Supplement of Geochronology, 2, 411–423, 2020
https://doi.org/10.5194/gchron-2-411-2020-supplement

Supplement of

Calibrating a long-term meteoric ^{10}Be delivery rate into eroding western US glacial deposits by comparing meteoric and in situ produced ^{10}Be depth profiles

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Supplementary Material

Updated independent age constraints

Considering our recalculation of denudation rates using updated parameters (Table S1), it is also necessary to recalculate the surface exposure dates of boulders used to constrain the ages of these moraines, where feasible. For the Pinedale moraine, the best age estimate (21.7 ± 0.7 ky) is derived from the surface exposure ages of two boulders (WY-92-108 and WY-91-032) that mark the advancement of the Fremont Lake lobe to its last Pinedale Glacial Maximum position (Gosse et al., 1995). While this age is broadly corroborated by other Pinedale moraine ages (ranging between ~16 and ~23 ky) from elsewhere in the Wind River range and other western US localities (Phillips et al., 1997; Benson et al., 2004; 2005), a recalculation of the boulder exposure ages from this moraine results in a corrected exposure age of 25 ± 2 ky, still within the observed age range for Pinedale moraines (within error). We thus take this recalculated exposure age as the independent age constraint for the Pinedale moraine, as it is the best estimate for this particular landform.

This approach is not well suited for the Bull Lake moraine, which shows a considerably larger range in boulder exposure ages in the Fremont Lake area, from ~115 to ~160 ky (Phillips et al., 1997; Gosse and Phillips, 2001; Easterbrook et al., 2003). A mean Bull Lake age of 140 ky is reported in Easterbrook et al. (2003) and utilized in Schaller et al. (2009), however this age is derived from more boulders than those located on the Bull Lake moraine sampled and analyzed in this study, in contrast to the independent age constraint for the Pinedale moraine. In fact, the ^{36}Cl exposure ages derived strictly from boulders on this moraine have a mean age of 105 ± 14 ky, assuming no erosion (FL92-1 through FL92-7 of *Phillips et al, 1997*). A recalculation of those ages with modern parameters results in a mean age of 97 ± 13 ky, still considerably lower than the previous independent age constraint. Granted, this discrepancy is not particularly surprising as these ages are generally regarded as minimums due to denudation effects, snow shielding, and spallation from nearby fires (Benson et al., 2004). Due to these factors, which decrease the apparent cosmogenic nuclide-derived age, we chose to leave the independent age constraint for the Bull Lake moraine at its previous estimate of 140 ky.

Previous denudation constraints details

The reported rates of Schaller et al. (2009) utilize multiple approaches that combine measured $^{10}Be_{in\ situ}$ concentrations at depth with 1) a model based on the ratio of concentrations from a mixed surface layer (either the average or from the lowermost sample of mixed surface layer) and the undisturbed layer just below (following *Lal and Chen, 2005*) and 2) a numerical model of moraine erosion and nuclide production/decay that predicts concentrations at depth based on varying assumptions of age, denudation rate, mixing depth, and level of inheritance, within reasonable bounds, allowing for a comparison with the measured nuclide concentration. Schaller et al. (2009) then considers two scenarios, one of constant denudation over time since moraine deposition that utilizes the framework of Lal and Chen (2005), and the other of transient denudation rate that decreases over time; both scenarios rely on a Chi-square statistical analysis to determine best-fit solutions for the data.

Each approach requires an estimation of (or allowable range in) mixing depth, derived from the $^{10}Be_{in\ situ}$ depth profiles that show a relatively uniform nuclide concentration in the surface layer (see Table 1; Figs. 3, 4 of Schaller et al., 2009) as well as best fit solutions from their model. The estimated mixing depths for the Pinedale and Bull Lake depth profiles are ~40 and 50 cm, respectively. The first approach of Lal and Chen (2005) requires that the surface layer be completely mixed for an accurate age and denudation rate estimation, which appears to not be the case for the Bull Lake depth profile due to a slight decrease in ^{10}Be concentration with depth in surface layer (Table 1), potentially due to recent and/or depth-dependent mixing (Schaller et al., 2009). Reported denudation rates are thus based on independent age constraints along with the concentrations of samples below the mixed layer (i.e. results from Models 2, 4, 6, and 8 of *Schaller et al., 2009*); this approach results in more reliable and accurate rates than those based on all samples (Schaller et al., 2009a).

Paleomagnetic normalization workflow

As described in the Section 3.6 of the main text, we must normalize all meteoric flux estimates for geomagnetic intensity variations over the Holocene in order to properly compare them. Below (Fig. S1), we provide a helpful flow-chart of the normalization procedure we employ (Deng et al. 2020), using the flux estimate of Graly et al. (2011) as a worked example. All values necessary to carry out these normalizations are listed in Table 3 of the main text.

Supplementary Material References

Benson, L., Madole, R., Phillips, W., Landis, G., Thomas, T., and Kubik, P.: The probable importance of snow and sediment shielding on cosmogenic ages of north-central Colorado Pinedale and pre-Pinedale moraines, Quaternary Science Reviews, 23(1-2), 193-206, https://doi.org/10.1016/j.quascirev.2003.07.002, 2004.

Benson, L., Madole, R., Landis, G., and Gosse, J.: New data for late Pleistocene Pinedale alpine glaciation from southwestern Colorado, Quaternary Science Reviews, 24(1-2), 49-65, https://doi.org/10.1016/j.quascirev.2004.07.018, 2005.

Braucher, R, Merchel, S., Borgomano, J., and Bourlès, D. L., Production of cosmogenic radionuclides at great depth: a multi element approach, Earth and Planetary Science Letters, 309(1-2), 1-9, https://doi.org/10.1016/j.epsl.2011.06.036, 2011.

Borchers, B., Marrero, S., Balco, G., Caffee, M., Goehring, B., Lifton, N., ... and Stone, J.: Geological calibration of spallation production rates in the CRONUS-Earth project, Quaternary Geochronology, 31, 188-198, https://doi.org/10.1016/j.quageo.2015.01.009, 2016.

Chmeleff, J., von Blanckenburg, F., Kosser, K., and Jakob, D.: Determination of the 10Be half-life by multicollecter ICP-MS and liquid scintillation counting, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 268(2), 192–199, https://doi.org/10.1016/j.nimb.2009.09.012, 2010.

Deng, K., Wittmann, H., and von Blanckenburg, F.: The depositional flux of meteoric cosmogenic 10Be from modelling and observation, Earth and Planetary Science Letters, 550, 116530, https://doi.org/10.1016/j.epsl.2020.116530, 2020.

Easterbrook, D. J., Pierce, K., Gosse, J., Gillespie, A., Evenson, E., and Hamblin, K.: Quaternary geology of the western United States, in: Quaternary Geology of the United States, edited by: Easterbrook, D. J., Desert Res. Inst., Reno, Nev., 19-79, 2003.

Gosse, J. C., Klein, J., Lawn, B., Middleton, R., and Evenson, E. B.: Beryllium-10 dating of the duration and retreat of the last Pinedale glacial sequence, Science, 268(5215), 1329-1333, https://doi.org/10.1126/science.268.5215.1329, 1995.

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

Heikkilä, U. and Smith, A. M.: Influence of model resolution on the atmospheric transport of 10Be, Atmospheric Chemistry and Physics, 12(21), 10601-10612, https://doi.org/10.5194/acp-12-10601-2012, 2012.

Lal, D. and Chen, J.: Cosmic ray labeling of erosion surfaces II: Special cases of exposure histories of boulders, soils and beach terraces, Earth and Planetary Science Letters, 236(3-4), 797-813, https://doi.org/10.1016/j.epsl.2005.05.025, 2005.

Masarik, J., and Beer, J.: An updated simulation of particle fluxes and cosmogenic nuclide production in the Earth's atmosphere, Journal of Geophysical Research: Atmospheres, 114(D11), https://doi.org/10.1029/2008JD010557, 2009.

Phillips, F. M., Zreda, M. G., Gosse, J. C., Klein, J., Evenson, E. B., Hall, R. D., Chadwick, O.A., and Sharma, P.: Cosmogenic 36Cl and 10Be ages of Quaternary glacial and fluvial deposits of the Wind River Range, Wyoming, Geological Society of America Bulletin, 109(11), 1453-1463, https://doi.org/10.1130/0016-7606(1997)109<1453:CCABAO>2.3.CO;2, 1997.

Phillips, F. M., Argento, D. C., Balco, G., Caffee, M. W., Clem, J., Dunai, T. J., ... and Jull, A. T.: The CRONUS-Earth project: a synthesis, Quaternary Geochronology, 31, 119-154, https://doi.org/10.1016/j.quageo.2015.09.006, 2016.

Schaller, M., Ehlers, T. A., Blum, J. D., and Kyrllenberg, M. A.: Quantifying glacial moraine age, denudation, and soil mixing with cosmogenic nuclide depth profiles, Journal of Geophysical Research: Earth Surface, 114(F1), https://doi.org/10.1029/2007JF000921, 2009.

Steinhilber, F., Abreu, J. A., Beer, J., and McCracken, K. G.: Interplanetary magnetic field during the past 9300 years inferred from cosmogenic radionuclides, Journal of Geophysical Research: Space Physics, 115(A1), https://doi.org/10.1029/2009JA014193, 2010.

Willenbring, J. K., and von Blanckenburg, F.: Meteoric cosmogenic Beryllium-10 adsorbed to river sediment and soil: Applications for Earth-surface dynamics. Earth-Science Reviews, 98(1-2), 105-122, https://doi.org/10.1016/j.earscirev.2009.10.008, 2010.

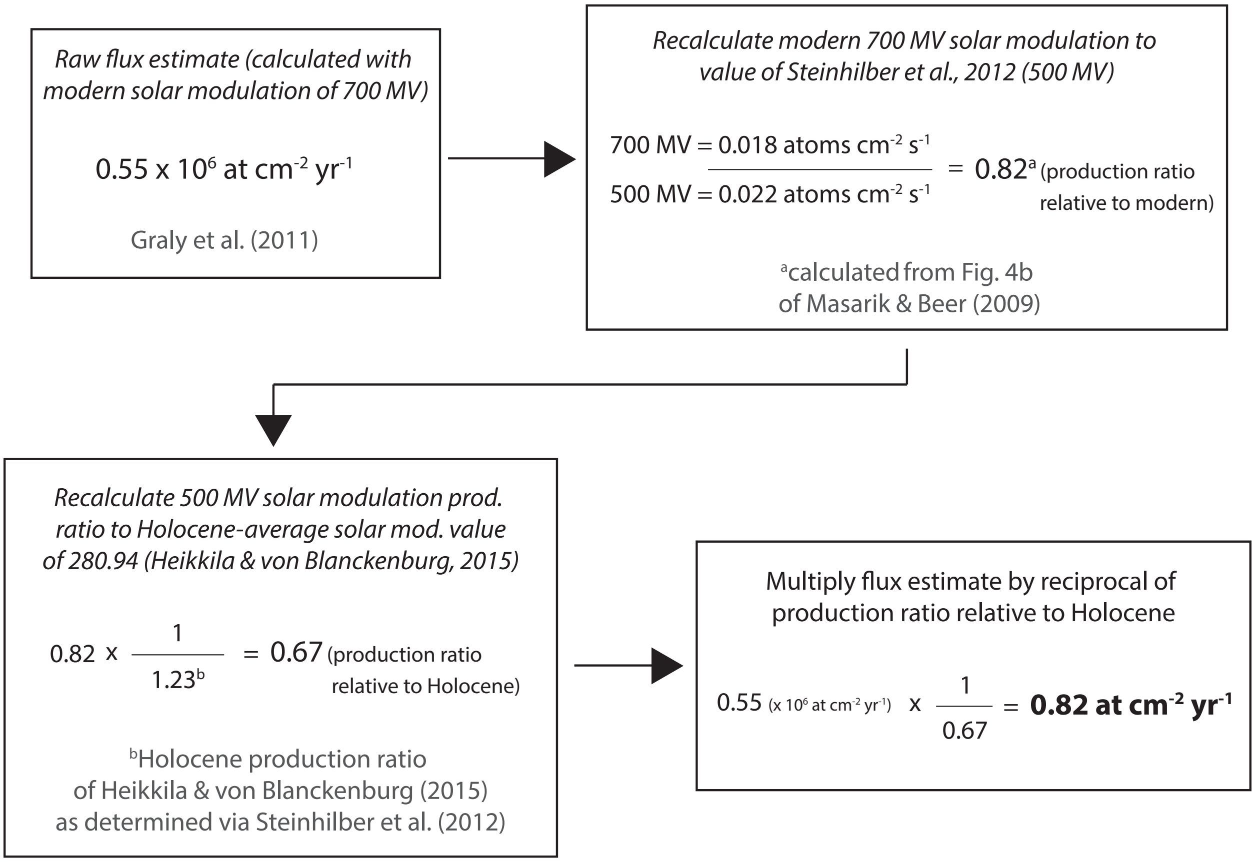

Fig. S1) Flow-chart of the paleomagnetic normalization procedure (Deng et al., 2020) used to normalize the meteoric flux estimate of Graly et al. (2011) at our study site such that all derived fluxes reflect average Holocene paleomagnetic and solar intensity variations. For longer integration periods like those relevant for the moraines studied here, this scheme can be adapted by using the Principle Component 1 of the ^{10}Be marine core record of Christl et al. (2010) instead of the Holocene record of Steinhilber et al. (2012) over the appropriate time scales. In our case, we use time scales of 6 ky and 24 ky for the Pinedale and Bull Lake moraines, respectively, (see Section 3.6 of the main text for an explanation of these time scales) to determine the production ratio relative to modern (i.e. the second step above).

Table S1. Parameters for Recalculated *in situ* ^{10}Be Exposure Ages and Denudation Rates

	General	Pinedale[1]	Bull Lake[1]
Half Life ($x\ 10^{6}$ y)[2]	1.39		
Decay Constant ($10^{-7}\ y^{-1}$)	4.998		
Nucleonic production rate (at g^{-1})[3]	3.92		
Stopped muonic production rate (at g^{-1})[3]	0.012		
Fast muonic production rate (at g^{-1})[3]	0.039		
Nucleonic scaling factor		6.631	6.7458
Stopped muonic scaling factor		2.8093	2.8432
Fast muonic scaling factor		2.8093	2.8432
Nucleonic adsorption length (g cm^{-2})[4]	157		
Stopped muonic adsorption length (g cm^{-2})[4]	1500		
Fast muonic adsorption length (g cm^{-2})[4]	4320		

[1]For denudation rate recalculations only; ^{10}Be exposure age recalculations are scaled by individual location via CRONUS-Earth web based calculator (Phillips et al., 2016)

[2]from *Chmeleff et al., 2010*

[3]from *Borchers et al. (2016)* at sea level-high latitude

[4]from *Braucher et al. (2011)*