Quaternary Research 82 (2014) 1–13

Contents lists available at ScienceDirect

Quaternary Research

journal homepage: www.elsevier.com/locate/yqres

Timing of glacier advances and climate in the High Tatra Mountains (Western Carpathians) during the Last Glacial Maximum

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ARTICLE INFO

Article history:
Received 27 August 2013
Available online 3 May 2014

Keywords:
Cosmogenic ^{36}Cl
Glacier–climate modeling
Paleoclimate
LGM
High Tatra Mountains

ABSTRACT

During the Last Glacial Maximum (LGM), long valley glaciers developed on the northern and southern sides of the High Tatra Mountains, Poland and Slovakia. Chlorine-36 exposure dating of moraine boulders suggests two major phases of moraine stabilization, at 26–21 ka (LGM I — maximum) and at 18 ka (LGM II). The dates suggest a significantly earlier maximum advance on the southern side of the range. Reconstructing the geometry of four glaciers in the Sucha Woda, Pańszczyca, Mlynicka and Velicka valleys allowed determining their equilibrium-line altitudes (ELAs) at 1460, 1460, 1650 and 1700 m asl, respectively. Based on a positive degree-day model, the mass balance and climatic parameter anomaly (temperature and precipitation) has been constrained for LGM I advance. Modeling results indicate slightly different conditions between northern and southern slopes. The N–S ELA gradient finds confirmation in slightly higher temperature (at least 1 °C) or lower precipitation (15%) on the south-facing glaciers during LGM I. The precipitation distribution over the High Tatra Mountains indicates potentially different LGM atmospheric circulation than at the present day, with reduced northwesterly inflow and increased southerly and westerly inflows of moist air masses.

Introduction

The course of climate fluctuations is one of the most important targets of recent studies on the last glacial cycle in Europe. In addition to the study of wide-ranging inter-hemispheric processes that relate to the atmosphere–ocean–climate interactions (Jost et al., 2005; Clark et al., 2009), there have been many regional and local investigations, especially in mountainous regions.

The Last Glacial Maximum (LGM, 26.5–19 ka: Clark et al., 2009) LGM paleoclimate in Europe has previously been reconstructed based on both proxy data and modeling results (Peyron et al., 1998; Jost et al., 2005; Kageyama et al., 2006; Allen et al., 2008; Strandberg et al., 2011). For non-glaciated regions, the pollen record has been used for climate reconstructions. According to Peyron et al. (1998), the mean annual temperature north of the Alps was 12 ± 3 °C cooler than today and the annual precipitation was reduced by 60 ± 20%. Mass-balance modeling used by Allen et al. (2008) indicates that the mean annual temperature depression was between 12 and 17.3 °C across mountain ranges in Europe. Usually the pollen-based reconstructions give greater temperature depressions than model-based climate reconstructions. The regional climate model presented by Strandberg et al. (2011) confirmed a 5–10 °C LGM temperature depression relative to the present-day climate in central Europe. The degree-day model used in the central European uplands indicates an 8–15 °C depression of the mean annual temperature and a 25–75% reduction in precipitation (Heyman et al., 2013). Previously presented results of the climate modeling in the Polish High Tatra Mountains are concordant with those from other sites in central Europe. The LGM mass balances of the Biała Woda and Sucha Woda/Pańszczyca glaciers suggest a mean annual temperature depression of 12 °C and a 60% lower annual precipitation (Makos and Nitychoruk, 2011).

Because mountain glaciers are sensitive indicators of climate fluctuations, their former geometries and equilibrium-line altitudes (ELAs) yield useful data for paleoclimate reconstructions. Development of exposure dating methods has provided the opportunity to determine ages of glacial events across the globe and their correlation between different locations. Recently, chronological studies of late Pleistocene glaciations have been made in the Alps (Ivy-Ochs et al., 2008, 2009), the Pyrenees (Delmas et al., 2011), the Scottish Highlands (Ballantyne, 2010), the Carpathians (Reuther et al., 2007; Rinterknecht et al., 2012; Makos et al., 2013a,b), the Dinarides (Hughes et al., 2010), the Šara Range (Kuhlemann et al., 2009) and the Rila Mountains (Kuhlemann et al., 2013). The main controversies relate to the timing of the maximum extent of glaciers during the last glacial cycle and to the response of glaciers to the Last Glacial Maximum (LGM) cooling. The general

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http://dx.doi.org/10.1016/j.yqres.2014.04.001
0033-5894/

model of atmospheric circulation over Europe was proposed by Florineth and Schlüchter (2000), and then partly confirmed and modified by Kuhlemann et al. (2008). Both models assume a more southward location of the polar front during the LGM. In consequence the polar air masses were transported into the Mediterranean area through the funnel between the Alps and the Pyrenees. To the south of the Alps, cyclones were born and then transported first to the southeast and then to the north through the Adriatic Sea. However, much of the moisture from the Mediterranean was absorbed by the western and southern Alps and the Dinarides (Kelly et al., 2004; Jost et al., 2005; Hughes et al., 2010). This huge barrier likely caused an insufficient moisture supply for glaciers in the continent interior. Kuhlemann et al. (2013) have argued for more frequent northwesterly flow from the Atlantic at the beginning and at the end of LGM. Such conclusion finds confirmation in a study of prevailing LGM wind direction in the Southern Carpathians (Mindrescu et al., 2010). According to the recent data from the Dinarides (Hughes et al., 2011), the LGM ELA at that location seems to be much higher than previously assumed. Therefore, further investigation on timing, distribution and significance of the last glacial cycle in the mountains of Europe is necessary.

The aim of this paper is to present the timing of formation of the most-extended moraines and the outline of climatic conditions in the High Tatra Mountains (southern Poland/northern Slovakia) during the LGM based on cosmogenic exposure dating and modeling of the glacier–climate interactions there.

Last glacial cycle in the Tatra Mountains

Glacial deposits of the Würm glaciation have been recognized in the High Tatra Mountains by many authors (e.g. Partsch, 1923; Halicki, 1930), however, the chronology of climatic fluctuations during the last glacial period has been established based mainly on geomorphic evidence and luminescence dating (Lukniš, 1973; Halouzka, 1977; Klimaszewski, 1988; Baumgart-Kotarba and Kotarba, 1997, 2001; Lindner et al., 2003). Lukniš (1973) and Halouzka (1977) distinguished five stadials (A–E) in the Slovakian part of the mountains, with the two latter ones being subdivided into three oscillations (D, D1, D2 and E1, E2, E3 respectively). Nine generations of moraines were formed during the last glacial cycle in the Slovakian High Tatra Mountains (Lukniš, 1973). In its northern (Polish) part, Lindner et al. (2003) found the evidence of three stadials: Sucha Woda (89 ± 13 to 81 ± 12 ka), Bystra (69 ± 10 to 57 ± 8 ka) and Białka (27 ± 4 and 25 ± 3 ka), respectively, based on TL (thermoluminescence) dating of glacifluvial deposits (Butrym et al., 1990; Lindner et al., 2003). According to Dzierżek et al. (1986) four major recessional phases occurred during the Białka Stadial, with the last recessional phase being represented by at least four minor oscillations. On the other hand, Baumgart-Kotarba and Kotarba (1997, 2001) distinguished the maximum extents (WA and WB) of up to ten recessional phases (BW1–BW10) in the Biała Woda Valley. Their OSL (optically stimulated luminescence) dating in the Sucha Woda Valley indicates that the maximum extent of the glacier occurred between 25 and 22.5 ka. Recent ^{36}Cl dating indicates that there are no moraine ridges older than the LGM in the northern part of the Tatra Mountains (Dzierżek, 2009). An older glaciation is represented only by isolated strongly weathered boulders on the foreland of the LGM moraines. Makos et al. (2013a,b) confirmed three late-glacial phases based on cosmogenic dating.

Study area

Geology and relief

The Tatra Mountains, located on the Polish/Slovak border, are the highest range of the Western Carpathians (Fig. 1). Geographically and geologically, the mountains are divided into two parts: the Eastern High Tatra Mountains, which are composed of granodiorite and partly covered by sedimentary Mesozoic nappes in the north, and the Western Tatra Mountains, which are mainly composed of metamorphic gneiss and schists and also covered by sedimentary nappes of the same age as in the eastern part of the range.

Both the Velicka Valley and Mlynicka Valley are incised in the crystalline core of the High Tatra Mountains. The length of the Velicka Valley is 5.3 km. The lowest moraine ridge is located at an altitude of 1250 m asl and the highest headwalls reach 2350 m asl. Its longitudinal profile shows two clear steps, at 1810 m asl and 2130 m asl. In the lower part of the valley there are very well-formed lateral moraine ridges. Glacial trimlines are located on the slopes surrounding the cirque area. Lukniš (1973) distinguished seven generations of moraines in the Velicka Valley (stadials B–E2) and attributed them to the Würm glaciation (Fig. 2A).

The Mlynicka Valley is 5.5 km long. The lowest part of the valley is filled with Strbske Lake at 1350 m asl. The lowest moraine ridges extend almost 3 km SW from the lake into the Tatra foreland. These are terminal moraines that continue from the lateral ridges present on both sides of the valley. They are part of the large moraine system below the Mlynicka and Mengusovska valleys. According to Lukniš (1973) there are at least three generations of moraines on the foreland (C–D1) and another four inside the valley (D2–E3). The longitudinal profile of the valley has a step at 1800 m asl. The highest headwalls reach 2350 m asl and glacial trimlines are located on the cirque sides (Fig. 2B).

Sucha Woda Valley and Pańszczyca Valley, both located in Poland, have a northern aspect. Their cirques are in the crystalline core of the High Tatra Mountains; their lower valleys are in Mesozoic sedimentary rocks, mainly carbonates. They are wide and shallow, much shallower than those incised in the crystalline rocks. This is probably due to the presence of a well-developed karst system in the valley which could have been afforded additional drainage system for subglacial meltwater (Klimaszewski, 1988). The cirque area of the Sucha Woda catchment is deeply incised and filled with lakes, while the Pańszczyca catchment has less rugged topography. The distance between the headwall and the terminal moraine in the Sucha Woda Valley is 8.5 km. The length of the Pańszczyca Valley measured from the confluence zone up to the headwall is around 5.6 km. A well-developed system of terminal moraines is located at an elevation of 1050 m asl. Three terminal ridges represent a maximum advance and two younger oscillations (WB-1; WB-2 and WB-3). The maximum moraines continue on the flanks of both valleys as lateral ridges almost all the way to the cirques. Seven recessional moraines in Sucha Woda Valley and Pańszczyca Valley were distinguished by Baumgart-Kotarba and Kotarba (2001). The well-formed glacial trimlines are located mainly in the cirque area (Fig. 2C).

Climate

The High Tatra Mountains are located in the transitional climatic zone, under the influence of the polar-oceanic humid air masses. We used meteorological data from stations in Zakopane (850 m asl), Hala Gąsienicowa (1520 m asl), Kasprowy Wierch (1991 m asl), Poprad (694 m asl), Strbske Pleso (1355 m asl) and Lomnicky Stit (2630 m asl) in our study. The data set from one of the two warmest periods of the 20th century between 1990 and 2000 demonstrates that the distribution of mean annual temperature is nearly uniform on both sides (northern and southern) of the massif with only slightly higher values (0.5 °C) on the southern slope. The temperatures range from 5 to 6 °C inside the dales on the foreland of the Tatras and −4 °C on the highest peaks (Fig. 3). However on both sides of the massif there is a temperature inversion, especially during the winter season, observed in the lower stations (Zakopane and Poprad). This is due to inflow of relatively dense cold-air masses from higher elevations into the wide dales on the foreland of the Tatras. The annual temperature on the northern slope of