Updated Independent Age Constraints

Considering our recalculation of denudation rates using updated parameters (Table 2), 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 kyr) is derived from the surface exposure ages of two boulders (WY-92-108 and WY-91-032; Fig. 1) 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 kyr) 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 kyr, 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 kyr (Phillips et al., 1997; Gosse and Phillips, 2001; Easterbrook et al., 2003). A mean Bull Lake age of 140 kyr 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 kyr, 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 kyr, still considerably lower than the previous independent age constraint. Granted, this discrepancy is not particularly surprising as these ages are generally taken as minimums due to denudation effects, snow shielding, and spallation from nearby fires (Benson et al., 2004). In lieu of knowledge of these factors that decrease the apparent cosmogenic nuclide-derived age, we choose to leave the independent age constraint for the Bull Lake moraine at its previous estimate of 140 kyr.

The reported rates of Schaller et al. (2009) utilize multiple approaches that combine measured $^{10}\mathrm{Be}_{\mathrm{in\ situ}}$ 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.

Paleo-precipitation Rates

Precipitation rates in the western US have varied considerably over the past 25 kyr and 140 kyr in response to glacial-interglacial climate fluctuations, with glacial times broadly representing periods of temperature decrease and concurrent precipitation increase (e.g. Hostetler and Benson, 1990; Allen and Anderson, 1993). There is currently a debate related to the effect of precipitation on $^{10}Be_{met}$ flux to a site (See Wilenbring and von Blanckenburg, 2010; Graly et al., 2011). A 100% additive precipitation-control on flux, if true, would lead to the potential for time-integrated precipitation rates to be higher than those historically recorded, thus leading to a higher predicted flux from the method in Graly et al. (2011) [Eq. 3]. A recent reconstruction of the ice cap that formerly spanned the Wind River Range via a glaciological model indicates that precipitation rates here must have increased during the Last Glacial Maximum (LGM) to accommodate a concomitant decrease in temperature (Birkel et al., 2012) and the locations of the end moraine positions. Their reconstruction allows for local rates of precipitation increase to be estimated during this time on the basis of modeled temperature anomalies, using a vertical lapse rate of -6 C°/km, and can be used to calculate a time-integrated precipitation rate from ~25 kyr to present, and also extrapolated to 140 kyr from present in a relatively conservative fashion. They present a range of possible temperature fluctuations that result in a stable ice cap over the Wind River range that also match the existing ^{10}Be moraine chronologies from the Fremont Lake and Bull Lake ice lobes, ranging from -5° to -10°C. This temperature reconstruction requires an increase respective precipitation values of 50 to 300% that of modern values to attain mass balance equilibrium within their model. While there are shortcomings with their model calibrations, the best-fit tuning for their model was obtained with a temperature decrease of 6.5° C, which corresponds with a precipitation increase of 200%. A 200% increase would result in a precipitation rate of 55.2 cm yr^{-1} for the study area and a calculated flux of 1.09 atoms cm^{-2} yr^{-1} using the method of Graly et al. (2011) during LGM conditions. If we conservatively use these conditions to represent a fifth of the history from present to 25 kyr and 140 kyr, the time-integrated calculated flux would be 0.66 atoms cm^{-2} yr^{-1}, an increase of 20%.

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