of glaciers in the study area has been estimated to be at 1690–1770 m a.s.l. approximately 130–300 m lower than in north-facing valleys of the High Tatra Mts.

The proposed chronology of glaciations in the Roháčská Valley is based on a limited dataset of exposure ages that allows only a tentative comparison with the timing of glacier expansions in the High Tatra Mts. For exposure dating of moraines in other valleys within the Western Tatra Mts. it is necessary to establish a reliable glaciation chronology that would reflect variable conditions for glacier formation in this range.

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