https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

The Cryosphere Discussions

Asynchronous glacial extent during the Last Glacial Maximum in Ih Bogd massif of Gobi-Altay range, southwestern Mongolia: Aspect control on glacier mass balance

Purevmaa Khandsuren [1], Yeong Bae Seong [1]*, Hyun Hee Rhee [2], Cho-Hee Lee [1], Mehmet Akif Sarikaya[3], Jeong-Sik Oh [4], Khadbaatar Sandag [5], Byung Yong Yu [6]

[1] Department of Geography, Korea University, Seoul 02841, Korea;
[2] Division of Glacial Environment Research, Korea Polar Research Institute, Incheon 21990, Korea;
[3] Istanbul Technical University, Eurasian Institute of Earth Science, Sarıyer-Istanbul, 34469, Turkey;
[4] Department of Geography, Dongguk University, Seoul 04620, Korea;
[5] Department of Geography, Mongolian National University of Education, Ulaanbaatar 210648, Mongolia;
[6]AMS laboratory, Korea Institute of Science and Technology, Seoul 02792, Korea;
Correspondence to: Yeong Bae Seong (ybseong@korea.ac.kr)

Abstract. Most mid-latitude mountain glaciers reached their maximum extent around the global Last Glacial Maximum (gLGM). However, some also strongly responded to the regional climate change or local non-climatic factors such as topography, leading to asynchronous maximum advances. This study documents the maximum extent and chronology of two paleoglaciers in the Ih Bogd massif of Mongolia: one facing north into the Jargalant Valley and the other facing south into the Ih Artsan valley. ^{10}Be surface exposure age dating revealed that the Ih Artsan short valley glacier reached its maximum position (M_{Ih1}) around 20.1 ± 0.7 ka, coinciding with the gLGM. In contrast, the Jargalant paleoglacier (M_{J1}) reached its maximum extent around 17.2 ± 1.5 ka, around Heinrich 1 stadial and during the post-gLGM northern hemisphere warming. Our 2D ice surface model, which includes the temperature-index melt model, suggests that an aspect can result in a melt difference between north and south-facing slopes. Glaciers retreated from their maximum modeled extent asynchronously when we assign a 0.5 °C lower temperature for Jargalant valley (northern slope), based on the observation that present-day mean annual Jargalant temperatures are lower than in the south-facing Ih Arstan. Modelled timing of the maximum extents (20.23 ka in Ih Artsan, 17.13 ka in Jargalant) are consistent with ^{10}Be exposure age results (20.1 ka in Ih Artsan, 17.2 ka in Jargalant). We also observed several sequences of post LGM or/and Holocene moraines in both cirques. Extremely old ages ranging from 636.2 ka to 35.9 ka were measured for the inner moraines in the Jargalant cirque (M_{J2}-M_{J4}), suggesting a problem with inheritance from boulders eroded from the summit plateau.

Keywords: Glacier, late Quaternary, Mongolia, Ih Bogd, ^{10}Be surface exposure dating, paleo-erosion surface, uplifted peneplain, 2D ice surface modelling

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

1. INTRODUCTION

Massive ice sheets or mountain glaciers respond to various climatic forcing functions that operate on wide scales from local to global. Winter precipitation and summer air temperature are generally considered the most critical factors in controlling glacial mass balance and extent. Understanding the impact of climate on past glacial cycles necessitates a thorough understanding of the timing and amplitude of glacial dynamics. The most recent planet-wide glacial expansion occurred during the Global Last Glacial maximum (gLGM) as a result of changes in major climate forcings, e.g., reduced summer insolation, tropical sea surface temperatures, and atmospheric CO_2. The remnants of paleoglacial deposits of gLGM are the best preserved among all the ice ages. The gLGM has been extensively studied to ascertain the late Pleistocene changes in ice volume, sea-level fluctuations, feedback on climate, etc. The timing of gLGM has been established using both the marine (e.g., Skinner and Shackleton, 2005; Thompson et al., 2003; Shackleton, 2000; Shackleton, 1967) and terrestrial (e.g., Fletcher et al., 2010; Clark et al., 2009; Jouzel et al., 2007; Wang et al., 2001; An et al., 1991) paleoclimatic proxies. Based on proxy records, the timing of gLGM is constrained between 26.5 to 19 ka, during which the ice sheets and mountain glaciers reached their maximum and the global sea level was at its minimum (Clark et al., 2009).

The timing and extent of the maximum glaciation in many regions are still poorly understood and may differ from one region to another in due to distinct ice masses respond differently to local and regional climatic conditions. However, new geochronological techniques such as in situ cosmogenic surface exposure dating (e.g., Heyman, 2014; Hughes et al., 2013) permit reliable temporal comparisons between the maximum advances of different mountain glaciers.

Evidence from mid-latitude glaciers reveals a more complex behavior than that of synchronized ‘global’ glaciations. In some parts of central Asia, for example, the largest glacial extent occurred before MIS 2, > ~100 ka in the northeastern Tibetan plateau (Heyman et al., 2011a) and late MIS 5/MIS 4 in the Kanas lake, Chinese Altay (Gribenski et al. 2018). In the Tian Shan (Blomdin et al., 2016; Li et al., 2014; Koppes et al., 2008), Altay (Blomdin et al., 2018), Khangay (Batbaatar et al., 2018; Pötsch, 2017; Smith et al., 2016; Rother et al., 2014), and Eastern Sayan (Batbaatar and Gillespie, 2016; Gillespie et al., 2008) mountains of the central Asia, the largest glaciers dated to MIS 3, while the MIS 2 glaciers appeared to be smaller. It is noteworthy that most of the MIS 3 advances are based on a few and/or widely scattered ages of moraine boulders (Gribenski et al., 2018; Blomdin et al., 2016). On the other hand, in the Gichgene range with arid climate conditions, the significant cirque glacier advanced during MIS 1 (Batbaatar et al., 2018). These studies suggest that glaciers in continental central Asia respond to regional-scale climate fluctuation in different ways; hence, the last glacial maxima differed from place to place on a scale of a few hundred kilometers from the arid to humid continental environments.

In addition to regional climate conditions, non-climatic factors may also control the local extent and dynamics of glaciation. Topographic factors such as catchment morphology, valley width, length, slope, and aspect, can influence glacier dynamics and affect the style of glaciation (Barr and Lovell, 2014; Kirkbride and Winkler, 2012). Glacier mass balance varies with slope aspect, snow avalanche, and wind drifting snow. Particularly, the north-south aspect contrast in mid-latitude regions with steeper slopes, higher relief, and higher insolation can generate substantial

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

The Cryosphere Discussions
Open Access
EGU

differences in insolation and melt. This difference may be more significant for cirque, small mountain glaciers, or niche glaciers than for large valley glaciers or ice caps (Evans and Cox, 2005).

Although spatio-temporal variations in the glacial extent in response to regional climate change have been mentioned in numerous studies, the influence of topographic changes has not been adequately explored. The present study aims to reconstruct the glacier extent and chronology of major glacial events during the last glacial cycle in previously unstudied Ih Bogd massif of southwestern Mongolia. Our original hypothesis was the north and south facing valleys would experience synchronous paleoglacial advances. Upon falsifying this hypothesis using ^{10}Be surface exposure dating, we then turned to a 2D glacier surface model to determine if the impact of aspect could have influenced the chronology for two contrastively oriented (north-facing and south-facing) valleys.

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

The Cryosphere Discussions

2. STUDY AREA

2.1 Geology

The Gobi-Altay range, a ~800 km long NW-SE trending isolated arc of mountains, is bordered in the northwest by the Mongolian Altay range and separated from the Khangay range by Gobi Lakes Valley. Ih Bogd massif (Ih Bogd means 'great saint' or 'great sacred mountain' in Mongolian) is located in the northern Gobi-Altay range. Its position in the heart of the Gobi makes it an important site to understand the extent and timing of glacial changes in arid central Asia.

This massif is over 50 km long, 25 km wide, and rises ~2 km above the surrounding arid piedmont. The highest peak of the massif, Terguun Bogd (3957 m a.s.l), is the highest point of the Gobi-Altay Mountain range as well (Fig. 1). A sequence of thrust faults and sinistral strike-slip faults, which together form transpressional pop-up structures, govern the current stress regime of Ih Bogd (Vassallo et al., 2011; Vassallo et al., 2007; Bayasgalan et al., 1999; Cunningham et al., 1996). The highest part (>3000 m) of the flat summit plateau consists mainly of Mesozoic granite, while lower parts are mostly occupied by Cenozoic gneisses (Vassallo et al., 2011; Jolivet et al., 2007; Tomurtogoo, 1999).

The flat summit plateau is thought to be a remnant of a formerly extensive Mesozoic erosion surface (Jolivet et al., 2007; Devyatkin, 1974; Berkey and Morris, 1924), surviving most of the Cenozoic due to its rapid and recent uplift after long-term quiescence (Jolivet et al., 2007). Accordingly, erosion in Ih Bogd is limited to several deep gorges. The summit plateau is well-preserved in unincised areas because of the young age of the massif and arid regional climate (Vassallo et al., 2011).

2.2 Climate

Ih Bogd massif is situated in the cold Gobi Desert, having a high amplitude in diurnal and annual temperatures. The climate of the study area is characterized by a dry, cold winter with limited snowfall and hot summer with more than 65% annual precipitation coming in summer (Batbaatar et al., 2018). Bayankhongor (Fig. 2), the nearest aimag center (the largest unit of the Mongolian province) is 140 km distant and receives less than 200 mm of precipitation per year (188 mm, an average of 2005–2019, NAMEM, 2020), while precipitation reaches ~100 mm (Yu et al., 2017, Fig. 2b, 2c and 2d) near Orog lake (1168 m a.s.l, Zhang et al., 2022). The closest weather stations to Ih Bogd are Bayangobi (1540 m a.s.l) in the south and Bogd (1240 m a.s.l) in the north. The long-term mean annual temperature measured as 3.1 ℃ in Bayangobi and 4.4 ℃ in Bogd (Fig. 2c and 2d). The average January temperature was approximately -18 ℃ in both stations (NAMEM, 2020).

In the adjacent Gobi Lakes Valley, starts to snow at the end of September but melts rapidly. However, a thin snow cover persists on the summit plateau of Ih Bogd between the end of September and the middle of April. Sometimes, precipitation falls as snow from June to August (Landsat imagery, Farr et al., 2007). On the other hand, summer is warm and wetter. The July temperature rises to about 21.8 ℃ in Bayangobi and 23.0 ℃ in Bogd (Fig. 2d; NAMEM, 2020).

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

Ih Bogd has a long-living snow cover, lower mean annual temperature (-10 ℃), and receives more precipitation (~200 mm) than its surrounding (Fig. 2a, 2b). Strong Siberian high pressure prohibits the entrance of westerlies during winter, while westerlies and southwesterlies are still effective during summer time in the study region. The orientation and shape of mobile dunes northwest of Orog lake record the prevailing winds as being from the northwest (Mischke et al., 2020; NAMEM, 2020; Yu et al., 2019).

2.3 Glacial landforms and study site setting

The Ih Bogd massif contains abundance well-developed alpine glacial erosional landforms such as cirques, valleys and depositional landforms such as lateral, terminal and recessional moraine ridges, glacial tills on its northern and southern slopes. Headwater systems of intermittent streams merge and turn into main streams, which later flow out of the mountain front as large alluvial fans. The sediment transported by alluvial fan or intermittent streams accumulates in large endorheic intermontane basins like Gobi Lakes Valley (Fig. 2). Our particular interest in the present study is to compare the timing of the largest glacier extent in the two small paleo valley glaciers flowed to the south (Ih Artsan) and the north (Jargalant; Fig. 1).

Glaciers in both valleys were started from cirque shaped headwater above ~3100 m and flowed down to elevations of ~3000–3200 m. Jargalant valley merge down to the largest valley on the northern flank called Bituut river valley. This large drainage only experienced glaciations in the form of short cirque-valley glaciers on its headwaters, like in Jargalant valley. A few well-preserved moraine ridges have been previously identified near the headwater of Bituut river (Batbaatar et al., 2018). The massif was limited to small cirque-valley glaciers is best explained by the arid climate of the interior of the Gobi Desert.

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

The Cryosphere Discussions

3. METHODOLOGY

3.1. Field investigation and geomorphologic mapping

We conducted the fieldwork in July of 2018 riding horses. Prior to fieldwork, glacial extent and moraine ridges were pre-analyzed in a GIS environment and mapped on 30 m Shuttle Radar Topographic Mission (SRTM), ALOS PALSAR DEM with 12.5 m resolution (JAXA/METI, 2007), and Landsat 8 imagery with one arc-second resolution (Roy et al., 2014; Farr et al., 2007). Names of the study areas and physical characteristics of the specific landforms were identified from a 1:100000-scale topographic map of Mongolia (NAGC, 1969) using their morphology and depositional properties. Pre-identified moraines were confirmed during fieldwork. They were then categorized based on their stratigraphic position, morphology, and weathering traits.

3.2. Moraine morphostratigraphy

As indicated previously, late Quaternary moraines are only preserved in headwaters. Ih Artsan cirque is smaller and glacial valley is shorter (~ 1 km) than Jargalant. The best-preserved moraines, with at least seven to eight morainal crests, occur in the Ih Artsan cirque (Fig. 3; Batbaatar et al., 2018). The farthest moraine sequence (M_{Ih1}) from the summit plateau was distinguished by abundant matrix-rich glacial sediments, large granitic boulders, and a bulge-like moraine ridge higher than the inner moraine crests (Fig. 3).

The Jargalant paleoglacier has a larger accumulation area and length than Ih Artsan glacier, advancing 1.5 km downvalley. Stratigraphically, we identified four different moraine sequences in the Jargalant complex: M_{J4}, M_{J3}, M_{J2}, M_{J1} (from youngest to oldest). M_{J4} moraine lies between 3365–3410 m a.s.l, containing angular to sub-angular clast supported pebble to boulders. Downvalley from M_{J4} moraine, M_{J3} and M_{J2} moraines have smooth matrix-supported flat tops and steep clast supported sides. These sequences are longitudinally dissected by intermittent streams draining toward Bituut valley. The oldest moraine (M_{J1}) was deposited further downvalley, consisting of a bulging morainal form with large granitic boulders lying on the finer matrix-supported deposit. We speculate that this oldest preserved material might have extended far enough to reached the Bituut valley (trunk valley). The sequences were very clearly distinctive in the field as well as in the satellite images (Fig. 4; Fig. 5b).

3.3. Equilibrium Line Altitude

Ih Bogd massif is unglaciated today. Furthermore, the nearest modern glaciers are glaciers in Otgontenger (Khangay), Sutai (Mongolian Altay), which are approximately 350 to 550 km west of the study area. Thus, we could not calculate present ELAs or ELA depression; hence only ELAs for former glaciers were estimated.

The THAR method may include a large error when glacier geometry is complex (Benn & Lehmkuhl 2000). Yet, it is more suitable for our study area because it has simple glacier morphology. In this study, we obtained the altitude of the lower and upper limit of past glaciers using GPS, Google Earth imagery, and an ALOS PALSAR DEM with 12.5 m resolution (JAXA/METI, 2007). The glacial toe was considered to be the minimum altitude of the terminal moraine, while the glacial headwall altitude was considered to be 1/3 of the altitude difference between the cirque floor and top of the rock cliff (Goldthwait, 1970). Estimates of the headwall altitude for high and steep cirques can range from tens to hundreds of meters, and determination of the glacial headwall is elusively subjective and arbitrary

(Porter 1981). The median altitude method (MEM; THAR=0.5) is commonly used; however, according to glacier type or location, lower (Meierding 1982) or higher (Gillespie et al. 2008) ratios may be used. For this reason, we also used a higher THAR ratio of 0.58 (Gillespie et al. 2008) because Ih Bogd massif must have higher ratio due to its arid environment during the last glaciation (Lehmkuhl et al., 2018; Felauer et al., 2012).

3.4. Cosmogenic ^{10}Be surface exposure dating

We used cosmogenic ^{10}Be surface exposure dating based on the specific sampling procedure below to determine the timing of the last glacial advances in Ih Bogd massif (Khandsuren et al., 2019; Gosse and Phillips, 2001). We sampled quartz-rich granitic boulders on the moraine crests, which were not reworked and represented single, distinguishable ice-marginal positions. We sampled boulders that are rooted in the upper flat surface of the moraine crest and away from steep slopes to avoid post-depositional movement such as rolling and sliding downslope. We avoided boulders smaller than 50 cm above ground level that are likely to have been buried, exhumed, or heavily eroded. Samples were obtained by chisel and hammer from the top surfaces of boulders (less than 5 cm thick) to avoid the edging effect. We sampled at least five boulders from each single moraine crest to statistically screen any outliers such as inheritance or post-glaciation reworking.

We followed the laboratory works of Korea University Geochronology Laboratory (Seong et al., 2016), with the revised procedure of Kohl and Nishiizumi (1992). Rock samples were crushed and sieved to obtain a monomineralic quartz sample and avoid grain size dependency. Meteoric ^{10}Be and other contaminations were removed by successive HF/HNO_3 leaching. Purified quartz samples (250~500 µm) were first spiked with ~1047.8 ppm concentrated ^{9}Be carrier and then dissolved with HF/HNO_3. Fluorides were removed by Perchloric ($HClO_4$) acid, while Be was separated from other ions (cations/anions) using ion-exchange chromatography columns. Beryllium hydroxide was recovered using ammonium hydroxides. Consequently, $Be(OH)_2$ gels were dried at high-temperature hotplates. They were calcinated to be oxide forms in a furnace at higher temperatures (800 °C). BeO samples were mixed with Niobium powder to get conductivity and targeted in aluminum target to be loaded into 6 MV tandem Accelerator Mass Spectrometry (AMS) for ^{10}Be/^{9}Be ratio measurement in the Korea Institute of Science and Technology. ^{10}Be/^{9}Be ratios for each sample were measured relative to the 07KNSTD standard sample 5-1 (Nishiizumi et al., 2007), having a ^{10}Be/^{9}Be ratio of $2.71 \times 10^{-11} \pm 4.71 \times 10^{-13}$ (calibrated error). The measured average ^{10}Be to ^{9}Be ratio of the processing blank was $4.53 \times 10^{-15} \pm 1.6 \times 10^{-15}$ (n=2). The exposure ages were calculated using Cronus-Earth online calculator v3 (Balco et al., 2008). ^{10}Be Production rate scaling was based on the time-dependent and nuclide-specific LSDn scaling (Lifton et al., 2014) as well as the non-time-dependent scaling model (Stone, 2000). Errors of exposure ages were represented by external uncertainty (1σ confidence level). We tested the boulder populations for finding outliers using the Chauvenet and Pierce criterion and normalized deviation methods (Ross, 2003; Chauvenet, 1960) before we assigned deglaciation ages of moraine sequences. For the normalized deviation, a sample in populations was rejected if its normalized deviation from the group mean (excluding the tested sample) was greater than two (Batbaatar et al., 2018). We also calculated the reduced chi-square value and the relative uncertainty of the group (Blomdin et al., 2018). The arithmetic mean and standard deviation (1σ) of the exposure ages in the group was considered as a representation of the age. We assumed zero erosion for all samples because it has been negligible

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

(at least for the sampled surface) since the boulders were deposited, based on field observations. We omitted corrections for snow cover and vegetation change due to the ephemeral winter snow cover at the elevations of the sampled boulders (e.g., Gosse and Phillips, 2001) because modern winter snow cover (Oct-Apr) is very thin and no tree cover exists due to aridity.

4. RESULTS

4.1. Late Pleistocene ELA reconstruction

LGM ELA was calculated for M_{Ih1} and M_{J1} moraines (Table 1). We estimated the former ELA using a headwall altitude of 3508–3532 m. The terminal moraine was also identified at an elevation of 3222 m a.s.l in the Ih Artsan valley. Accordingly, the ELA for the M_{Ih1} moraine was 3388 m a.s.l.. In contrast, a large terminal moraine was deposited at 2998 m a.s.l in Jargalant valley. The ELA associated with M_{J1} moraine was 3308 m a.s.l., about 80 m lower than M_{Ih1} moraine.

4.2. ^{10}Be surface exposure age dating

We present the new 28 ^{10}Be exposure ages obtained from the boulders associated with five different moraine sequences, M_{Ih1} in Ih Artsan valley and M_{J1}, M_{J2}, $M_{J3,}$ and M_{J4} sequences in Jargalant (Table 2; Fig. 5).

Ih Artsan valley: seven granitic boulders (IAM001–007) collected from the most distal moraine ridge ranged in age between 21.2 ± 1.5 to 19.1 ± 1.3 ka. ^{10}Be exposure ages from this moraine sequence were well clustered, and no outlier was detected, yielding a group mean of 20.1 ± 0.7 ka. $R\chi^2$ was 0.29, and group relative uncertainty was calculated as 4% (Fig. 6).

Jargalant valley: twenty-one granitic moraine boulders on the four moraine sequences were collected. Five to seven boulders from each moraine crest were sampled. Exposure ages from the innermost M_{J4} moraine ranged from 636.2 ± 45.1 to 177.3 ± 11.3 ka. The oldest age (JAM003, 636.2 ± 45.1 ka) was excluded, and the four remaining ^{10}Be exposure ages provided a mean age of 212.9 ± 45.9 ka. Five boulders from the M_{J3} moraine ranged in age between 209.0 ± 26.1 to 35.9 ± 8.0 ka. Group mean age was calculated as 69.9 ± 39.4 ka after rejecting an outlier of 209.0 ± 26.1 ka (JAM008). Boulders from the M_{J2} moraine yielded ages from 284.9 ± 18.4 to 162.1 ± 10.2 ka with a mean exposure age of 193.7 ± 36.7 ka after rejecting the oldest age of 284.9 ± 18.4 ka (JAM012). Samples from the distal moraine of Jargalant valley (M_{J1}) ranged in age from 18.9 ± 1.7 to 10.6 ± 0.8 ka. The arithmetic mean age for this moraine sequence was 17.2 ± 1.5 ka without the youngest age of 10.8 ± 0.5 ka (JAM016). Group was relatively well clustered, and its relative uncertainty was 9% and $R\chi^2 = 1.18$ (Fig. 6).

Boulders from inner moraines (M_{J4}, M_{J3}, M_{J2}) presented older (~636.2–35.9 ka) exposure than the timing of the maximum extent unlike morphostratigraphy-the inner moraines should be younger than the distal moraine (M_{J1}). We interpret that the unexpected older exposure ages (~636.2–35.9 ka) from M_{J4}, M_{J3}, M_{J2} moraines of Jargalant valley strongly imply the inheritance from the summit plateau. These unusually old boulders are pieces of the summit plateau that were transported onto the glacier surface by rockfall as the cirque walls were undermined by growing ice, which seems to happen in the recent times as well (Table 2; Fig. 5b). The unexpected, significant inheritance has been widely recognized around the globe in the literature of cosmogenic nuclides dating (Ciner et al., 2017; more references therein), possibly overestimating the real age of moraine.

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

The Cryosphere Discussions

5. THE 2D ICE SURFACE MODELLING: METHODS AND RESULTS

Our original hypothesis was that the north and south-facing cirques of the Ih Bogd massif would be concordant. The results were that the glaciers on the opposite aspects were asynchronously behaved, by about 3 millennia. These findings led to a second hypothesis, that aspect might provide enough of a difference to explain the asynchrony. Thus, to stay true to the research events, we combine methods and results of simulating a simple 2D ice surface model including mass balance calculation covering the time period of 22–16 ka. Our exercise cannot simulate actual glaciers, however, rather simply assess the idea that aspect might produce enough of a difference in mass balance and ice surface via different melt rates to explain the empirical dating results.

5.1. Glacial surface mass balance model

Glacier mass balance (m) is determined by the summation of net accumulation (c) and ablation (a) over a stated period (t):

$$m = c + a = \int_{t_1}^{t_2} (c + a)\, dt \qquad (1)$$

To infer the net gain and loss of glacier mass along the longitudinal profile (Fig. 7a, b, c) for both catchments, we calculated and plotted the variations in summer (JJA) mean melt rate and winter precipitation (i.e., snow in the whole year) during 22-16 ka ago. Site parameters and input parameters of this model are described in Tables 3 and 4.

5.1.1 Temperature-index glacier melt model including potential clear-sky direct solar radiation

We calculated time-dependent incoming solar radiation of the study area by applying the potential clear-sky direct solar radiation method to a 12.5 m resolution DEM to realize the aspect effect on insolation distribution in mountainous areas. For simplicity, we rerun this insolation model along a longitudinal profile line drawn for Ih Artsan and Jargalant glacial valleys (Fig. 7). Subsequently, we combined the insolation values with the temperature index melt model. To calculate melt, we used a series of equations in the following steps, calculating: 1) orbital parameters; 2) topography; 3) hour angle on an arbitrary inclined surface and day length; 4) local zenith angle and angle of incidence with hour interval; 5) hourly insolation; 6) integrate hourly insolation into daily insolation; 7) daily melt; and 8) summer (JJA) melt integration for given time of interval (22-16 ka).

The earth's rotation around its axis causes the diurnal changes in incoming solar radiation; the position of this axis relative to the sun causes seasonal changes; the variations in eccentricity, axial tilt, and precession cause combined to result in long-term cyclical changes in climate. Correspondingly, two main orbital parameters, solar declination (δ) and eccentricity correction factor $(R_m\ R^{-1})^2$ were used for the calculation of the further paleo solar radiation for 22-16 ka (Berger and Loutre, 1991).

According to the aspect effect, north-facing slopes must receive less direct solar radiation than south-facing slopes in the mid-latitude northern hemisphere. To define aspect-driven contrast in potential direct solar radiation between south-facing and north-facing valleys, we applied the same input parameters, except for the topography (aspect and slope). Sunrise and sunset hour angles on the inclined surface were calculated as a function of latitude, solar declination, slope, and azimuth (Iqbal, 1963).

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

The Cryosphere Discussions

Sunrise hour angle for horizontal surface:

$$\omega_s = \cos^{-1}(-\tan\varphi \tan\delta) \qquad (2)$$

To obtain hour angles on the inclined surface, x and y were extracted from formula 1.6.7 created by Iqbal (1963).

$$x = \frac{\cos\varphi}{\sin\gamma \tan\beta} + \frac{\sin\beta}{\tan\gamma} \qquad (3)$$

$$y = \tan\delta \left(\frac{\sin\varphi}{\sin\gamma \tan\beta} - \frac{\cos\varphi}{\tan\gamma}\right) \qquad (4)$$

The following equations give the sunrise and sunset hour angles on the surface oriented toward the east.

$$\omega_{sr} = \min\left[\omega_s, \cos^{-1}\left(\frac{-xy-\sqrt{x^2-y^2+1}}{x^2+1}\right)\right] \qquad (5)$$

$$\omega_{ss} = -\min\left[\omega_s, \cos^{-1}\left(\frac{-xy+\sqrt{x^2-y^2+1}}{x^2+1}\right)\right] \qquad (6)$$

The following equations give the sunrise and sunset hour angles on the surface oriented toward the west.

$$\omega_{sr} = \min\left[\omega_s, \cos^{-1}\left(\frac{-xy+\sqrt{x^2-y^2+1}}{x^2+1}\right)\right] \qquad (7)$$

$$\omega_{ss} = -\min\left[w_s, \cos^{-1}\left(\frac{-xy-\sqrt{x^2-y^2+1}}{x^2+1}\right)\right] \qquad (8)$$

Equations 2 to 8 are for calculating hour angles in arbitrary surfaces, where ω_s is the sunrise hour angle for horizontal surfaces, ω_{sr}, ω_{ss} is the sunrise and the sunset hour angles on the inclined surface, φ is the latitude, δ is the solar declination angle, β is the slope inclination angle, and γ is the surface azimuth angle.

Furthermore, the local zenith angle (Z) and the angle of incidence (θ) were calculated using a one-hour interval of hour angle (ω). The zenith angle is approximated as a function of latitude, solar declination angle, and hour angle (Iqbal, 1983):

$$Z = \sin\delta \sin\varphi + \cos\delta \cos\varphi \cos\omega \qquad (9)$$

and the angle of incidence on the arbitrary oriented surfaces is expressed as:

$$\cos\theta = (\sin\varphi \cos\beta - \cos\varphi \sin\beta \cos\gamma) \sin\delta + (\cos\varphi \cos\beta + \sin\varphi \sin\beta \cos\gamma) \cos\delta \cos\omega + \cos\delta \sin\beta \sin\gamma \sin\omega \qquad (10)$$

where β is the slope inclination angle and γ is the surface azimuth angle.

Hourly potential clear-sky direct solar radiation (I) during daytime is calculated as (Hock, 1999):

$$I = I_0 \left(\frac{R_m}{R}\right)^2 \Psi_a^{\left(\frac{P}{P_0 \cos Z}\right)} \cos\theta \qquad (11)$$

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

The Cryosphere Discussions
Open Access
EGU

where I_0 is solar constant (1368 W m^{-2};), $(R_m R^{-1})^2$ is the eccentricity correction factor of the Earth's orbit for the time considered with R the instantaneous Sun-Earth distance, and R_m is the mean Sun-Earth distance, Ψ_a is the mean atmospheric clear-sky transmissivity (Ψ_a=0.75: (Hock, 1998)), P_h is the atmospheric pressure (OAF, 1976), P_0 is the mean atmospheric pressure at sea level, Z is the local zenith angle, and θ is the angle of incidence between the normal to the grid slope and the solar beam. Daily solar radiation resulted from integration of hourly solar radiation for each day

We calculated daily melts with equation (12) and integrated them into annual summer melt.

$$a = \begin{cases} \left(\frac{1}{n}\mathrm{MF} + a_{ice}\, I\right) T & : \; T > 0 \\ 0 & : \; T \leq 0 \end{cases} \qquad (12)$$

MF is a melt factor (mm d^{-1} $°C^{-1}$), a_{ice} is a radiation coefficient for ice surfaces, I is potential clear-sky direct solar radiation at the ice surface (W m^{-2}), and T is the monthly mean temperature (°C).

We calculated the paleotemperature of the study area in the following order.

1st) Present-day monthly air temperatures (T) for both cirque headwall altitudes (3533.3 m in Jargalant, 3508.3 m in Ih Artsan) were calculated from the two nearest national weather stations using a summer adiabatic lapse rate of 8 °C km^{-1} (Batbaatar et al., 2018). Bayangobi weather station locates (1540 m a.s.l) ~27 km SE and Bogd (Horiult) weather station (1240 m a.s.l) is ~45 km NE from the study area (Fig. 2c).

2nd) We use only summer temperature because even today, monthly mean temperatures between August to May are less than 0 °C, in which no melt occurs (NAMEM, 2020). Present-day precipitation falls as snow between the end of September to the middle of April. Sometimes it snows even in summer (Landsat imagery, Farr et al., 2007). The summer mean temperature (JJA) at the cirque headwall altitude was measured as 3.5 °C in Jargalant valley and 5.4 °C in the Ih Artsan valley. We chose the value of 5.4 °C for the summer temperature of the study area and used further calculations (see supplementary 1 file).

3rd) We obtained a time-dependent summer temperature since 22 ka. LGM summer temperature was easily calculated by subtracting known LGM summer temperature anomaly (1–7 °C by Tarasov et al., 1999) from the present-day temperature of the study area. The study area's present-day and LGM summer temperature was calibrated to Greenland temperature data (from NGRIP ice core) since 22 ka (Buizert et al., 2018) to obtain time-dependent temperature variation (see supplementary 2 file).

4th) LGM summer temperature anomalies ranging from -5.0 °C to -6 °C were applied to calculate glacial melt since 22 ka (see supplementary 2 file).

5.1.2. Glacier accumulation and snow data

Climatologies at high resolution for the earth's land surface areas (CHELSA) provides a high resolution, downscaled centennial climate model data since 20 ka. We used CHELSA-TraCE21k 1 km monthly precipitation time series (Karger et al., 2021). Precipitation data between 22–20 ka was considered the same as 20 ka data. Only snowfall at

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

the mean altitude of each valley was considered glacial accumulation, which occurs when the monthly average temperature is below 0 °C.

5.2. 2D ice surface model based on glacier thickness change

Finally, a simple 2D ice surface model reconstructed paleo glacier behavior from 22–16 ka in the study area. First, we created small initial glacial surface profiles on both valleys using the 2D ice surface model developed by Benn and Hulton (2010). The model calculates the ice surface elevation (ice thickness) along the profiles (Fig. 7a, b, c) in both valleys. The model only requires an input of the yield stress that is assumed to describe a glacier's basal shear stress regime and a shape factor accounting for the valley-drag effects. We plot the ice profile with 5 m spacing, assuming constant basal shear stress of 50, 100, 150, 200, and 300 kPa. According to the glacial valley scale and paleoglacier extent, we chose the higher basal shear stress of initial glacier for Jargalant valley (200 kPa) and the smaller value for Ih Artsan valley (100 kPa). Shape factors were calculated perpendicular to the profile at intervals of 5 m. Subsequently, we calculated the glacier mass balance for 22–16 ka using our temperature-index melt model results and paleo snow accumulation data. Therefore, we applied corresponding paleo mass balance values on the initial ice thickness profiles. A cross-section of the thickest ice was recognized as ELA. Accordingly, paleo ELAs were calculated regarding the ice thickness change. Eventually, we used the simple quadratic function formula ($f(x)=ax^2 + bx + c$) to determine the location of the glacial toe based on ELA and headwall altitude values (Benn and Hulton 2010). With the glacial toe location, we could evaluate the paleoglacier advance and retreat at any time of interest.

5.3. 2D Ice surface modelling result

We ran the potential direct solar radiation model applying to a 12.5 m resolution DEM for a more realistic comparison. The model suggests that the aspect largely affects the incoming potential clear-sky solar radiation. The result approved that the south-facing slopes in mountainous regions receive more significant solar radiation than the north-facing slope in the northern hemisphere. According to the exact orientation (aspect) of the valleys (northeast to southwest), hourly maximum insolation in Ih Artsan and minimum insolation in Jargalant were observed between 15 to 16 o'clock, not at noon. The present-day June solstice incoming daily solar radiation was 8527.34 WH m^{-2} in Ih Artsan valley and 7714.35 WH m^{-2} in Jargalant valley but the solar radiation was smaller in 22 ka, 8460.07 WH m^{-2} in Ih Artsan, and 7604.54 WH m^{-2} in Jargalant. Although both valleys received maximum insolation in the first to middle half of June, the maximum difference in incoming daily solar radiation occurred at the end of August. The main difference in the daily incoming solar radiation ranges from 10–24% in summer days over 22-16 ka. The spatial distribution of potential direct solar radiation of the study area is given in Fig. 7. Typically, total daily insolation of summer solstice for 20 ka (Fig. 7a), summer insolation for thousand years (21–20 ka), and total summer insolation over 22–16 ka was described on the 12.5 m grid cells. In the same way, 14% excess of total summer insolation was observed on the southern slope during over modelling time interval of 22–16 ka (Fig. 7b, c, see supplementary 2 file).

For simplicity, the melt was calculated along valley profile of Ih Artsan and Jargalant valleys (Fig. 7). In accordance with the incoming solar radiation contrast, melt rates on south-facing slopes exceed those on north-facing slopes, as would be expected. If modern glaciers existed in Ih Bogd, the present-day summer melt would be calculated

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

as 4.02 m in Jargalant valley and 3.7 m in Ih Artsan valley, respectively. This was a substantially higher melt rate in the arid, cool climate of the study area. The temperature-index melt model discovered that 5% of melt excess in June solstice of any year between 22–16 ka was observed on the south-facing slope. Approximately 8% of the difference in summer melt in any year was observed during 22–16 ka (Fig. 7, see supplementary 2 file)

Except for the present-day temperature and topographic data, the same input parameters were applied to both valleys. LGM summer temperature anomalies ranging from -6 ℃ to -5 ℃ with 0.1 ℃ intervals were applied the same for both glaciers. We used input parameter of 100 kPa of basal shear stress for Ih Artsan initial glacier (22 ka), while a twofold value (200 kPa) for Jargalant in proportion to the size of the glaciers. We applied two different present-day temperature values for the Jargalant glacier, but LGM summer temperature anomalies were the same for both cases. We ran the 2D ice surface model from 22 ka to 16 ka with two cases according to the different temperature inputs: 1) using the same present-day temperature; and 2) using the different present-day temperature for both valleys.

Case 1. Applying the same present-day temperature: The timing of maximum extent was similar for both valleys when using the same site temperature. When we give LGM anomaly -5.5 ℃, the timing of the maximum extents (20.23 ka) for both valleys were consistent with the Ih Artsan terminal moraine age dating result (20.1 ka).

Case 2. Applying the different present-day temperatures: For the Jargalant glacier, we applied lower present-day temperature by -1 ℃ to -0 ℃ (at 0.1 ℃ interval) than Ih Artsan. The run yielded different chronologies of maximum ice expansions. The gaps between maximum ice advance timings range from 2.70–3.46 kyr. When we applied -5.5 ℃ of LGM summer temperature anomaly and present-day summer temperature in Jargalant 0.5 ℃ lower than in Ih Artsan, Ih Artsan glacier reached its maximum extent near 20.23 ka. In contrast, the Jargalant glacier maximally advanced approximately at 17.13 ka. This result perfectly fits our ^{10}Be moraine age dating results (20.1 ka and 17.2 ka).

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

The Cryosphere Discussions

6. DISCUSSION

6.1. Asynchrony in LGM ice expansion across the western Mongolia

Our study shows the glaciers of Ih Artsan valley reached its maximum extent during gLGM at 20.1 ± 0.7 ka. Several inner moraine ridges (Fig. 5a) were recognized and some of them dated to 15–13 ka (Batbaatar et al., 2018).

In the other hand, our study also documents the farthest found moraine (M_{J1}) in Jargalant valley formed around 17 ka (17.2 ± 1.5 ka), three millennia later than the south-facing Ih Artsan valley. We could not find any other evidence that the Jargalant glacier reached the trunk valley of Bituut river. Probably geological markers could have been erased by the main river of Bituut or earlier advances were less extensive. However, we suggest the exposure age (17.2 ± 1.5 ka) of the distal moraine (M_{J1}) is the age for maximum extent for the Jargalant valley (Fig. 5b and 6), because this moraine was not like the small ridge left as a glacier stagnates during its retreat. The M_{J1} moraine was larger than the other moraine sequences, large enough to mark the maximum advance of the glacier.

Some ^{10}Be exposure ages of the glacial erratic from the mountain ranges nearby Ih Bogd show the significant glacial advances between LGM to the Holocene (Fig. 8). The largest ice extent was dated as ~22.0 ka on the western flank of the Sutai (Batbaatar et al., 2018). On the other hand, the farthest ice expansion corresponds to MIS 3 in the Khangay mountain range (Batbaatar et al., 2018; Pötsch, 2017; Smith et al., 2016; Rother et al., 2014). In the Gichgene mountains, Holocene (8–7 ka) glaciers advanced with a similar magnitude to their local LGM position. Generally, two main glacial stages, LGM and post LGM (~17–16 ka), were observed within MIS 2 in Mongolia (Batbaatar et al., 2018; Pötsch, 2017; Batbaatar and Gillespie, 2016; Smith et al., 2016; Rother et al., 2014).

A suite of granulometric, palynological, ostracod, and geochemical proxies from the Gobi Lakes Valley reveal several harsh and dry climates, including the local LGM (19–18 ka) and Younger Dryas (Mischke et al., 2020; Yu et al., 2019; Lehmkuhl et al., 2018; Yu et al., 2017; Lee et al., 2013; Felauer et al., 2012, Fig. 8). Abrupt deglaciation occurred near 20 ka in Ih Artsan valley, whereas the lower boundary of deglaciation likely began at 17.2 ka on Ih Bogd's northern slope (Jargalant). The warming trend was also present in the Gobi Lakes Valley, where lakes once were desiccated during local LGM, and experienced water level increase after local LGM (e.g., Mischke et al., 2020; Yu et al., 2017).

6.2. Asynchronous LGM glaciation in other mid-latitude ranges

Recent glacial chronologies from mid-latitude mountain ranges in North Atlantic region document that Laurentide, Scandinavian ice sheets and number of valley glaciers behaved synchronously, advancing to their maximum extent at roughly the same time as the gLGM (26.5–19 ka). However, some experienced pre-LGM glacial maxima, while others stagnated, re-advanced, continuously advanced even farther during the subsequent Heinrich Stadial 1 (HS-1, 17.5-14.5 ka), displaying both inter-range and intra-range asynchrony (Palacio et al., 2020; Licciardi and Pierce 2018; Young et al., 2011, Laabs et al., 2009).

Large scale inter-range asynchrony (several tens of kyr) of last glacial termination was common in Europe. Cosmogenic surface dating from Alps and Turkey provides nearly synchronous last glacial maxima with the gLGM (26.5–19 ka, MIS 2), whereas other numerical dating techniques including radiocarbon, U-series, and OSL indicate

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

earlier local glacial maxima (80–30 ka, MIS 4 to MIS 3) in the Cantabrian Mountains, Pyrenees, Italian Apennines and Pindus Mountains (e.g., Oliva et al., 2019; Jimenez-Sanchez et al., 2013). Another inter-range asynchrony was observed in mountain glaciers of North America. They reached their maximum extent from as old as 25–24 ka for some moraines and outwash in Sierra Nevada to as young as 17–15 ka for some terminal moraines in the Rocky Mountains but a clear central tendency exists with a mean of ~19.5 ka (Laabs et al., 2020; Palacios et al., 2020; Young et al., 2011). Relatively younger ages (HS-1) across the mountains located in the higher latitude were interpreted as a sign of glacial post-LGM culmination in response to increased delivery of westerly derived moisture which reached the northern continental interior of the western U.S after the large ice sheets started to retreat (Thackray, 2008, Licciardi et al., 2004, Licciardi et al., 2001). For instance, younger exposure ages of last glacial maxima in the western Uinta mountains, compared to mountain ranges farther east and north, reflected the influence of pluvial Lake Bonneville after recession of Laurentide ice sheet to the north (Laabs et al., 2009).

Medium scale inter-range asynchrony (several thousand years) was observed in Yellowstone plateau. Terminal moraines dated to ~17 ka are common in valleys along the north eastern mountains (e.g. Eightmile, Chico, Pine Creek, S.Fork Deep Creek, Cascade Canyon and Gallatin) of the Great Yellowstone plateau. Glaciers in Teton Range (south western part of the plateau) have terminal moraine with age of ~15 ka. Local LGM maxima dated to ~19.8 to 18.2 ka in the western part of the plateau (Beartooth Uplift). Licciardi and Pierce (2018) suggested that shifting orographic precipitation pattern due to formation of ice dome and change in ice flow direction caused asynchrony in the Great Yellowstone region.

No or very small number of glacial chronologies document intra-range asynchrony for the latest glacial termination. Age dating results from some relatively well-studied mountain ranges (Wasatch, Uinta, Bighorn ranges in North America) present that intra-range asynchrony in glacial maxima in their various aspect (Laabs et al., 2020). Some of them had LGM age ranging from hundreds to thousands of years from valley to valley. In the Wasatch range, terminal moraines dated to ~21.9 ka (Laabs and Munroe, 2016), ~20.8 ka, 17.3 ka (Laabs et al., 2011) in three western valleys, 19.6 ka in the southwestern valley and 17.6 ka, 17.3 ka in the southeastern valleys (Quirk et al., 2020). Similarly, last glacial terminal moraine age difference of ~1 kyr observed between north-facing and south-facing slope, Eastern Pyrenees (Delmas et al., 2011; Delmas et al., 2008). Even glaciers on the same oriented slope contain some chronology difference. LGM moraine chronology from the three valleys on the east side of the central Sawatch range varies from 22.3 ka to 19.9 ka (Young et al., 2011). Nevertheless, we suggest that some internal, external, analytical uncertainties associated with sampling, measurements, or/and statistical approach can cause the low magnitude of asynchrony in such small intra-range or massif. Some studies have attributed intra-range asynchrony in terminal moraine ages to contrasting valley glacier response times related to topography, ice dynamics and/or differences in glacier shape and hypsometry (Young et al., 2011, Licciardi and Pierce, 2018). As mentioned above, large and medium scale asynchrony in the mountain glaciers across the North Atlantic region mostly explained by precipitation distribution due to the relative location of the moisture source area and atmospheric circulation contributed by topography. However intra-range or intra-massif scale of asynchrony in last glacial period needs further research to be fully understood.

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

6.3. Aspect effect on asynchronous maximum glacier extent

Previous research indicates that the retreat or advance pattern of glaciers in some regions is not necessarily expected to be uniform, coincidental, or synchronous with the primary factors (Fig. 8). Based on proxies from lacustrine (Orog) sediment cores, the local LGM ranges between 19 and 18 ka near the Ih Bogd massif (Yu et al., 2017; Yu et al., 2019). However, deglaciation started in Ih Artsan valley (south-facing) nearly a thousand years earlier (20.1 ± 0.7) than local LGM. For the Jargalant valley (north-facing), we could not find the actual evidence of the latest deglaciation. If we consider both glaciers moved synchronously, the geological evidence (terminal moraine) near 20 ka must have been degraded by Bituut mainstream or/and reworked with the mass movement. Contrary, if the Jargalant glacier advanced maximally near 17.2 ka based on exposure age dating, deglaciation must have begun 3000 years later in Jargalant valley than in Ih Artsan valley. In this case, the most extensive glacial extent in Jargalant valley should represent LGM glacial survival or significant glacial re-advance near 17 ka as the same as glacier advance in Mongolia and North Atlantic region during HS-1.

In either case, changes in glacier mass balance in small massif or mountain (intra-range) could show large spatial variation due to local topography-driven climatic factors: 1) snow avalanching, 2) preferential deposition of wind-drifted snow (Florentine et al., 2020), 3) solar radiation, 4) temperature.

1. Periodically occurring snow avalanches support glacial accumulation. Most avalanches have steep slopes between 25° and 50° to slide down (Luckman, 1977). Both valleys are connected to the flat top and are less steep than the threshold slope of 25°; Jargalant valley is 23° for Jargalant and 18.2° for Ih Artsan. Very wet snow lubricated with water can cause an avalanche on a slope of only 10 to 25° (Luckman, 1977). However, it is not significantly relevant to our study area because Ih Bogd and its neighboring area experienced very cold and dry conditions during MIS 2 (e.g., Yu et al., 2019).
2. Wind-drifted snow accumulation occurs either with or without snowfall. Wind deflates the snow from the windward slope and redistributes it into the leeward slope. However, the prevailing wind direction of the study area is northwest to southeast, which is the almost perpendicular direction to the orientations of the two valleys. We assume the wind direction during MIS 2 was similar to the present with much strength. Therefore, wind drifted snow may not significantly affect glacier accumulation. For that reason, we used the same precipitation value in both valleys.
3. North-facing slopes in the northern hemisphere receive less solar radiation because of the aspect effect. Ih Bogd locates in a mid-latitude great sunlight climate; furthermore, it has steeper relief which can enhance the aspect effect. (Evans and Cox, 2005). Topographic shading can also influence glacier response and mass balance in mountainous areas (Olson and Rupper, 2019). As expected, our modelling results demonstrate that the north-facing slope receives less summer insolation than the south-facing slope, resulting in reduced glacial melt (5-10%) under the same temperature conditions. Our 2D ice surface model suggests that an aspect affects the amount of melt, however in a very small amount. This small reduction in the melt due to the shading effect could not stagnate glaciers or cause significant glacier to advance for 3000 years. Under the same temperature, glaciers on the north and south-facing slopes across small regions behave almost synchronously.

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

4. Some previous studies suggest that temperature is lower on the north-facing slopes at the same altitude. On the north-facing slope of Taibai, Qinling mountains, JJA monthly mean temperature is measured 0.5–1 °C lower than on the south-facing slope in the altitude range of 1250–3750 m (Tang & Fang, 2006). The vegetation distribution on Mongolia's north-facing and south-facing slopes can prove the contrast in temperature and moisture on sunny and shady slopes. In the field, we can easily see that trees grow only on the northern slope within the forest-step zone in Mongolia (Fig. 7d, 7e). According to these facts, a small temperature difference is real and needs to be considered. When we set the present-day temperature of Jargalant to 0.5 °C colder than in the Ih Artsan, 2D ice surface modelling results perfectly match with the ^{10}Be age dating results (Fig. 9). In this case, glaciers retreated from their distal location asynchronously. The retreat of Ih Artsan glacier started near 20.23 ka (age dating result was 20.1 ka), while Jargalant glacier started to retreat near 17.13 ka (age dating result was 17.2 ka). There were small fluctuations in the ice advance and retreat with temperature changes in both cases, synchronous and asynchronous.

In conclusion, glacier volume and area changes are likely to be sensitive to temperature change during cold periods (22–16 ka) in semi-arid and arid regions, such as Ih Bogd (Batbaatar et al., 2018). Based on the age dating and 2D ice surface modelling, we propose that the glaciers on the north- and south-facing slopes of Ih Bogd were able to reach their maximum extent at different times with a 3 kyr temporal gap, caused by a combination of aspect-driven melt rate and temperature difference.

6.4. Morphostratigraphic mismatch in exposure age dating from erratic boulders, Jargalant valley

6.4.1. Inheritance from the summit plateau

The massif has a steep slope; in particular, the slope reaches 32–70° along cirque walls and incised valleys . Colluvial materials covering hillslopes and long boulder corridors were mainly the results of the active mass wasting process. Particularly, rockfall deposits forming scree and talus apron must be the product of steep slope failure of the summit plateau (Fig. 10). We expected that inner moraine crests would present Holocene or HS-1 exposure in light of morphostratigraphy. M_{J2}, M_{J3}, and M_{J4} moraine crests have exposure ages ranging from 636.2 to 35.9 ka (Table 2, Fig. 5). According to moraine stratigraphy, exposure ages of inner moraines cannot be older than the age of the distal moraine. The apparent ages show antiquity and scatter in its distribution, which cannot be a single geologic event; associating the mean age with the specific timing of glacial termination is not appropriate (Heyman et al., 2011b). It was more likely that the exposure ages from M_{J2}, M_{J3}, and M_{J4} moraines were due to the inherited ^{10}Be concentration produced during prior exposure in the boulders recycled from the cirque wall or paleo summit plateau by rockfall or toppling during glaciation and/or paraglacial period. The shorter distance from the cirque wall was not enough for a glacier to erode the rock surface, including inheritance during transportation to the final position (Fig. 11d-f). On the other hand, this pattern would be contributed by enhanced rock-slope failure (de-buttressing) right after rapid deglaciation (Hashemi et al., 2022; Ballantyne and Stone, 2012; Cossart et al., 2008).

6.4.2. Cenozoic evolution of the low-lying, high-elevated summit plateau

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

The Cryosphere Discussions
Open Access
EGU

We recalculated the exposure age and erosion rate for the paleo-summit plateau using ^{10}Be concentrations from those reworked boulders and production rate at the elevation of 3625 m which is the highest point between Jargalant and Ih Artsan cirques (Fig. 11). Maximum exposure age of the flat summit plateau was calculated as 442.3 ± 29.8 ka, and the corresponding erosion rate of the summit plateau was 1.23 ± 0.10 m Myr^{-1}, which falls well into the common denudation rate of arid region. (Table 2).

The flat summit plateau of the Ih Bogd massif is considered an uplifted paleo-peneplanation surface. The basement structure of Ih Bogd was formed by the collision of the WNW-ESE to ENE-WSW oriented amalgamated terranes throughout the Precambrian and Paleozoic (Şengör et al., 1993). ^{40}Ar/^{39}Ar ages from extrusive volcanic on the Ih Bogd summit and apatite fission-track data show two significant uplifts that occurred in the Gobi-Altay range and Ih Bogd history (Jolivet et al., 2007; Vassallo et al., 2007). The first uplift related to early to mid-Jurassic, the region experienced crustal shortening events greater than 2 km. Gobi-Altay has been observed elsewhere in central Asia through this event that is possibly due to a collision between Mongol-Okhotsk and Siberia or the Lhasa and Qiangtang block to the far south in Tibet (Cunningham, 2010; Dewey et al., 1988; Traynor and Sladen, 1995). The present erosional surface of the summit plateau formed just after this Jurassic exhumation and was preserved under a negligible erosion rate. Preservation of this flat summit plateau and its fission-track age indicate quiescence without significant vertical crustal motions continued until the last uplift began (Cunningham, 2010; Jolivet et al., 2007; Vassallo et al., 2007).

The Gobi-Altay range is one of the northernmost far-fields affected by the Cenozoic tectonic collision of India into Asia, which initiated the late Cenozoic reactivation and present-day stress regime (Cunningham et al., 1996; Vassallo et al., 2007). According to the apatite fission track data of Vassallo et al. (2007), the onset of the last and ongoing uplift corresponds to the late Cenozoic, 5 ± 3 Ma. This tectonic reactivation is responsible for creating the high topography (~4000 m a.s.l) seen today, in the response to which faster exhumation is initiated as well (Vassallo et al., 2007).

The paleo-erosion surfaces at high altitudes experienced rapid uplift after a long time of quiescence with low erosion. Cosmogenic nuclides-based denudation rates from global paleo-erosion surfaces in diverse climatic, tectonic, and lithologic environments do not exceed ~20 m Myr^{-1} (Byun et al., 2015). We obtained erosion rate for flat summit plateau using production rate at summit plateau and ^{10}Be concentrations of reworked boulders from M_{J4}, M_{J3}, and M_{J2} moraines. Calculated bedrock erosion rate for last ~600 ka for summit plateau ranged from 1.23 ± 0.10 m Myr^{-1} to 25.8 ± 5.75 m Myr^{-1}. The erosion rate of 25.8 ± 5.75 m Myr^{-1} was thought to be a maximum value because erosion probably increases with the increasing elevation of the uplifting massif. This result was harmonious with the long-term (since the last uplift) exhumation rate of 23.6 ± 3 m Ma^{-1} (Vassallo et al., 2011) and Holocene erosion rate of 28 m Myr^{-1} (Jolivet et al., 2007) for the massif. Whereas flatness and the lowest erosion rate of 1.23 ± 0.10 m Myr^{-1} reveal negligible erosion and notable preservation of paleo-surface for several hundred thousand years. If this erosion rate reflects an average rate that can be applied to the entire flat surface and has been maintained for the total uplift period of the massif (Vassallo et al., 2007), it would account for only the 2 to 7.6 m of erosion.

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

The Cryosphere Discussions

7. CONCLUSIONS

Central Asian valley glaciers, including Ih Bogd massif, expanded and shrank, presenting more complex behavior relative to large ice sheets in the northern hemisphere. Regional climate and local non-climatic factors have been playing an essential role in this complexity. Our ^{10}Be dating documents that the maximum advance in Ih Artsan valley on the southern slope occurred at 20.1 ka (M_{Ih1}), generally falling within the gLGM, whereas large terminal moraine formed around 17.2 ka (M_{J1}) in the Jargalant valley on the northern slope.

Asynchrony in glacier expansion has been reported from some of areas in the globe but has not been clearly studied with a combination of geochronologic and numerical modeling approaches. The glacier chronology itself provides the possibility of both explanations, synchronous and asynchronous expansion of glacier. Glaciers of Ih Artsan and Jargalant valleys advanced and retreated synchronously in the same LGM summer temperature. Due to aspect-driven solar insolation change, paleoglacier in the north-facing Jargalant valley melted slower (5-10%) than the glacier in Ih Artsan valley. However, this amount of melt difference could not produce glacier advance or stagnation for a long period. Asynchronous glaciation was observed across the study area if the LGM summer temperature in Jargalant valley was 0.5 °C lower than in Ih Artsan due to aspect-driven temperature change. According to the lower temperature case, Jargalant glacier retreated from the most extensive position 3000 years later than Ih Artsan glacier. The temperature difference driven by aspect on both slopes significantly affects the glaciers to survive longer than when the aspect-driven insolation only affects the glacier melt.

The glacial retreat began soon after the peak of local glacial maximum on both valleys and left several sequences of inner moraines in their heads (cirques). Inner moraine at the south-facing cirque dated to ~ 13.5 ka (Batbaatar et al., 2018), however on the north-facing cirque, transported boulders show a significantly old exposure age (636.2 to 35.9 ka) for inner moraines (M_{J2} - M_{J4}). The summit plateau of the Ih Bogd massif is one of the oldest known tectonically uplifted surfaces on Earth. It is more likely that extremely old exposure ages are the result of inheritance recycled from rock falls from the paleo-erosional surface of the summit plateau.

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

Data availability. The data that supports the findings of this study are available within the article [and its supplementary material]

Author contributions. YBS planned the study and proceeded a field investigation with JSO, PK, KS, and CHL. YBS designed a funding acquisition. JSO designed ^{10}Be lab experiments with RHH and BYY. CHL and MKS developed a matlab code of the 2D ice surface modelling and performed the simulation. PK and YBS prepared the manuscript with contributions from all co-authors.

*Competing interests***.** The contact author has declared that neither they nor their co-authors have any competing interests.

Disclaimer. Publisher's note: Copernicus Publications remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Acknowledgments. This work was supported by the Ministry of Education of the Republic of Korea and the National Research Foundation of Korea (NRF-2018S1A5A2A01031348 for Y.B.S)**.**

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

The Cryosphere Discussions
Open Access
EGU

REFERENCES

©JAXA/METI., 2007. ALOS PALSAR L1.0 High-resolution terrain corrected dataset. Accessed through ASF DAAC, https://asf.alaska.edu, 25 June 2009. https://doi.org/10.5067/J4JVCFDDPEW1

An, Z., Kukla, G., Porter, S.C., Xiao, J.: Late Quaternary dust flow on the Chinese loess plateau, Catena, 18(2), 125-132, https://doi.org/10.1016/0341-8162(91)90012-M, 1991.

Balco, G., Stone, J.O., Lifton, N.A., Dunai, T.J.: A complete and easily accessible means of calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements, Quat. Geochronol., 3(3), 174-195, https://doi.org/10.1016/j.quageo.2007.12.001, 2008.

Ballantyne, C.K., Stone, J.O.: Timing and periodicity of paraglacial rock-slope failures in the Scottish Highlands, Geomorphology, 186, 150-161, https://doi.org/10.1016/j.geomorph.2012.12.030, 2013.

Barr, I.D., Lovell, H.: A review of topographic controls on moraine distribution, Geomorphology, 226, 44-64, https://doi.org/10.1016/j.geomorph.2014.07.030, 2014.

Batbaatar, J., Gillespie, A.R.: Outburst floods of the Maly Yenisei. Part II–new age constraints from Darhad basin, Int. Geol. Rev., 58(14), 1753-1779, https://doi.org/10.1080/00206814.2016.1193452, 2016.

Batbaatar, J., Gillespie, A.R., Fink, D., Matmon, A., Fujioka, T.: Asynchronous glaciations in arid continental climate, Quat. Sci. Rev., 182, 1-19, https://doi.org/10.1016/j.quascirev.2017.12.001, 2018.

Bayasgalan, A., Jackson, J., Ritz, J.F., Carretier, S.J.T.: Field examples of strike-slip fault terminations in Mongolia and their tectonic significance. Tectonics, 18(3), 394-411, https://doi.org/10.1029/1999TC900007, 1999.

Benn, D. I., and Hulton, N. R.: An ExcelTM spreadsheet program for reconstructing the surface profile of former mountain glaciers and ice caps, Comput. Geosci, v. 36, no. 5, p. 605-610, https://doi.org/10.1016/j.cageo.2009.09.016, 2010,

Benn, D.I., Lehmkuhl, F.: Mass balance and equilibrium-line altitudes of glaciers in high-mountain environments, Quat. Int., 65(Supplement C), 15-29, https://doi.org/10.1016/S1040-6182(99)00034-8, 2000.

Berger, A., and Loutre, M.-F.: Insolation values for the climate of the last 10 million years, Quat. Sci. Rev, v. 10, no. 4, p. 297-317, https://doi.org/10.1016/0277-3791(91)90033-Q, 1991,

Berkey, C.P., Morris, F.K.: The peneplanes of Mongolia, Am. Mus. Novit., 136, 1-11, 1924.

Blomdin, R., Stroeven, A.P., Harbor, J.M., Gribenski, N., Caffee, M.W., Heyman, J., Rogozhina, I., Ivanov, M.N., Petrakov, D.A., Walther, M.: Timing and dynamics of glaciation in the Ikh Turgen Mountains, Altai region, High Asia, Quat. Geochronol., 47, 54-71, https://doi.org/10.1016/j.quageo.2018.05.008, 2018.

Blomdin, R., Stroeven, A.P., Harbor, J.M., Lifton, N.A., Heyman, J., Gribenski, N., Petrakov, D.A., Caffee, M.W., Ivanov, M.N., Hättestrand, C., Rogozhina, I., Usubaliev, R.: Evaluating the timing of former glacier expansions in the Tian Shan: A key step towards robust spatial correlations, Quat. Sci. Rev., 153, 78-96, https://doi.org/10.1016/j.quascirev.2016.07.029, 2016.

Buizert, C., Keisling, B., Box, J., He, F., Carlson, A., Sinclair, G., and DeConto, R.: Greenland-wide seasonal temperatures during the last deglaciation, Geophys. Res. Lett., v. 45, no. 4, p. 1905-1914, https://doi.org/10.1002/2017GL075601, 2018,

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

The Cryosphere Discussions
Open Access
EGU

Byun, J., Heimsath, A.M., Seong, Y.B., Lee, S.Y.: Erosion of a high-altitude, low-relief area on the Korean Peninsula: implications for its development processes and evolution, Earth Surf. Process. Landf., 40(13), 1730-1745, https://doi.org/10.1002/esp.3749, 2015.

Chauvenet, W.: A Manual of spherical and practical astronomy-Vol. 1: Spherical astronomy; Vol. 2: Theory and use of astronomical instruments. Method of least squares, 5th ed., revised and corr, Dover Publication, New York, 1960

Chen, Y., Li, Y., Wang, Y., Zhang, M., Cui, Z., Yi, C., Liu, G.: Late Quaternary glacial history of the Karlik Range, easternmost Tian Shan, derived from ^{10}Be surface exposure and optically stimulated luminescence datings, Quat. Sci. Rev., 115, 17-27, https://doi.org/10.1016/j.quascirev.2015.02.010, 2015.

Ciner, A., Sarikaya, M. A., Yildrimm, C.: Misleading old age on a young landform? The dilemma of cosmogenic inheritance in surface exposure dating: Moraines vs. rock glaciers, Quat. Geochronol., 42, 76-88, https://doi.org/10.1016/j.quageo.2017.07.003, 2017.

Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W., McCabe, A.M.: The last glacial maximum, Science, 325(5941), 710-714, https://doi.org/10.1126/science.1172873, 2009.

Cossart, E., Braucher, R., Fort, M., Bourlès, D., Carcaillet, J.: Slope instability in relation to glacial debuttressing in alpine areas (Upper Durance catchment, southeastern France): evidence from field data and 10Be cosmic ray exposure ages, Geomorphology, 95(1-2), 3-26, https://doi.org/10.1016/j.geomorph.2006.12.022, 2008.

Cunningham, D.: Tectonic setting and structural evolution of the Late Cenozoic Gobi Altai orogen, J. Geol. Soc. London., 338(1), 361-387, https://doi.org/10.1144/SP338.17, 2010.

Cunningham, W.D., Windley, B.F., Dorjnamjaa, D., Badamgarov, J., Saandar, M.: Late Cenozoic transpression in southwestern Mongolia and the Gobi Altai-Tien Shan connection, Earth Planet. Sci. Lett., 140(1-4), 67-81, https://doi.org/10.1016/0012-821X(96)00048-9, 1996.

Delmas, M., Calvet, M., Gunnell, Y., Braucher, R., & Bourlès, D.: Palaeogeography and 10Be exposure-age chronology of Middle and Late Pleistocene glacier systems in the northern Pyrenees: implications for reconstructing regional palaeoclimates, Palaeogeo. Palaeoclimatol. Palaeoecol., 305(1-4), 109-122, https://doi.org/10.1016/j.palaeo.2011.02.025, 2011.

Delmas, M., Gunnell, Y., Braucher, R., Calvet, M., & Bourlès, D.: Exposure age chronology of the last glaciation in the eastern Pyrenees, Quat. Res., 69(2), 231-241, https://doi.org/10.1016/j.yqres.2007.11.004, 2008.

Devyatkin, E.: Structures and formational complexes of the Cenozoic activated stage. Tectonics of the Mongolian People's Republic, Nauka, 41, 182-195, 1974.

Dewey, J.F., Shackleton, R.M., Chengfa, C., Yiyin, S.: The tectonic evolution of the Tibetan Plateau, Philos. Trans. Royal Soc. A., 327(1594), 379-413, https://doi.org/10.1098/rsta.1988.0135, 1988.

Evans, I.S., Cox, N.J.: Global variations of local asymmetry in glacier altitude: separation of north–south and east–west components, J. Glaciol., 51(174), 469-482, https://doi.org/10.3189/172756505781829205, 2005.

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

The Cryosphere Discussions

Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L.: The shuttle radar topography mission, Rew. Geophys., 45(2) DOI: https://doi.org/10.1029/2005RG000183, 2007.

Felauer, T., Schlütz, F., Murad, W., Mischke, S., Lehmkuhl, F.: Late Quaternary climate and landscape evolution in arid Central Asia: A multiproxy study of lake archive Bayan Tohomin Nuur¢, Gobi desert, southern Mongolia, J. Asian. Earth. Sci., 48, 125-135, https://doi.org/10.1016/j.jseaes.2011.12.002, 2012.

Fletcher, W.J., Goni, M.F.S., Allen, J.R., Cheddadi, R., Combourieu-Nebout, N., Huntley, B., Lawson, I., Londeix, L., Magri, D., Margari, V.: Millennial-scale variability during the last glacial in vegetation records from Europe, Quat. Sci. Rev., 29(21-22), 2839-2864, https://doi.org/10.1016/j.quascirev.2009.11.015, 2010.

Florentine, C., Harper, J., Fagre, D.: Parsing complex terrain controls on mountain glacier response to climate forcing, Glob. Planet. Change., 191, 103209, https://doi.org/10.1016/j.gloplacha.2020.103209, 2020.

Garnier, B., and Ohmura, A.: A method of calculating the direct shortwave radiation income of slopes, J. Appl. Meteorol. Climatol., v. 7, no. 5, p. 796-800, https://doi.org/10.1175/1520-0450(1968)007<0796:AMOCTD>2.0.CO;2, 1968.

Gillespie, A., Molnar, P.: Asynchronous maximum advances of mountain and continental glaciers, Rew. Geophys., 33(3), 311-364, https://doi.org/10.1029/95RG00995, 1995.

Gillespie, A.R., Burke, R.M., Komatsu, G., Bayasgalan, A.: Late Pleistocene glaciers in Darhad basin, northern Mongolia, Quat. Res., 69(2), 169-187, https://doi.org/10.1016/j.yqres.2008.01.001, 2008.

Goldthwait, R.P.: Mountain glaciers of the Presidential Range in New Hampshire, Arc. Alp. Res., 2(2), 85-102, https://doi.org/10.1080/00040851.1970.12003566, 1970.

Gosse, J.C., Phillips, F.M.: Terrestrial in situ cosmogenic nuclides: theory and application, Quat. Sci. Rev., 20(14), 1475-1560, https://doi.org/10.1016/S0277-3791(00)00171-2, 2001.

Hashemi, K., Sarıkaya, M.A., Görüm, T., Wilcken, K.M., Çiner, A., Žebre, M., Stepišnik, U., Yıldırım, C.: The Namaras rock avalanche: Evidence of mid-to-late Holocene paraglacial activity in the Central Taurus Mountains, SW Turkey, Geomorphology, 408, 108261, https://doi.org/10.1016/j.geomorph.2022.108261, 2022.

Heyman, J.: Paleoglaciation of the Tibetan Plateau and surrounding mountains based on exposure ages and ELA depression estimates, Quat. Sci. Rev., 91, 30-41, https://doi.org/10.1016/j.quascirev.2014.03.018, 2014.

Heyman, J., Stroeven, A.P., Caffee, M.W., Hättestrand, C., Harbor, J.M., Li, Y., Alexanderson, H., Zhou, L., Hubbard, A.: Palaeoglaciology of Bayan Har Shan, NE Tibetan Plateau: exposure ages reveal a missing LGM expansion, Quat. Sci. Rev., 30(15-16), 1988-2001, https://doi.org/10.1016/j.quascirev.2011.05.002, 2011a.

Heyman, J., Stroeven, A.P., Harbor, J.M., Caffee, M.W.: Too young or too old: evaluating cosmogenic exposure dating based on an analysis of compiled boulder exposure ages, Earth Planet. Sci. Lett., 302(1-2), 71-80, https://doi.org/10.1016/j.epsl.2010.11.040, 2011b.

Hock, R.: Modelling of glacier melt and discharge: ETH Zurich-, 1999, A distributed temperature-index ice-and snowmelt model including potential direct solar radiation, J. Glaciol., v. 45, no. 149, p. 101-111, https://doi.org/10.3189/S0022143000003087, 1998, Hock, R.: A distributed temperature-index ice-and snowmelt model including potential direct solar radiation, J. Glaciol., 45(149), 101-111, https://doi.org/10.3189/S0022143000003087, 1999.

Hughes, P.D., Gibbard, P.L., Ehlers, J.: Timing of glaciation during the last glacial cycle: evaluating the concept of a global 'Last Glacial Maximum'(LGM). Earth-Sci. Rev., 125, 171-198, https://doi.org/10.1016/j.earscirev.2013.07.003, 2013.

Iqbal, M.: An Introduction to Solar Radiation, New York, Academic Press, 1983

Jiménez-Sánchez, Montserrat, et al.: "A review of glacial geomorphology and chronology in northern Spain: timing and regional variability during the last glacial cycle.", Geomorphology, 196, 50-64, https://doi.org/10.1016/j.geomorph.2012.06.009, 2013.

Jolivet, M., Ritz, J.-F., Vassallo, R., Larroque, C., Braucher, R., Todbileg, M., Chauvet, A., Sue, C., Arnaud, N., De Vicente, R.: Mongolian summits: an uplifted, flat, old but still preserved erosion surface, Geology, 35(10), 871-874, https://doi.org/10.1130/G23758A.1, 2007.

Jones, R., Small, D., Cahill, N., Bentley, M., Whitehouse, P.: iceTEA: tools for plotting and analysing cosmogenic-nuclide surface-exposure data from former ice margins, Quat. Geochronol., 51, 72-86, https://doi.org/10.1016/j.quageo.2019.01.001, 2019.

Jouzel, J., Stievenard, M., Johnsen, S.J., Landais, A., Masson-Delmotte, V., Sveinbjornsdottir, A., Vimeux, F., Von Grafenstein, U., White, J.W.: The GRIP deuterium-excess record, Quat. Sci. Rev., 26(1-2), 1-17, https://doi.org/10.1016/j.quascirev.2006.07.015, 2007.

Karger, D.N., Conrad, O., Böhner, J., Kawohl, T., Kreft, H., Soria-Auza, R.W., Zimmermann, N.E., Linder, H.P., Kessler, M.: Climatologies at high resolution for the earth's land surface areas. Sci. Data., 4, 170122, https://doi.org/10.1038/sdata.2017.122, 2017.

Khandsuren, P., Seong, Y.B., Oh, J.S., Rhee, H.H., Sandag, K., Yu, B.Y.: Late Quaternary glacial history of Khentey Mountains, Central Mongolia, Boreas, 48(3), 779-799, doi.org/10.1111/bor.12386, 2019.

Kirkbride, M., Winkler, S.: Correlation of Late Quaternary moraines: impact of climate variability, glacier response, and chronological resolution, Quat. Sci. Rev., 46, 1-29, https://doi.org/10.1016/j.quascirev.2012.04.002, 2012.

Klinge, M., Böhner, J., Lehmkuhl, F.: Climate Pattern, Snow-and Timberlines in the Altai Mountains, Central Asia (Klimaverhältnisse, Schnee-und Waldgrenzen im Altai Gebirge, Zentralasien), Erdkunde, 296-308, 2003.

Kohl, C.P., Nishiizumi, K.: Chemical isolation of quartz for measurement of in situ -produced cosmogenic nuclides, Geochim. Cosmochim. Acta, 56(9), 3583-3587, https://doi.org/10.1016/0016-7037(92)90401-4, 1992.

Koppes, M., Gillespie, A.R., Burke, R.M., Thompson, S.C., Stone, J.: Late quaternary glaciation in the Kyrgyz Tien Shan. Quat. Sci. Rev., 27(7-8), 846-866, https://doi.org/10.1016/j.quascirev.2008.01.009, 2008.

Laabs, B. J., Licciardi, J. M., Leonard, E. M., Munroe, J. S., & Marchetti, D. W.: Updated cosmogenic chronologies of Pleistocene mountain glaciation in the western United States and associated paleoclimate inferences, Quat. Sci. Rev., 242, 106427, https://doi.org/10.1016/j.quascirev.2020.106427, 2020.

Laabs, B. J. C., & Munroe, J. S.: Late Pleistocene mountain glaciation in the Lake Bonneville basin, In Developments in Earth. Surf. Process., Vol. 20, pp. 462-503, https://doi.org/10.1016/B978-0-444-63590-7.00017-2, 2016

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

The Cryosphere Discussions
Open Access
EGU

Laabs, B. J., Refsnider, K. A., Munroe, J. S., Mickelson, D. M., Applegate, P. J., Singer, B. S., & Caffee, M. W.: Latest Pleistocene glacial chronology of the Uinta Mountains: support for moisture-driven asynchrony of the last deglaciation, Quat. Sci. Rev., 28(13-14), 1171-1187, https://doi:10.1016/j.quascirev.2008.12.012, 2009

Lal, D.: Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models, Earth Planet. Sci. Lett., 104(2), 424-439, https://doi.org/10.1016/0012-821X(91)90220-C, 1991.

Lee, M.K., Lee, Y.I., Lim, H.S., Lee, J.I., Yoon, H.I.: Late Pleistocene–Holocene records from Lake Ulaan, southern Mongolia: implications for east Asian palaeomonsoonal climate changes, J. Quat. Sci., 28(4), 370-378, https://doi.org/10.1002/jqs.2626, 2013.

Lehmkuhl, F., Grunert, J., Hülle, D., Batkhishig, O., Stauch, G.: Paleolakes in the Gobi region of southern Mongolia, Quat. Sci. Rev., 179, 1-23, https://doi.org/10.1016/j.quascirev.2017.10.035, 2018.

Li, Y., Liu, G., Chen, Y., Li, Y., Harbor, J., Stroeven, A.P., Caffee, M., Zhang, M., Li, C., Cui, Z.: Timing and extent of Quaternary glaciations in the Tianger Range, eastern Tian Shan, China, investigated using ^{10}Be surface exposure dating, Quat. Sci. Rev., 98, 7-23, https://doi.org/10.1016/j.quascirev.2014.05.009, 2014.

Licciardi, J. M., Clark, P. U., Brook, E. J., Elmore, D., & Sharma, P.: Variable responses of western US glaciers during the last deglaciation, Geology, 32(1), 81-84, https://doi.org/10.1130/G19868.1, 2004

Licciardi, J. M., Clark, P. U., Brook, E. J., Pierce, K. L., Kurz, M. D., Elmore, D., & Sharma, P.: Cosmogenic 3He and 10Be chronologies of the late Pinedale northern Yellowstone ice cap, Montana, USA, Geology, 29(12), 1095-1098, https://doi.org/10.1130/0091-7613(2001)029<1095:CHABCO>2.0.CO;2, 2001.

Licciardi, J. M., & Pierce, K. L.: History and dynamics of the Greater Yellowstone Glacial System during the last two glaciations, Quat. Sci. Rev., 200, 1-33, https://doi.org/10.1016/j.quascirev.2018.08.027, 2018

Lifton, N., Sato, T., Dunai, T.J.: Scaling in situ cosmogenic nuclide production rates using analytical approximations to atmospheric cosmic-ray fluxes, Earth Planet, Sci. Lett., 386, 149-160, https://doi.org/10.1016/j.epsl.2013.10.052, 2014.

Luckman, B. H.: The Geomorphic Activity of Snow Avalanches. Geografiska Annaler: Series A, Phys. Geogr., 59(1-2), 31-48, https://doi.org/10.1080/04353676.1977.11879945, 1977.

Mischke, S., Lee, M.K., Lee, Y.I.: Climate history of southern Mongolia since 17 ka: The ostracod, gastropod and charophyte record from Lake Ulaan, Front, Earth Sci., 8, 221, https://doi.org/10.3389/feart.2020.00221, 2020.

NAGC, N.A.f.G.a.C., 1969. Topographic map of Mongolia Administration of Land Affairs of Mongolia, Ulaanbaatar, Mongolia.

NAMEM, N.A.f.M.a.E.m., 2020. Climate data. Mongolian Statistical Information Service, Ulaanbaatar, Mongolia.

Nishiizumi, K., Imamura, M., Caffee, M., Southon, J., Finkel, R., McAninch, J.: Absolute calibration of ^{10}Be AMS Standards, Nucl. Instrum. Methods Phys. Res. B., 258(2), 403-413, https://doi.org/10.1016/j.nimb.2007.01.297, 2007.

National Oceanic and Atmospheric Administration.: US standard atmosphere (Vol. 76)., 1976

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

Oliva, M., Palacios, D., Fernández-Fernández, J. M., Rodríguez-Rodríguez, L., García-Ruiz, J. M., Andrés, N., ... & Hughes, P. D.: Late Quaternary glacial phases in the Iberian Peninsula, Earth-Sci, Rev., 192, 564-600, https://doi.org/10.1016/j.earscirev.2019.03.015, 2019.

Olson, M., & Rupper, S.: Impacts of topographic shading on direct solar radiation for valley glaciers in complex topography, The Cryosphere, 13(1), 29-40, 2019.

Palacios, D., Stokes, C. R., Phillips, F. M., Clague, J. J., Alcalá-Reygosa, J., Andrés, N., ... & Ward, D. J.: The deglaciation of the Americas during the Last Glacial Termination, Earth-Sci. Rev., 203, 103113, https://doi.org/10.1016/j.earscirev.2020.103113, 2020.

Pötsch, S.: Dynamics and paleo-climatic forcing of late Pleistocene glaciers in the Turgen and Khangai mountains (Mongolia) reconstructed from geomorphology, ^{10}Be surface exposure dating, and ice flow modelling. Ph.D. thesis, Greifswald, Finsterwalde, 2017.

Quirk, B. J., Moore, J. R., Laabs, B. J., Plummer, M. A., & Caffee, M. W.: Latest Pleistocene glacial and climate history of the Wasatch Range, Utah, Quat. Sci. Rev., 238, 106313, https://doi.org/10.1016/j.quascirev.2020.106313, 2020.

Ross, S.M.: Peirce's criterion for the elimination of suspect experimental data, J. Eng. Technol., 20(2), 38-41, 2003.

Rother, H., Lehmkuhl, F., Fink, D., Nottebaum, V.: Surface exposure dating reveals MIS-3 glacial maximum in the Khangai Mountains of Mongolia, Quat. Res., 82(2), 297-308, https://doi.org/10.1016/j.yqres.2014.04.006, 2014.

Roy, D.P., Wulder, M.A., Loveland, T.R., Woodcock, C., Allen, R.G., Anderson, M.C., Helder, D., Irons, J.R., Johnson, D.M., Kennedy, R.: Landsat-8: Science and product vision for terrestrial global change research,Remote. Sens. Environ., 145, 154-172, 2014.

Sahsamanoglou, H., Makrogiannis, T., Kallimopoulos, P.: Some aspects of the basic characteristics of the Siberian anticyclone, Int. J. Climatol., 11(8), 827-839, https://doi.org/10.1002/joc.3370110803, 1991.

Şengör, A., Natal'In, B., Burtman, V.: Evolution of the Altaid tectonic collage and Palaeozoic crustal growth in Eurasia, Nature, 364(6435), 299-307, https://doi.org/10.1038/364299a0, 1993.

Seong, Y.B., Dorn, R.I., Yu, B.Y.: Evaluating the life expectancy of a desert pavement, Earth-Sci.Rev., 162, 129-154, https://doi.org/10.1016/j.earscirev.2016.08.005, 2016.

Shackleton, N.: Oxygen isotope analyses and Pleistocene temperatures re-assessed, Nature, 215(5096), 15-17, https://doi.org/10.1038/215015a0, 1967.

Shackleton, N.J.: The 100,000-year ice-age cycle identified and found to lag temperature, carbon dioxide, and orbital eccentricity, Science, 289(5486), 1897-1902, https://doi.org/10.1126/science.289.5486.1897, 2000.

Skinner, L., Shackleton, N.: An Atlantic lead over Pacific deep-water change across Termination I: implications for the application of the marine isotope stage stratigraphy, Quat. Sci. Rev., 24(5-6), 571-580, https://doi.org/10.1016/j.quascirev.2004.11.008, 2005.

Smith, S.G., Wegmann, K.W., Ancuta, L.D., Gosse, J.C., Hopkins, C.E.: Paleotopography and erosion rates in the central Hangay Dome, Mongolia: Landscape evolution since the mid-Miocene, J. Asian. Earth. Sci., 125, 37-57 DOI: https://doi.org/10.1016/j.jseaes.2016.05.013, 2016.

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

The Cryosphere Discussions

Stone, J.O.: Air pressure and cosmogenic isotope production, J. Geophys. Res. Solit Earth., 105(B10), 23753-23759, https://doi.org/10.1029/2000JB900181, 2000.

Tang, Z., & Fang, J.: Temperature variation along the northern and southern slopes of Mt. Taibai, China, Agric. For. Meteorol., 139(3-4), 200-207, https://doi.org/10.1016/j.agrformet.2006.07.001, 2006.

Tarasov, P., Peyron, O., Guiot, J., Brewer, S., Volkova, V., Bezusko, L., Dorofeyuk, N., Kvavadze, E., Osipova, I., and Panova, N.: Last Glacial Maximum climate of the former Soviet Union and Mongolia reconstructed from pollen and plant macrofossil data, Clim. Dyn., v. 15, no. 3, p. 227-240, https://doi.org/10.1007/s003820050278, 1999,

Thackray, G. D.: Varied climatic and topographic influences on Late Pleistocene mountain glaciation in the western United States, J. Quat. Sci.,: Published for the Quaternary Research Association, 23(6-7), 671-681, https://doi.org/10.1002/jqs.1210, 2008.

Thompson, W.G., Spiegelman, M.W., Goldstein, S.L., Speed, R.C.: An open-system model for U-series age determinations of fossil corals, Earth Planet. Sci. Lett., 210(1-2), 365-381, https://doi.org/10.1016/S0012-821X(03)00121-3, 2003.

Tomurtogoo, O.: Geological map of Mongolia, 2014.

Traynor, J., Sladen, C.: Tectonic and stratigraphic evolution of the Mongolian People's Republic and its influence on hydrocarbon geology and potential, Mar. Pet. Geol., 12(1), 35-52, https://doi.org/10.1016/0264-8172(95)90386-X, 1995.

Vassallo, R., Jolivet, M., Ritz, J.-F., Braucher, R., Larroque, C., Sue, C., Todbileg, M., Javkhlanbold, D.: Uplift age and rates of the Gurvan Bogd system (Gobi-Altay) by apatite fission track analysis, Earth Planet. Sci. Lett., 259(3-4), 333-346, https://doi.org/10.1016/j.epsl.2007.04.047, 2007.

Vassallo, R., Ritz, J.-F., Carretier, S.: Control of geomorphic processes on ^{10}Be concentrations in individual clasts: Complexity of the exposure history in Gobi-Altay range (Mongolia), Geomorphology, 135(1-2), 35-47, https://doi.org/10.1016/j.geomorph.2011.07.023, 2011.

Wang, Y.-J., Cheng, H., Edwards, R.L., An, Z., Wu, J., Shen, C.-C., Dorale, J.A.: A high-resolution absolute-dated late Pleistocene monsoon record from Hulu Cave, China, Science, 294(5550), 2345-2348, https://doi.org/10.1126/science.1064618, 2001.

Young, N. E., Briner, J. P., Leonard, E. M., Licciardi, J. M., & Lee, K.: Assessing climatic and nonclimatic forcing of Pinedale glaciation and deglaciation in the western United States, Geology, 39(2), 171-174, https://doi.org/10.1130/G31527.1, 2011.

Yu, K., Lehmkuhl, F., Diekmann, B., Zeeden, C., Nottebaum, V., Stauch, G.: Geochemical imprints of coupled paleoenvironmental and provenance change in the lacustrine sequence of Orog Nuur, Gobi Desert of Mongolia, J. Paleolimnol., 58(4), 511-532, https://doi.org/10.1007/s10933-017-0007-7, 2017.

Yu, K., Lehmkuhl, F., Schlütz, F., Diekmann, B., Mischke, S., Grunert, J., Murad, W., Nottebaum, V., Stauch, G., Zeeden, C.: Late Quaternary environments in the Gobi Desert of Mongolia: Vegetation, hydrological, and palaeoclimate evolution, Palaeogeogr. Palaeoclimatol. Palaeoecol., 514, 77-91, https://doi.org956/10.1016/j.palaeo.2018.10.004, 2019.

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

The Cryosphere Discussions
Open Access
EGU

Zhang, S., Zhao, H., Sheng, Y., Chen, S., Li, G., & Chen, F.: Late Quaternary lake level record of Orog Nuur, southern Mongolia, revealed by optical dating of paleo-shorelines, Quat. Geochronol, 72, 101370, https://doi.org/10.1016/j.quageo.2022.101370, 2022.

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

LIST OF TABLES

LIST OF FIGURES

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

The Cryosphere
Discussions
Open Access
EGU

909 **Table 1.** LGM ELA reconstruction

Sites	Top of the rock cliff (m a.s.l)	Altitude of cirque floor (m a.s.l)	Headwall altitude [a] (m a.s.l)	Toe altitude, LGM [b] (m a.s.l)	THAR ELA [c] (m a.s.l)
Jargalant valley	3620	3360	3533	2997	3308
Ih Artsan valley	3560	3385	3508	3222	3388
Average					3348

910 [a] Headwall altitude for LGM glaciers was selected at one-third of the altitude difference between the top of the rock
911 cliff and the cirque floor (Goldthwait, 1970).

912 [b] Toe altitude was selected as the minimum altitude of the terminal moraine

913 [c] THAR of 0.58 was used for calculating LGM ELA (Batbaatar et al., 2018)

914

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

Table 2. Result of ^{10}Be exposure age dating

Moraine group	Name	Latitude (˚N, DD)	Longitude (˚E, DD)	Eleva-tion (m a.s.l)	Thick-ness [a] (cm)	Shiel-ding factor [b]	Quartz [c] (g)	Be carrier [d] (g)	^{10}Be/^{9}Be [e, f] (10^{-13})	^{10}Be conc.[d, f] (10^{5} atoms g^{-1})	Exposure age [f, g, h] (ka)	Exposure age [f, g, i] (ka)
											St	LSDn
M_{Ih1}	IAM001	44.95421	100.2602	3289	2	0.7746	20.3	0.3729	6.0 ± 0.2	7.7 ± 0.3	22.1 ± 1.9	19.9 ± 1.4
	IAM002	44.95429	100.26022	3290	2.5	0.7746	17.52	0.3796	5.3 ± 0.2	8.0 ± 0.3	23.1 ± 2.0	20.7 ± 1.4
	IAM003	44.95427	100.2603	3289	3.5	0.7746	20	0.3849	6.1 ± 0.2	8.1 ± 0.3	23.7 ± 2.1	21.2 ± 1.5
	IAM004	44.95438	100.26035	3289	3.5	0.7746	14.69	0.3958	4.1 ± 0.1	7.6 ± 0.3	22.1 ± 1.9	19.9 ± 1.4
	IAM005	44.95435	100.26015	3290	3	0.7746	19.75	0.3704	5.7 ± 0.2	7.4 ± 0.2	21.4 ± 1.8	19.3 ± 1.3
	IAM006	44.95437	100.26006	3288	3.5	0.7746	19.54	0.3812	5.7 ± 0.2	7.7 ± 0.2	22.6 ± 1.9	20.3 ± 1.4
	IAM007	44.95438	100.26004	3288	4	0.7746	18.96	0.3738	5.3 ± 0.2	7.2 ± 0.2	21.2 ± 1.8	19.1 ± 1.3
M_{J4}	JAM001	44.97614	100.29007	3412	3	0.8218	16.91	0.3842	78.6 ± 0.6	124.9 ± 1.6	344.6 ± 30.1	278.9 ± 18.1
	JAM002	44.97627	100.29012	3411	4	0.8218	20	0.3993	57.0 ± 0.6	79.7 ± 1.1	214.7 ± 18.2	177.3 ± 11.3
	JAM003	44.97651	100.29021	3411	2.5	0.8218	20.03	0.3871	194.3 ± 1.2	262.9 ± 3.1	806.4 ± 79.3	636.2 ± 45.1
	JAM004	44.97654	100.28988	3409	3	0.8218	20	0.382	70.9 ± 0.6	94.8 ± 1.3	256.3 ± 21.9	208.9 ± 13.3
	JAM005	44.97665	100.29008	3409	2.5	0.8218	20.03	0.375	64.8 ± 0.5	84.9 ± 1.1	227.0 ± 19.2	186.6 ± 11.8
M_{J3}	JAM006	44.97891	100.29092	3350	3	0.8363	20.02	0.3708	12.3 ± 2.6	15.9 ± 3.4	41.5 ± 9.5	35.9 ± 8.0
	JAM007	44.97886	100.29079	3351	3	0.8363	20.03	0.3707	25.3 ± 5.0	32.8 ± 6.5	86.3 ± 18.9	74.1 ± 15.7
	JAM008	44.97894	100.29084	3350	3	0.8363	20.42	0.3932	68.9 ± 7.0	92.9 ± 9.5	255.2 ± 35.3	209.0 ± 26.1
	JAM009	44.97891	100.29095	3348	3.5	0.8363	19.97	0.3832	15.3 ± 2.7	20.5 ± 3.7	53.8 ± 10.7	45.8 ± 8.7
	JAM010	44.97897	100.29089	3348	3.5	0.8363	19.97	0.3856	40.9 ± 5.7	55.2 ± 7.7	148.7 ± 24.8	123.8 ± 19.4
M_{J2}	JAM011	44.98058	100.29328	3293	2.5	0.8598	19.91	0.3903	52.3 ± 0.5	71.7 ± 1.0	194.5 ± 16.4	162.1 ± 10.2
	JAM012	44.98083	100.29321	3289	2	0.8598	19.97	0.3785	93.6 ± 0.6	124.2 ± 1.5	349.1 ± 30.5	284.9 ± 18.4
	JAM013	44.98095	100.29263	3289	4	0.8598	20.22	0.3794	81.0 ± 4.1	106.4 ± 5.5	300.5 ± 30.6	246.6 ± 20.6
	JAM014	44.98096	100.29259	3292	3	0.8598	20.38	0.3812	61.0 ± 6.4	79.9 ± 8.4	218.9 ± 30.5	181.9 ± 23.0
	JAM015	44.98096	100.2926	3292	3	0.8598	20.04	0.3894	59.4 ± 5.2	80.8 ± 7.1	221.7 ± 27.6	184.0 ± 20.3
M_{J1}	JAM016	44.98224	100.29684	3193	3.5	0.8852	19.91	0.3872	3.0 ± 0.1	4.0 ± 0.2	10.8 ± 1.0	10.6 ± 0.8
	JAM017	44.98232	100.29693	3191	3	0.8852	20.05	0.3935	4.8 ± 0.3	6.6 ± 0.4	17.7 ± 1.7	16.3 ± 1.4
	JAM018	44.98232	100.29693	3191	2.5	0.8852	20.06	0.3864	5.8 ± 0.4	7.8 ± 0.5	20.8 ± 2.1	18.9 ± 1.7
	JAM019	44.98326	100.29745	3170	3	0.8935	20.17	0.3962	4.4 ± 0.2	6.0 ± 0.3	16.2 ± 1.6	15.1 ± 1.3
	JAM020	44.98379	100.29716	3172	3.5	0.9311	20.14	0.3865	5.8 ± 0.2	7.7 ± 0.2	19.9 ± 1.7	18.2 ± 1.2
	JAM021	44.98385	100.29712	3171	3	0.9311	20.04	0.3879	5.4 ± 0.2	7.3 ± 0.2	18.9 ± 1.6	17.4 ± 1.2
Summit Plateau [j]	SP001	44.58333	100.1725	3625	2.5	1	20.03	0.3871	194.3 ± 1.2	262.9 ± 3.1	560.8 ± 51.7	442.3 ± 29.8
	SP002	44.58333	100.1725	3625	3	1	20.02	0.3708	12.3 ± 2.6	15.9 ± 3.4	27.1 ± 6.2	23.4 ± 5.2

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

The Cryosphere
Discussions
Open Access

[a] Sampling thickness of the boulders' outermost exposed surfaces.
[b] Topographic shielding factors for each sampling site were measured at intervals of 30°.
[c] Weight of the pure quartz. The density of granite (2.7 g cm^{-3}) was used to calculate exposure age.
[d] A mean value of process blank samples ($4.53 \times 10^{-15} \pm 1.62 \times 10^{-15}$) was used for correction.
[e] Ratios of $^{10}Be/^{9}Be$ were normalized with 07KNSTD reference sample 5-1 prepared by Nishiizumi et al. (2007) with a $^{10}Be/^{9}Be$ ratio of $2.71\times10^{-11} \pm 4.71\times10^{-13}$ (calibrated error) and using a ^{10}Be half-life of 1.36×10^{6} years (Chmeleff et al., 2010; Korschinek et al., 2010)
[f] Uncertainties were calculated at the 1σ confidence level.
[g] Exposure ages, assuming zero erosion were calculated using CRONUS-Earth online calculator version 3.0.2 (Balco et al., 2008).
[h] Constant production rate of the ^{10}Be model of Stone (2000) was used for calculating exposure age.
[i] Constant production rate of the ^{10}Be model of Lifton et al. (2014) was used.
[j] SP001 and SP002 (SP is abbreviation of summit plateau) are not real samples. Exposure ages for summit plateau were calculated using the highest and lowest ^{10}Be concentration of boulders from inner moraines from Jargalant and production rate of summit plateau (3625 m a.s.l)

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

The Cryosphere
Discussions
Open Access

Table 3. Run and site parameters for the 2D ice surface model

Variable	Value	Unit
Time interval	22-16	ka
Day type	1 (calendar day)	
Day interval	152-243 (summer)	
Average elevation of site	3265.3	m
Modern summer temperature of Ih Artsan	5.4	℃
Modern summer temperature of Jargalant	4.9	℃
LGM anomaly	-5.5	℃
Snow ratio when temperature is below 0℃	0.35	
Elevation of initial glacier's toe (Ih Artsan)	3385.1	m
Elevation of initial glacier's toe (Jargalant)	3360.9	m
Elevation of the distal moraine (Ih Artsan)	3222.2	m
Elevation of the distal moraine (Jargalant)	2997.2	m
Headwall altitude (Ih Artsan)	3508.3	m
Headwall altitude (Jargalant)	3533.3	m
Glacial bed shear stress (Ih Artsan)	100	kPa
Glacial bed shear stress (Jargalant)	200	kPa

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

The Cryosphere Discussions
Open Access
EGU

Table 4. Input parameters of glacial mass balance model

	Variable	Optimized values/Unit		Variable	Optimized values/Unit
Mass balance calculation (m, mm)			**Air pressure calculation (P_h, Pa)**		
c	Accumulation	mm	P_0	Pressure at reference point (sea level)	1013.25 Pa
a	Ablation/melt	mm	T_h	Air temperature at the height h	Pa
Melt calculation (a, mm)			T_0	Air temperature at the reference point	288.15 K
n	Number of time steps per day		M	Mass per air molecule	0.0290 kg mol^{-1}
MF	Melt factor	1.8 mm d^{-1} °C^{-1}	g	Acceleration due to gravity	9.8067 m s^{-2}
a_{ice}	Radiation coefficient for ice surfaces	0.0008	R	Universal gas constant	8.3143 mol K
I	Potential clear-sky direct solar radiation at the glacier	W m-^{2}	L	Atmospheric lapse rate	-0.008 K m-^{1}
T	Monthly air temperature	°C	**Zenith angle calculation (Z, °) and angle of incidence (θ, °)**		
Insolation calculation (I, w m^{-2})			δ	Solar declination angle	°/Radian
I_0	Solar constant	1367 W m^{-2}	φ	Latitude	°/Radian
R_m/R	Eccentricity correction factor of the earth's orbit		ω	Hour angle	°/Radian
Ψ_a	Atmospheric transmissivity	0.75	β	Slope inclination angle	°/Radian
P_h	Air pressure at the height	Pa	γ	Surface azimuth angle	°/Radian
P_0	Air pressure at reference point (sea level)	1013.25 Pa			
Z	Zenith angle	°			
θ	Angle of incidence	°			

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

The Cryosphere
Discussions
Open Access

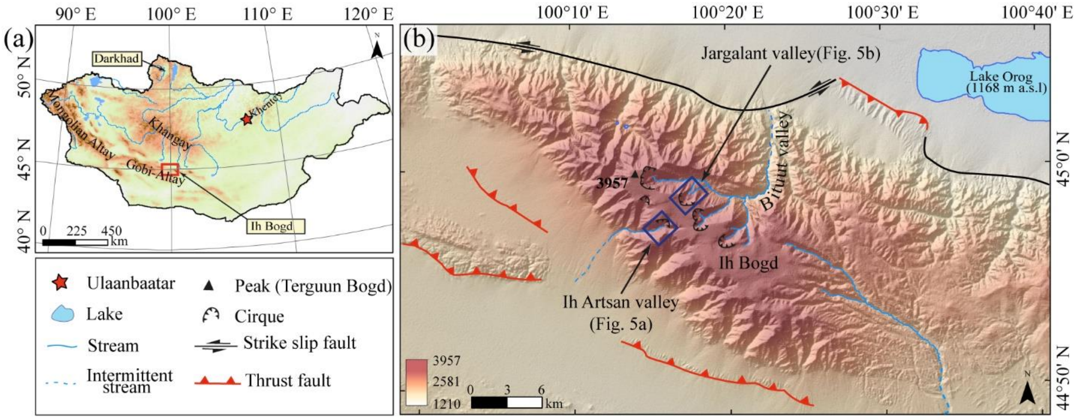


Fig. 1. Study area. (a) Location of the study area on the map of Mongolia. Ih Bogd massif is described as a red box. (b) Detailed map of the study area. Boxed areas show Ih Artsan and Jargalant valleys which were glaciated during late Quaternary. Detailed maps of both valleys were visualized in Fig. 3-5. The background image is shaded SRTM DEM with 30 m resolution.

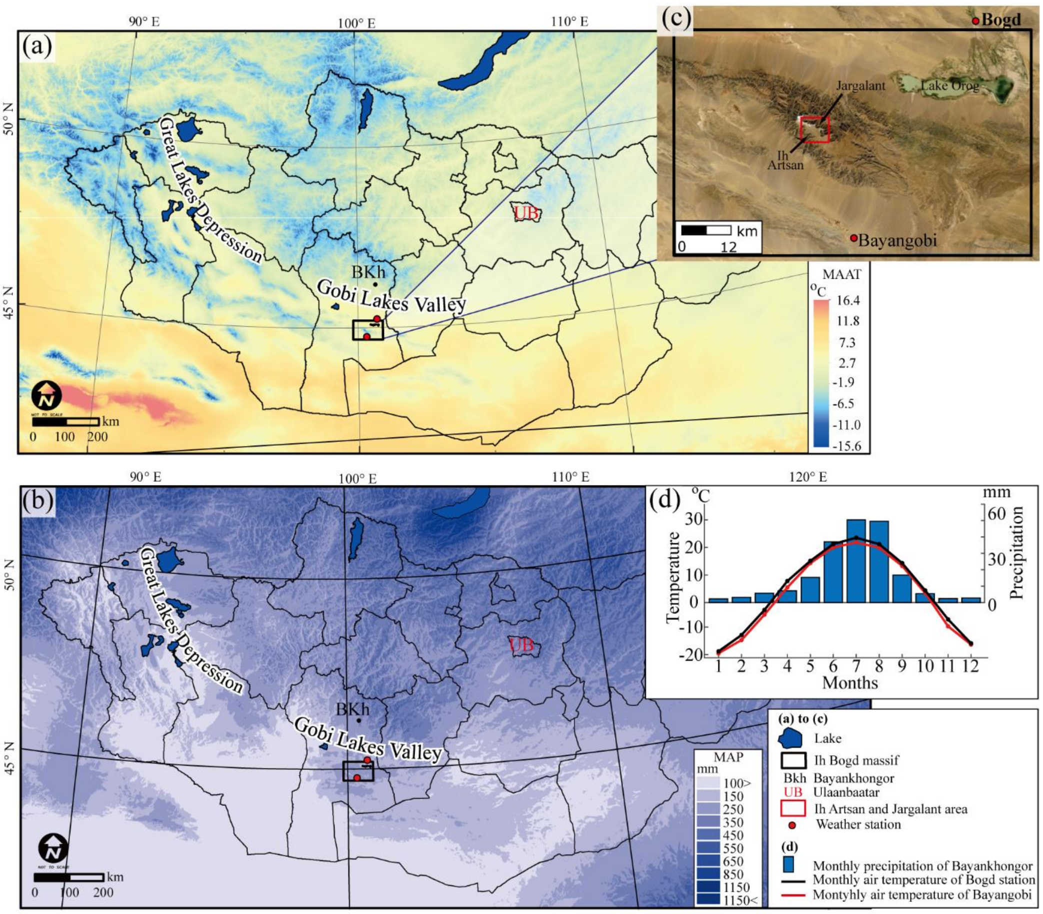


Fig. 2. The present-day climate of Mongolia. (a) Mean annual air temperature across Mongolia. (b) Mongolian mean annual precipitation. BKh (black dot) represents Bayankhongor aimag center (largest unit of the Mongolian province), and UB is Ulaanbaatar, the capital of Mongolia. Red dots mark the nearest weather stations to the study area. Temperature data (CHELSA_Bio10_01, at 30 arc-second) and precipitation data (CHELSA_Bio10_12, at 30 arc-second) are long-term (1973-2013) annual means. Source: Bioclim Bio1 data, CHELSA V 1.2 (Karger et al., 2017). (c) The exact locations of the nearest weather stations to the massif, Bayangobi (1540 m a.s.l) and Bogd (1240 m a.s.l). (d) Long-term (1989-2019) monthly mean temperature from Bogd station (black line) and Bayangobi station (red line). Monthly mean precipitation (2005-2019) of Bayankhongor is described as blue bar chart (NAMEM, 2020).

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

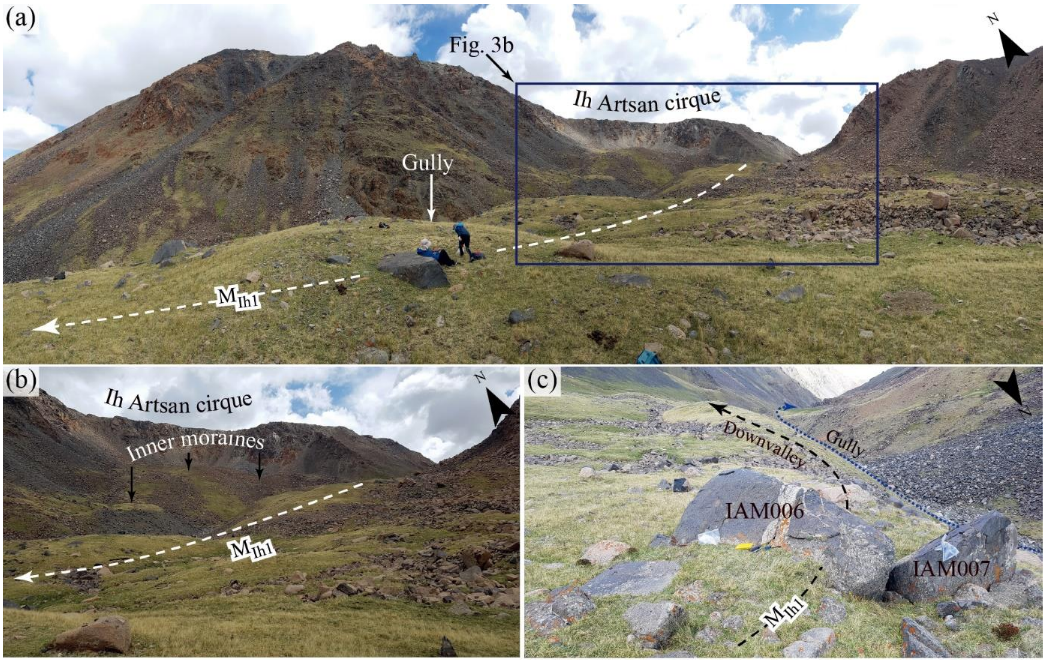


Fig. 3. Photo composites of the Ih Artsan valley and paleoglacial evidence. (a) Ih Artsan glacial cirque and distal moraine ridge. The white dashed arrow represents M_{Ih1} moraine ridge, which marks the farthest extent of late Quaternary glaciation. (b) Distal and inner moraine sequences (Batbaatar et al., 2018). (c) IAM006 and IAM007 sampling boulders are on the M_{Ih1} moraine ridge.

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

The Cryosphere
Discussions
Open Access

Fig. 4. Geomorphologic setting and moraine stratigraphy in Jargalant valley. (a) Jargalant valley and Bituut trunk valley that rises from the cirque near the highest peak (3957 m a.s.l). Jargalant valley is one of the larger tributary valleys of Bituut valley, while covered by a large amount of last Quaternary moraine complex. (b) The stratigraphic boundary between M_{J4} and M_{J3} moraines in the Jargalant cirque. Moraines are dissected by longitudinal gullies. (c) Pair of M_{J2} moraine and oldest M_{J1} moraine ridge. Horses (red circle) are for scale. (d) Boulder sizes on M_{J2} moraine range from sub-meter to several meters. (e) Downvalley view of the moraine sequences from the uppermost moraine sequence.

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

The Cryosphere
Discussions
Open Access
EGU

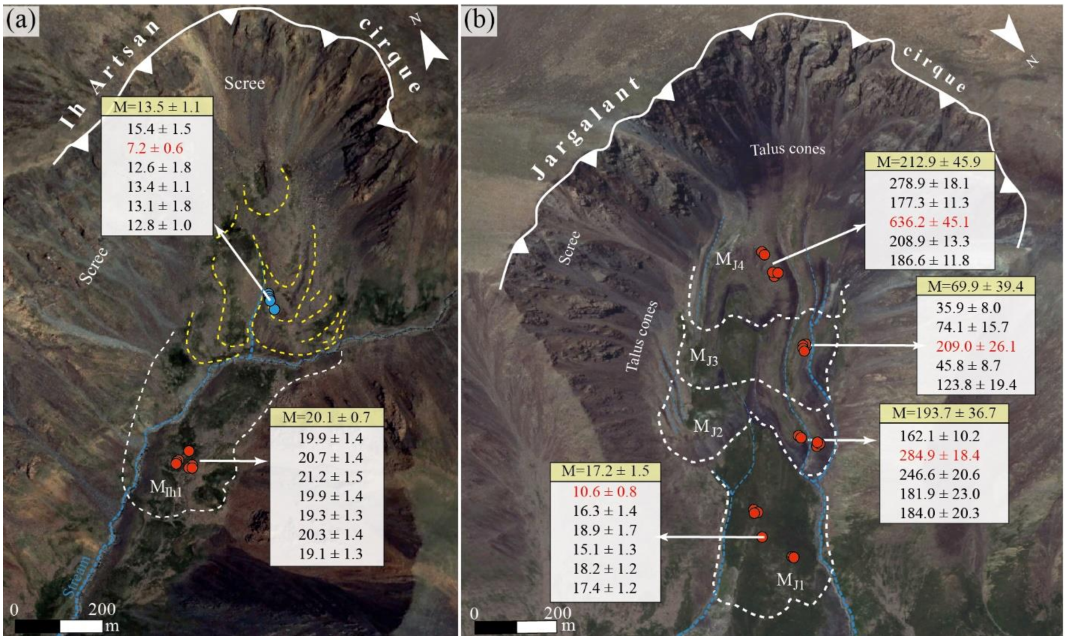


Fig. 5. ^{10}Be Exposure ages (ka) for moraine sequences. (a) Ih Artsan glacial cirque. Individual moraine sequences are marked by dashed white lines. Moraine ridges in yellow dashed lines indicate inner moraine sequences recognized in the previous study by Batbaatar et al. (2018). Blue dashed lines show intermittent stream channels. Red circles are the locations of boulder samples in this study, whereas blue circles indicate the sampling location from Batbaatar et al. (2018). (b) Jargalant cirque moraine complex, M_{J4} ~ M_{J1}. Exposure ages in red are outliers out of one sigma. Outlier excluded mean age (M) of each moraine sequence is written on the top (yellow background).

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

The Cryosphere Discussions
Open Access

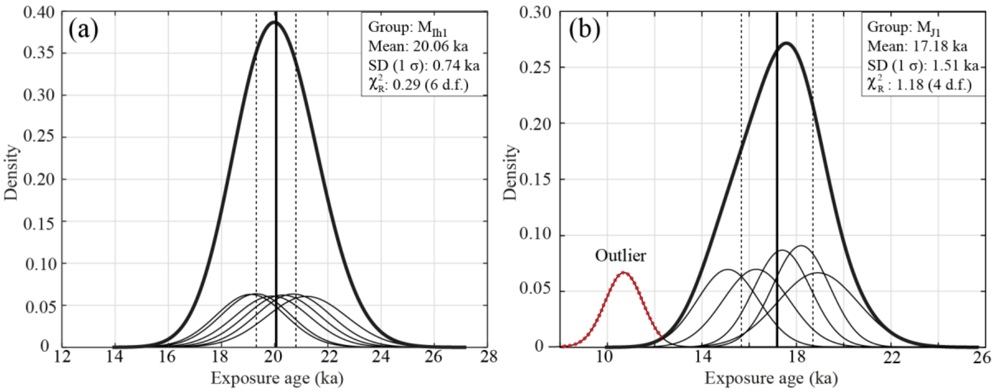


Fig. 6. Kernel density plot (KDP) of estimated ^{10}Be exposure ages from distal moraine crests in Jargalant and Ih Artsan valley. Plots were created using IceTEA Matlab code by Jones et al. (2019). (a) KDP of exposure ages of the most extensive moraine sequence (M_{Ih1}) in Ih Artsan valley. No outlier was detected. The arithmetic mean was calculated and marked as a bold solid vertical line. (b) KDP of exposure ages from the oldest (M_{J1}) moraine sequence in Jargalant valley. The outlier was excluded by Chauvenet, Pierce, and the standardized deviation method in the 1 sigma range. The thick solid lines represent the cumulative density curve, the dashed red line shows excluded outlier, and solid, narrow black lines show individual density curves for each sample. 1 sigma range of the group is marked as two vertical dashed lines. The sample statistics were calculated after rejecting outliers, while external errors were used to create KDP and calculate sample statistics.

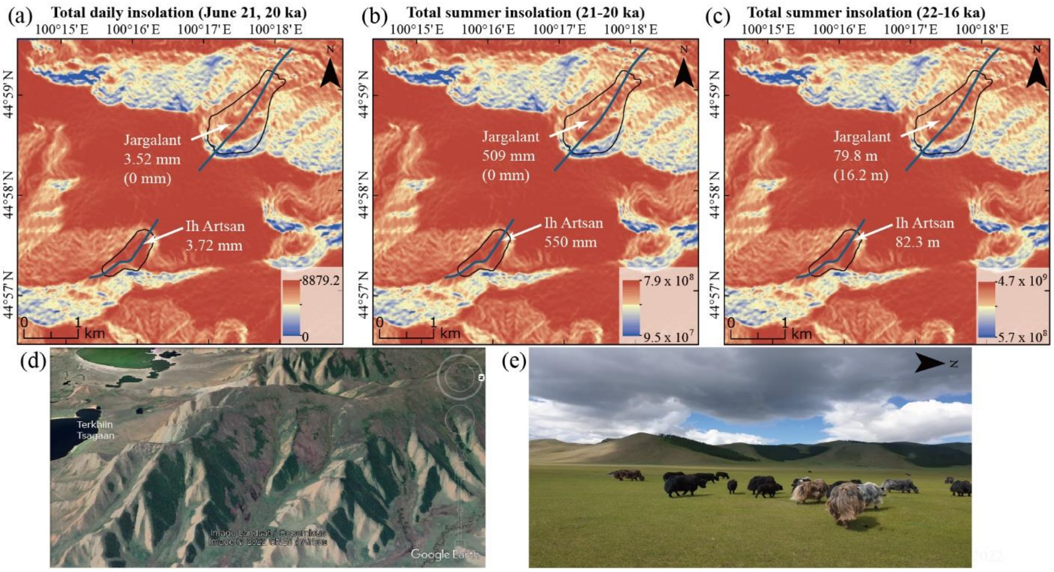
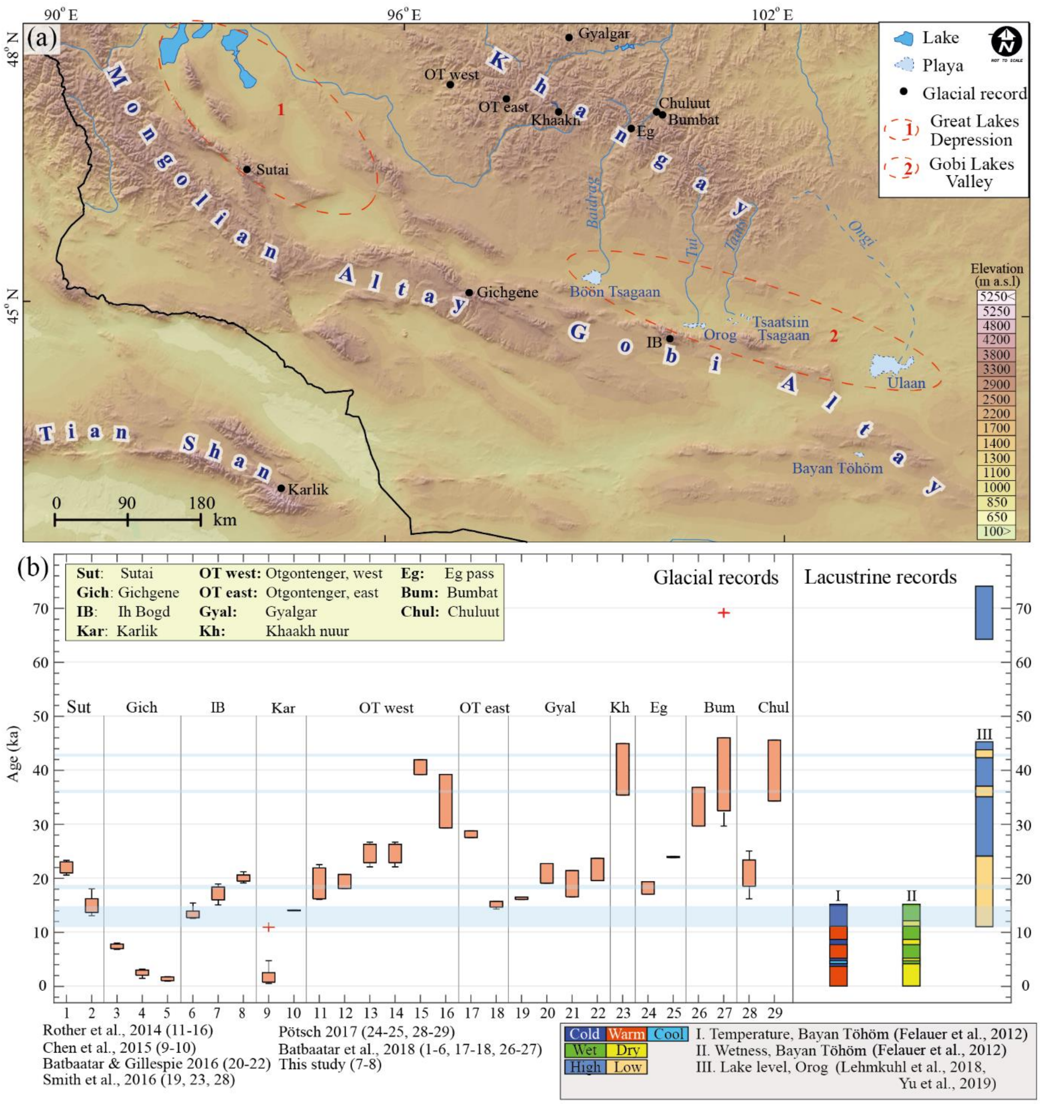


Fig. 7. Asynchronous distribution in potential clear-sky direct solar radiation (WH m^{-2}), glacial melt, and vegetation. (a) Daily insolation in the summer solstice, 20 ka. (b) Total clear-sky direct solar radiation during 21-20 ka. (c) Total summer insolation for 22-16 ka. Raster map shows integrated total daily insolation and summer insolation. The blue line represents profile along midline in Ih Artsan and Jargalant valley. Average melt along this profile is written in white text in mm and m (See supplementary file 2). Melt when the present-day temperature in Jargalant is considered 0.5 °C (LGM anomaly is the same, -5.5 °C) colder than Ih Artsan is written in parenthesis. (d, e) Tree distribution pattern in northern and southern slope. Both of © Google Earth (2022) imagery (d) and photo (e) present mountain to the north of lake Terkhiin Tsagaan, Khangay mountains.

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022



62

63 **Fig. 8.** Temporal and spatial distributions of glacial and paleo-lacustrine records in the neighboring regions of Ih Bogd massif. (a) Locations of the ^{10}Be age dating sites for paleo-glaciers and paleo lacustrine proxies. (b) Age dating results from glaciers and lacustrine proxies. Glacial records on the left are the ^{10}Be exposure age dating results representing 29 individual moraine groups. Exposure ages were recalculated with Cronus Earth V3, using the LSDn scaling factor (Lifton et al., 2014). Only effective ages were plotted after outlier rejection using the normalized deviation method (Batbaatar et al., 2018). The shaded light blue sections on the age interval present the major harsh periods (playa phase of Orog, Yu et al., 2019). Lacustrine records on the right present temperature (I) and wetness data (II) in lake Bayan Tohom and lake level record of lake Orog (III).

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

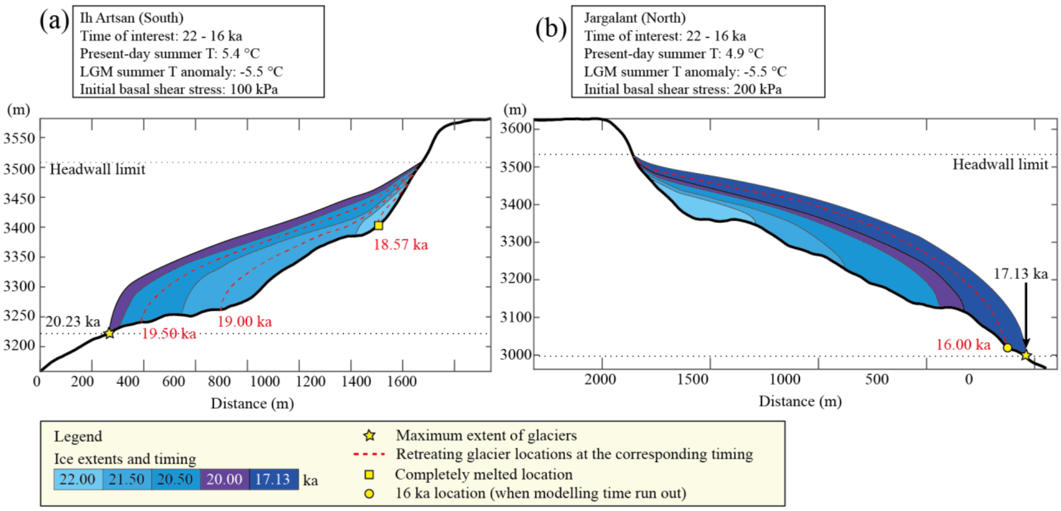


Fig. 9. Asynchronous advance and retreat pattern of Ih Bogd paleo glacier during 22-16 ka. (a) Paleo-glacier in Ih Artsan valley maximally advanced in 20.23 ka. (b) Paleo-glacier in Jargalant valley most expanded in 17.13 ka. The present-day summer paleotemperature in the north-facing valley was considered 0.5 °C lower than in the south-facing valley. The present-day temperature is calibrated to Greenland (NGRIP) paleotemperature data (Buizert et al., 2018) using an LGM summer temperature anomaly of -5.5 °C. Headwall altitudes of the LGM paleo glaciers were used to mark the maximum thickness of the glacier.

https://doi.org/10.5194/tc-2022-238
Preprint. Discussion started: 22 December 2022

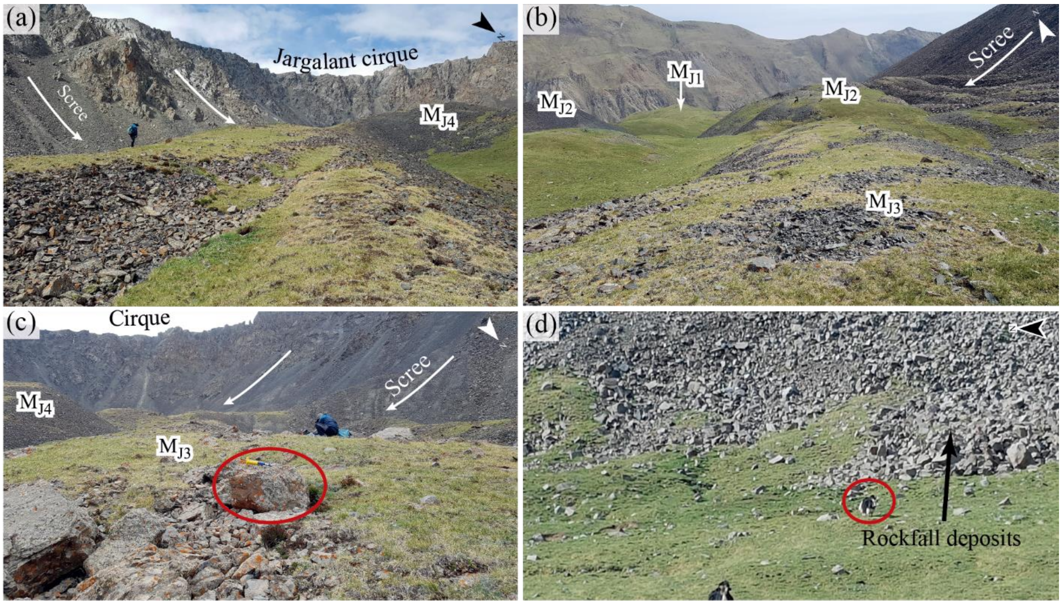


Fig. 10. Rockfall deposits in Jargalant valley. The scree or talus cone was on the cirque wall. M_{J4}, M_{J3}, and M_{J2} moraine formed within a Jargalant cirque, consequently outer edges of moraine ridges near the cirque wall were covered with talus deposit. (a) Rockfall deposit on the southeastern cirque wall, near M_{J4} moraine. (b) Scree covering on M_{J2} moraine that is dissected by an intermittent stream. (c) Sampling site of M_{J3} moraine and scree on the southern and southwestern wall of the cirque, near M_{J4}, M_{J3} moraine. JAM010 was taken from the circled boulder. Chisel, for scale, is on the boulder. (d) Rockfall deposit on the eastern slope of the cirque. Yak (circled) for scale.

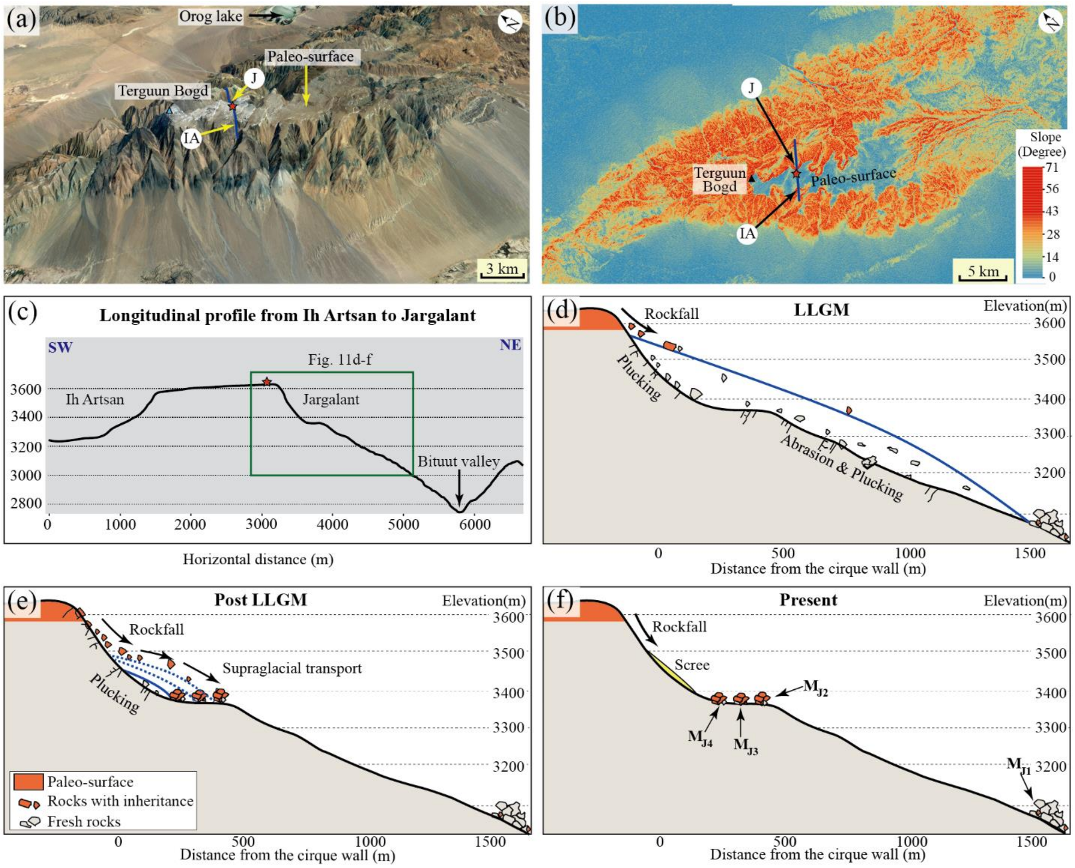


Fig. 11. Inheritance from the uplifted paleo-surface of Ih Bogd massif. (a) 3D view of the paleo-planation surface (© Google Earth, 2022). (b) Slope map of Ih Bogd, location of the Ih Artsan (IA) and Jargalant (J) valley. The green triangle represents the highest peak of the massif, Terguun Bogd. Exposure age and erosion rate (Table 2) were calculated using the highest concentration of the boulder from M_{J4}-M_{J2} (Fig. 11a) for the point location marked as red star (Fig. 11b; 3625 m). (c) Longitudinal profile along a dark blue line (See Fig. 11b) connecting Ih Artsan and Jargalant valley from SW to NE. (d) LGM glacial extent and intensive plucking of fresh rocks. (e) A series of M_{J4}, M_{J3}, and M_{J2} moraines formed by successive glacial advances. According to a shortage of glacier length and thinning of ice surface near cirque, less bed plucking, and more rockfall events from the paleo surface may have occurred. (f) Present-day rockfall deposit without supraglacial transport.