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GSA Supplemental Material

for

Glacier development in continental climate regions of central Asia

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Selection of the study sites and literature data

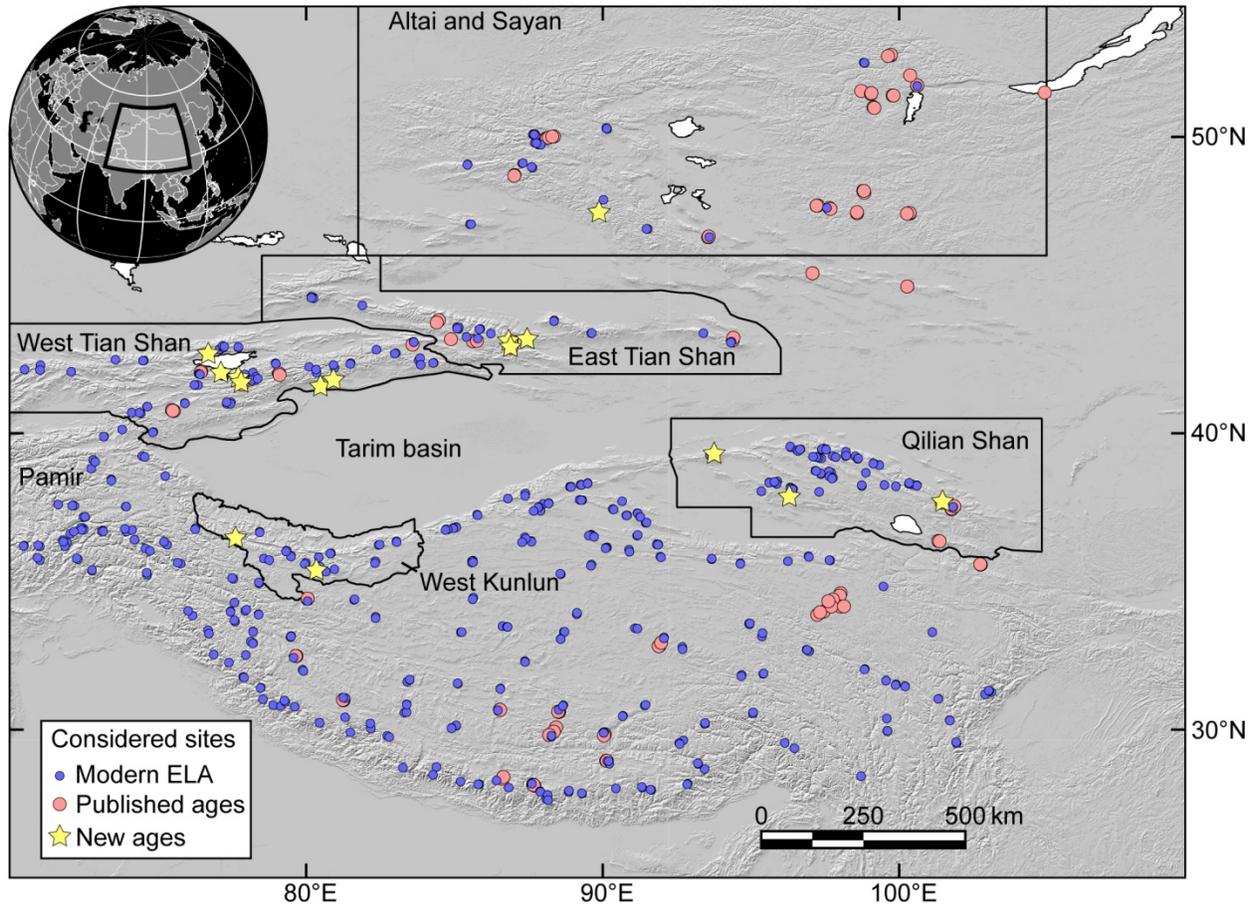


Figure S1. The sites considered in this study for modern and paleo ELAs. The locations of the modern glaciers are from Randolph Glacier Inventory 6.0 (RGI Consortium, 2017). The published ages are from the compilation by J. Heyman (<http://expage.github.io/data/expage/expage-201803.txt>, accessed 2018). The coordinates for all the sites and their respective references are provided in Supplementary Tables S4, S7, and S8.

Sensitivity of apparent exposure ages to boulder erosion

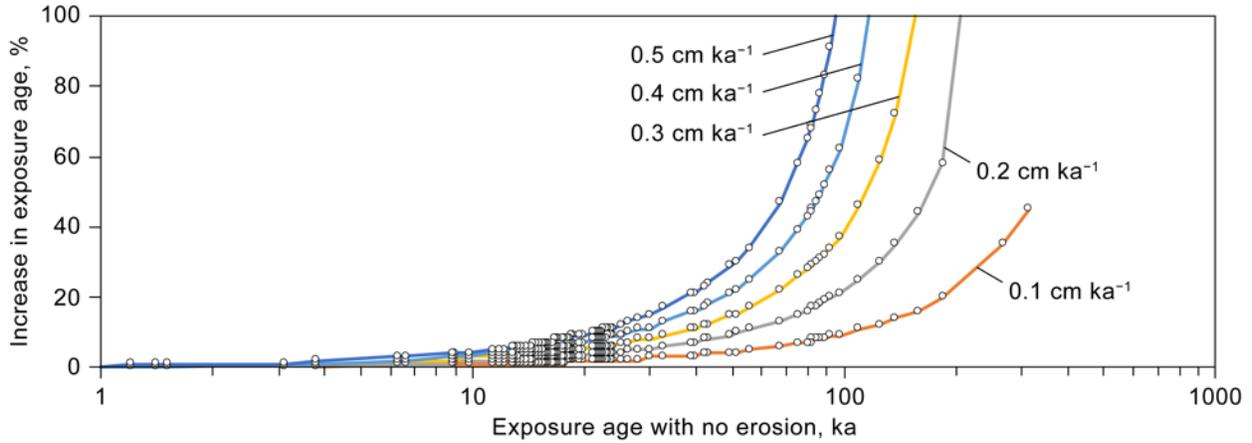


Figure S2. Increase in the apparent exposure ages if corrected for boulder erosion. All data points are for the new ages reported in this study. The increase in the exposure ages by more than 100% is excluded in the plot.

Quality assessment of the exposure ages

All researchers strive to acquire ages with high accuracy and high precision. Cosmic-ray exposure dating of moraines is not an exception, and many studies have developed a set of rules for this pursuit. Dortch et al. (2013) assumed that the ages from a moraine should be normally distributed and recommended accepting age groups with ≥ 3 ages and with the highest probability by visually evaluating the probability density function (PDF). In a similar approach, Owen and Dortch (2014) used Student's *t*-test to compare age groups for different sites. Another commonly used test to identify normally distributed ages is the reduced chi-squared statistic ($R\chi^2$; see Balco, 2011 and the references therein). For example, Heyman (2014), Hughes et al. (2016), and Small et al. (2017) required that a group should have ≥ 3 ages and exhibit a $R\chi^2$ value close to 1. After following the “robustness” classification system of Heyman (2014), Blomdin et al. (2016) and Gribenski et al. (2018) further required that the ratio of the mean age and 1σ total uncertainty (σ/μ) should be $\leq 15\%$.

Our approach in evaluating the ^{10}Be ages is similar to these statistical tests but differs in certain regards:

- 1) We used normalized deviation method of Batbaatar et al. (2018) to identify outliers in a group of ages. This method calculates a mean age excluding the tested age (excluded mean) and requires and identifies the tested age as outlier if the difference between the excluded mean and the tested ages was >2 than the compounded uncertainty of the excluded mean and the tested age.
- 2) We used Chauvenet's (1891) and Peirce's (Ross, 2003) criteria to check the outliers identified by normalized deviation method. In all instances, the normalized deviation method agreed with or identified more outliers than the other two criteria.
- 3) We accepted the age groups with two samples, including the groups that are left with two samples after rejecting the outlier(s).
- 4) We calculated $R\chi^2$ values for the age groups before and after rejecting the outliers with normalized deviation method. The $R\chi^2$ was not used as a criterion to reject outliers and was only provided for researchers to evaluate and render their own judgement.
- 5) We accepted the mean ages for groups with $\sigma/\mu < 50\%$. In doing so, we recognize that some ages with large uncertainty are accurate enough for the purpose of our broad comparison of glaciations between marine oxygen isotope stages at a scale of $>10^4$ yr, but not precise enough to make comparisons at $<10^4$ yr. For example, alpine glaciers respond to climate change in decades (Roe et al., 2017) and they can exhibit km-scale fluctuations around their end moraines in a steady climate without requiring a change in climate (Anderson et al., 2014). In other words, we recognize that some of the boulders on a moraine can be deposited at different times but within the limit of 2σ external uncertainty of ^{10}Be ages. Typical 1σ external uncertainty for ^{10}Be ages is $\sim 10\%$, and 2σ uncertainty would result in 4 ka uncertainty for a 20-ka sample).

Modern and MIS 2 ELA gradients along the latitude

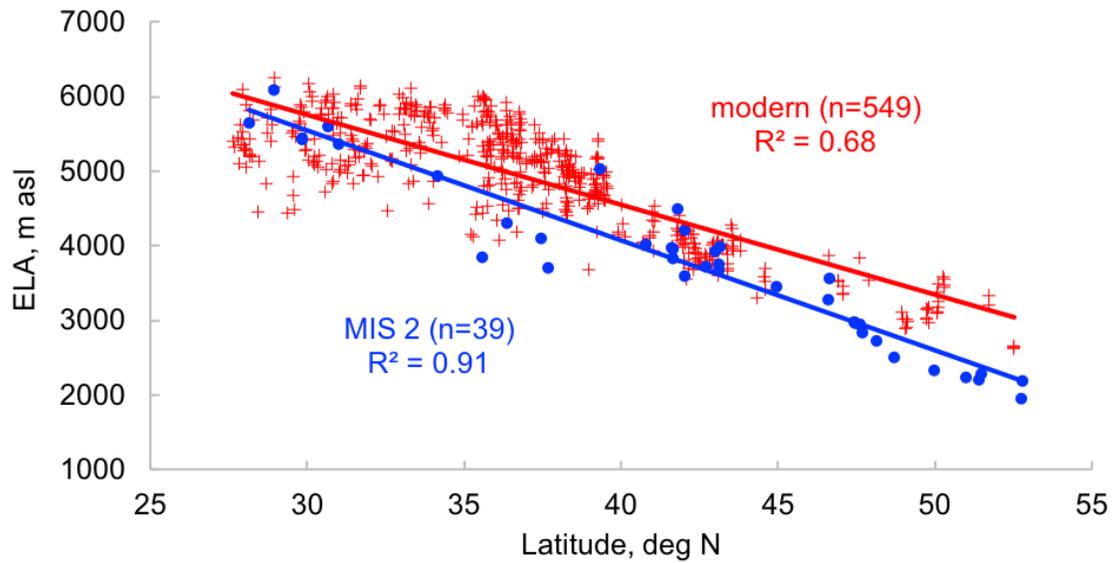


Figure S3. The modern ELAs (crosses) and the paleo-ELAs for the dated MIS 2 standstills (closed circles). This is the color version of Fig. 14A in the main text, in which the black and white data points are hard to distinguish. Modern and paleo-ELAs both show highly correlated latitudinal gradients, implying that the T_{air} and insolation are strong controls on glacier advances.

Photos of sampled boulders and surface features in the study sites



Figure S4. The sampled moraines near the Barskoon pass, Kyrgyzstan. The dashed lines indicate the moraine crests. Note the van in the foreground for scale. The photographer was facing southwest.



Figure S5. Boulder sample BS-001A (41.88323°N and 77.70568°E), on the crest of a moraine near Barskoon pass, Kyrgyzstan. The sledgehammer on the boulder is ~ 30 cm long.



Figure S6. Boulder sample BS-002 (41.88323 °N and 77.70568 °E), on a moraine near Barskoon pass, Kyrgyzstan. The sledgehammer on the boulder is ~30 cm long.



Figure S7. Boulder sample BS-004A (41.88288 °N and 77.7061 °E), on the crest of a moraine near Barskoon pass, Kyrgyzstan. Note the person walking on the crest of the sampled moraine. The photographer was facing south.



Figure S8. Boulder sample BS-007A (41.87017°N and 77.73407°E), on a moraine near Barskoon pass, Kyrgyzstan. Note the moraine crest that stretches from the boulder to the top of the photo. The glacier flowed from northwest to southeast (from top to bottom in the photo). The photographer was facing northwest.



Figure S9. View to the south from the location of boulder sample BS-007C (41.86975 °N and 77.73563 °E). The hummocky terrain, with telephone poles in the background, was the bed of a large glacier that flowed from west to east (from right to left in the photo). The photographer was facing southeast.



Figure S10. View to the south near the sampled moraine (42.01147 °N and 77.1996 °E), Gulbel pass, Kyrgyzstan. The people in the photo are walking on the slope of the right-lateral moraine of a paleoglacier that flowed southeast to northwest (from top left to bottom right in the photo). The photographer's approximate location was at 42.0219 °N and 77.1836 °E.



Figure S11. Panoramic view to the south from the location of the boulder sample GP-003A (42.038133 °N and 77.142083 °E), near Gulbel pass, Kyrgyzstan. Note the bouldery floor of the valley and the right-lateral moraines below the clouds (top left).



Figure S12. Panoramic view to the north of the hummocky valley floor, Choktal, Kyrgyzstan. The photo was taken at the location of boulder samples CR-001A–C (42.70139°N and 76.70089°E). Note the white shack in the middle for scale. The boulders on the crest of the left-lateral moraine (right) were sampled. A paleoglacier in this valley flowed from right to left.



Figure S13. Panoramic view to the northeast from the location of the boulder sample CR-003D (42.74707°N and 76.69433°E), Choktal, Kyrgyzstan. Due to optical distortion of the panoramic view the moraine crest in the foreground appears circular. The boulder samples CR-002A–E were taken from the moraine above the violet flower field in the middle of the photo.



Figure S14. Southward view of the Altyn Tagh range. The sampled moraine is from the glacier seen in the middle of the frame. The dust settling in the foreground emanates from the mining.



Figure S15. View to the southeast from the valley floor at Altyn Tagh. Note the people walking on the crest of a left-lateral moraine where boulder sample CAT-02C (39.3145 °N and 93.74186 °E) was taken. The dust from the mining down valley rose over the glacier by afternoon. Photo by Ari Matmon.



Figure S16. Boulder sample CAT-02C from Altyn Tagh. The cloth bag is ~30 cm wide.



Figure S17. The tongue of the glacier in the next valley (39.3213°N and 93.7230°E) to the west of the sampled moraine (Fig. S14). In this valley, an ice-cored moraine sits below the glacier and the hummocky surface in the foreground lies ~300 m from the glacier tongue. No other moraine was found in the valley.



Figure S18. Surface of the moraine sampled in Dumda valley, near Dunde ice cap (visible in the background). Note the low relief of the moraine surface and the rounded and embedded boulders. The photographer was facing northeast.



Figure S19. Boulder sample CH-DU-01 (37.85994°N and 96.28808°E), from Dumda valley, Dunde ice cap. Note the remnants of eroded boulders in the surrounding. The view of the photo is southward.



Figure S20. Boulder sample QS-GG-001 (37.69356 °N and 101.45208 °E) from Gangshiqia, Qilian Shan.



Figure S21. Boulder sample QS-GG-002 (37.69356 °N and 101.45208 °E) from Gangshiqia, Qilian Shan.



Figure S22. Boulder sample QS-GG-003 (37.69417 °N and 101.45319 °E) from Gangshiqia, Qilian Shan.



Figure S23. Boulder sample QS-GG-004 (37.69417 °N and 101.45319 °E) from Gangshiqia, Qilian Shan.



Figure S24. Boulder sample QS-GG-006 (37.69444°N and $101.45417^{\circ}\text{E}$) from Gangshiqia, Qilian Shan.



Figure S25. Boulder sample QS-GG-013 (37.65825°N and $101.43286^{\circ}\text{E}$) from Gangshiqia, Qilian Shan. The notebook on the boulder is ~ 20 cm long.



Figure S26. Terminus of the Quanshui glacier in 1995 (35.3996 °N and 80.3720 °E, 5460 m asl), Aksaiqin site, Kunlun. The proglacial lake is ~800 m across. The summer $T_{air} = -0.5 \pm 1.1$ °C; annual $ppt \sim 120$ mm. Photograph looking north, by Douglas H. Clark, 1995.



Figure S27. The view towards the terminus of the Quanshui glacier from the distal edge of the sampled end moraine (35.3982 °N and 80.3710 °E, 5460 m asl). The isolated proglacial lake in the left is about 200 m across. Photograph looking north, by Douglas H. Clark, 1995.



Figure S28. Heavily weathered granitic erratic on till plain ~300 m distal to the outer margin of the sampled moraine (36.4375 °N and 77.6556 °E, 5150 m asl), Karakax, Kunlun (Fig. 13B in main text). The sampled left lateral terminal moraine and the modern glacier are visible behind the erratic. The notepad in front of the erratic is ~30 cm long. White color on the ground around the boulders are surficial deposits of gypsum. The existence of gypsum and other soluble salt crystals and the lack of CaCO_3 in the soils provide evidence for hyperaridity in the region extending back for tens of thousands of years, suggesting that the glaciers there operated under low precipitation. Photograph looking north, by Douglas H. Clark, 1995.



Figure S29. Heavily weathered granitic erratic on till plain ~300 m distal to the outer margin of the sampled moraine (36.4375 °N and 77.6556 °E, 5150 m asl), Karakax, Kunlun (Fig. 13B in main text). The notepad in front of the erratic is ~30 cm long. White color on the ground around the boulders are surficial deposits of gypsum. The ELAs for the cirque glaciers visible in the background are ~5560 m asl. Photograph looking south, by Douglas H. Clark, 1995.



Figure S30. Left-lateral offset, ~3 m, of a modern channel along the active trace of the Altyn Tagh fault (36.4204 °N and 77.6571 °E, 4950 m asl), Karakax, Kunlun. Black backpack (~30 cm wide) just below the fault scarp (center) gives scale. Photograph looking north, by Douglas H. Clark, 1995.



Figure S31. Glaciated peaks and Glacier Station #2 viewed from the youngest moraine in Daxigou, Tian Shan. Photograph looking north, by Alan R. Gillespie, 1992.



Figure S32. Glaciated peaks viewed from the moraines sampled at Daxigou, Tian Shan.
Photograph looking east, by Alan R. Gillespie, 1992.



Figure S33. Modern glaciers in Daxigou, Tian Shan. The glacier on top is monitored from the Glacier Station #2. The two glaciers were in contact in 1992 and have retreated and separated since then. Photograph looking west, by Alan R. Gillespie, 1992.



Figure S34. The main trunk valley in Daxigou, Tian Shan. Glacier station #2 is visible in the foreground. Photograph looking east, by Alan R. Gillespie, 1992.



Figure S35. Overview of the two headwater glaciers in Daxigou, Tian Shan. Photograph looking west, by Alan R. Gillespie, 1992.



Figure S36. Surface features of the dated moraines in Tailan, Tian Shan. Photograph looking south towards the Taklamakan, by Alan R. Gillespie, 1992.

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