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Last Glacial Maximum and Lateglacial in the Polish High Tatra Mountains - Revised deglaciation chronology based on the ^{10}Be exposure age dating

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A B S T R A C T

Deglaciation chronology of the Polish High Tatra Mountains has been reconstructed based on ^{10}Be exposure age dating. Fifty-seven rock samples were collected from boulders located on the terminal and lateral moraines that limit the horizontal extent of the LGM and the Lateglacial glaciers in the Biała Woda and Sucha Woda catchments. The uncertainty-weighted mean age of 21.5 ± 2.5 ka obtained for the maximum terminal moraine in the Sucha Woda Valley indicates that the oldest preserved moraines were formed during the global LGM. The age population ranges between 15.1 ± 1.0 and 28.3 ± 2.0 ka, and suggests that glaciers reached their maximum position (LGM I) as early as 28–25 ka and the final stabilization of the form occurred much later possibly after melting of buried dead ice. The younger glacial oscillation (LGM II) occurred no later than 20.5 ka and is represented by well-preserved termino-lateral moraine systems in the Pańszczyca Valley. The first Lateglacial stage (LG1) in the study area is documented in the Rybi Potok Valley at the RP1 moraine (1300 m a.s.l.), which was stable at around 16.6 ± 0.3 ka. The younger LG2 stage has no defined absolute age, however, it is constrained between 16.5 and 15.5 ka by the timing of the LG3 stage. This cold event is represented by well-formed moraines in the Roztoka/Pięć Stawów Polskich, Rybi Potok and Pańszczyca valleys of which exposure age indicates their deposition between 15.0 ± 0.5 and 15.6 ± 0.1 ka. The LG1, LG2 and LG3 stages likely occurred during the Oldest Dryas cold stage (Greenland Stadial 2.1a) related to the North Atlantic cooling Heinrich Event 1. The youngest glacial oscillation is evidenced by moraines in the Pusta and Pańszczyca valleys. These moraines are composed of very large granitic blocks of which exposure ages often exhibit isotope inheritance. This is reflected by the youngest P3 moraine in the Pańszczyca Valley with a mean age of deposition close to the LGM. The R4 moraine system in the Pusta Valley, however, indicates two oscillations phases that occurred at around 13 ka and correlates well with the timing of RP5 moraine formation in the Za Mnichem Valley. The LG4 stage is related to the climate cooling during the Younger Dryas (Greenland Stadial 1).

LGM ELAs reconstructed for the Biała Woda and Sucha Woda/Pańszczyca glaciers were located at 1460–1480 m a.s.l. During the Oldest Dryas stages, the ELA in the High Tatras rose from 1600 to 1650 m a.s.l. in the Rybi Potok Valley and from 1700 to 1800 m a.s.l. in the Roztoka/Pięć Stawów Polskich Valley. The Younger Dryas ELA, depending on glacier's exposition, was located between 1950 and 2000 m a.s.l. Climate modelling results show that the LGM glaciers (maximum advance) could have advanced in the High Tatras when the mean annual temperature was lower than today by 11–12 °C and precipitation was reduced by 40–60%. During the Lateglacial stages the temperature decrease in the study area changed

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from 10 °C during the Oldest Dryas to 6 °C during the Younger Dryas and precipitation lowering decreased from −50% to −30% or even −10%, respectively compare to modern conditions.

1. Introduction

Chronologies of climatic fluctuations during the Late Pleistocene are well recorded in many mountain ranges across Europe because valley glaciers are very sensitive to temperature and precipitation changes. Therefore, the distribution of glacial moraines and trimlines along the floors and slopes of the mountain valleys reflect how palaeoglaciers responded to climatic forcings through time. The recent opportunity to directly date glacial features made studies on chronology of glacial episodes much more precise and easy to correlate. The widely used cosmogenic isotopes allow to determine the exposure age of inherited glacial landforms and then to interpret this age according to geomorphological, geological and glaciological principles. For the last 25 years, the terrestrial cosmogenic nuclide (TCN) methodology is commonly applied in studies on palaeoglaciation in mountains as well as in lowlands. Successive developments of the methodology bring additional data useful for regional estimation of production rates of cosmogenic isotopes, which is crucial for the accuracy and precision of exposure age calculation. Currently, the ^{36}Cl and ^{10}Be are the most commonly used isotopes for geochronological studies in mountainous areas due to their accuracy for carbonates (chlorine) and quartz rich lithology (chlorine and beryllium). TCN based glacial chronological studies have been developed in the Carpathian range for the last few years: Czarnohora (Rinterknecht et al., 2012); Tatra Mountains (Makos et al., 2013a,b; 2014, 2016; Engel et al., 2015, 2017); Retezat Mountains (Ruszkiczay-Rüdiger et al., 2016); Parâng Mountains (Gheorghiu et al., 2015).

The Carpathians are one of the biggest alpine orogens in midland Europe. They are 1500 km long and extend from the Balkan Peninsula in the south-east to the Eastern Alps in the west (Fig. 1). This extensive chain passes through the territories of Serbia, Romania, Hungary, Ukraine, Slovakia, Poland, Czech Republic and Austria. The Carpathians are relatively low and the alpine relief is common only in the ranges where the highest peaks reach well above 1500 m a.s.l. The glacial record across the chain occurs mostly in the southern part (Fagaras, Retezat, Parang, Bucegi), in the central part (Czarnohora, Gorgany) as well as in the western part (Tatra Mountains). Their location in the middle continent, between the atmospheric influence of the Mediterranean Sea and the North Atlantic, is especially significant for studies on past climate and atmospheric circulation pattern during the Late Pleistocene in the so called periglacial corridor between the Fennoscandian Ice Sheet and the Alpine Ice Cap. Thus, the exact chronology of the glacial cycles and the last deglaciation needs to be established in particular mountain ranges from the south to the north-west.

The evidence of past glaciation in the Carpathians was recognized in the Tatra Mountains in the mid XIX century when Zejszner (1856) described an extensive ridge of the lateral moraine in Kuźnice (Poland). After that, for over 150 years many studies have been carried out on the glacial history of the mountain range. Early work mostly focused on the glacial geomorphology and the extent of glaciation in the Tatras. On that basis several ideas related to the extent and number of glacial cycles occurred. Some researchers suggested a single glaciation of the Tatras (Lencewicz, 1937). Some of them found piedmont lobes on the Tatra's foreland during the maximum advance (Dénes, 1902). The most widely cited studies from the early XX century present hypotheses about two to four glacial episodes recorded in sediments and landscape (Partsch, 1923; Romer, 1929; Halicki, 1930). A similar point of view was presented by Klimaszewski (1988).

In 2003, Lindner et al. suggested up to eight glacial cycles in the Tatras range based on the relative position of glacial and fluvioglacial deposits supported by thermoluminescence (TL) dating but only the two youngest glacial cycles are evidenced by moraines or erratic boulders. The extent of the Riss glaciation is not well established due to the lack of well-preserved moraine ridges. The Würm glaciation, however, is subdivided into three stadials: Suchej Wody, Bystrej and Białki. Glaciofluvial deposits of these events gave TL ages of 89 ± 13–81 ± 12 ka, 69 ± 10–57 ± 8 ka, and 32 ± 5–25 ± 4 ka, respectively (Butrym et al., 1990; Lindner, 1994). According to Lindner et al. (2003), the maximum extent of the Białka Stadial occurred during the Hurkotne phase. The following recessional phases: Łysa Polana, Włosienica I - III and Pięć Stawów Polskich I - IV, took place 23 ± 3, 16 ± 2 and 14 ± 2 ka ago, respectively. It should be emphasized, however, that the TL dating method has a limited precision for glacial deposits, and that thermoluminescence-based stratigraphy should be treated with limited confidence.

A noticable deglaciation pattern of the High Tatra Mountains was presented by Baumgart-Kotarba and Kotarba (1997, 2001; 2002). The authors distinguished ten phases of deglaciation in the Biała Woda Valley and seven phases of deglaciation in the Rybi Potok Valley, Roztoka Valley, Pańszczyca Valley and Sucha Woda Valley. All of them are represented by recessional moraines. They were correlated with Alpine stadials according to Patzelt (1975). These findings are partly confirmed by OSL (optically stimulated luminescence) and SAR (single-aliquot regeneration) dating of the maximum moraine in the Sucha Woda Valley (Baumgart-Kotarba and Kotarba, 2002) as well as by ^{14}C dating of lacustrine sediments in the Czarny Staw Gąsienicowy Lake (Baumgart-Kotarba and Kotarba, 2001). In the late 1990s the TCN methodology was applied in the Tatra Mountains for the first time ever (Dzierżek et al., 1999). They measured exposure ages of moraine boulders and glacial polish, using the cosmogenic isotope ^{36}Cl. The data set partly confirmed previous assumptions and was very promising for future analysis. In 2009 Dzierżek presented the whole data set from the previous study (Dzierżek et al., 1999) and a number of previously unpublished data recalculated accordingly to the current knowledge of age calculation, production rate and correction factors. The recent ^{36}Cl dating of glacially abraded bedrock and moraines in the High Tatra Mountains made their deglaciation chronology more precise (Makos et al., 2013a, b; 2014, 2016). However, these studies relate to only single valleys and to limited time frames, mainly to the Last Glacial Maximum (LGM) and the Younger Dryas (YD). Two LGM oscillations in the High Tatra Mountains were dated at 26–21 ka (LGM I) and at around 18 ka (LGM II) (Makos et al., 2014). Exposure ages of the molded bedrock below glacial trimlines indicate that ice melting in the accumulation areas may have occurred as early as 21.5 ka. A subsequent impulse of glacier's downwasting is recorded after 15.9–15.4 ka (Makos et al., 2013a,b). The recent study of Engel et al. (2015) presents the complex deglaciation chronology of the Velká and Malá Studená valleys in the Slovakian High Tatras. Their findings