# Clow et al., 2020, GChron Submission Final Author Comments

Dear Dr. Tremblay,

Thank you for facilitating the initial round of reviews for our manuscript (gchron-2020-14) now entitled *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*. The three reviewers provided detailed, thorough reviews which have enhanced the readability and impact of this manuscript. We largely agree with the majority of the reviewer's comments and suggestions and summarize the final author 'major' comments for revisions as follows:

- The erosion rates used to calculate the meteoric $^{10}$Be fluxes are no longer the average between the constant and transient modeled denudation rates. Instead, we only use the average transient denudation rate (with uncertainties accounting for chemical weathering mass loss) for all calculations, as it is geologically incorrect to use the average rate between the constant and transient model runs -- only one can be correct. We have added text to explain and justify this treatment and have a note to the reviewers below that explains our rationale.
- Paleomagnetic intensity normalizations for the calculated fluxes for each moraine are now calculated for the residence time of the soil profile down to the e-folding adsorption depth of meteoric $^{10}$Be (20 and 30 cm, and thus 6 and 24 ky, for Pinedale and Bull Lake moraines, respectively) to properly weight and capture paleomagnetic variation effects on the production of meteoric $^{10}$Be over time (instead of over the entire ages of the moraines). The revised normalized meteoric fluxes now agree within uncertainty and are closer (and agree within uncertainty) to the atmospheric model flux estimate. The MATLAB code used for the Monte Carlo simulations has been added to the Supplementary Material, so that future readers can also carry out calculations themselves if desired.
- The Monte Carlo approach is now properly introduced and described before presenting results. Previously it was somewhat unclear what the purpose of this approach was (i.e. to determine uncertainties prior to paleomagnetic normalizations). Precipitation rate uncertainty has been removed (previously through an overly credulous paleo-precipitation rate estimation) in the simulation and associated text in the Supplementary Material.
- Fig. 3 has been moved to Supplementary Material and is presented alongside the MATLAB code. It no longer shows an appreciably skewed distribution with our updated treatment of erosion rates, and thus does not serve to improve the main text. Table 3 sufficiently and properly shows the results in a more meaningful and easier to comprehend manner.
- All typographical errors have been fixed and reported units corrected for the main equations used for this work. Equation 4, which previously had a typo by which an addition sign was instead a multiplication sign, has been fixed. Equation 4 now includes radioactive decay and meteoric inventory terms, and previous equation 3 has been removed. This did not result in any appreciable change to our calculation results (as previously described).
- Soil mixing discussion is now combined with the section on Cosmogenic Nuclide Profile discussion and slightly expanded upon.
- The Introduction, Methods, and Results sections have been considerably re-organized so that there is no ambiguity between sections.

- We choose to leave our treatment of inheritance corrections as is, but now explicitly define our treatment both qualitatively and analytically in the proper section.

See below for more detailed responses to each reviewers' specific comments by line number. Please let us know if there are any questions about our revisions. We look forward to your assessment of our revisions and the manuscript's suitability for publication in *Geochronology*.

Sincerely,

Travis Clow, Jane Willenbring, Mirjam Schaller, Joel Blum, Marcus Christl, Peter Kubik, and Friedhelm von Blanckenburg

### ***Important note to reviewers and editor:***

*We have chosen to alter our approach regarding the known erosion rate for these moraines. Previously, we chose the known erosion rate as the average between the recalculated transient and constant denudation rate models of Schaller et al. (2009a) after accounting for potential chemical weathering mass loss. We have realized since our first submission that this is geologically incorrect -- only one of the models can be valid -- thus using the average between the two is erroneous. Instead, we now use the recalculated average transient denudation rates for all calculations, as this model is much more likely to be correct. Our justification is as follows:*

*Moraines are deposited in a triangular shape at the terminus of a glacier. Today they have more of a concave down parabolic shape. These two geometries have very different slopes and curvatures to them, which means the erosion rates must change through time. If you apply a linear (or nonlinear) hillslope diffusion law to understand moraine erosion, then the erosion rate equals the hillslope diffusivity of the moraine multiplied by the second spatial derivative of the topography (i.e. the curvature of the topography, or dh/dt = k grad(h)). Thus, the erosion rate depends on the curvature of the moraine topography.*

*Going back to the initial triangular shape of a moraine, the apex of the triangle (and the bottom corner where it sits on the ground) have the highest curvature when initially deposited. This part of the moraine will erode quickly at the start. As the apex flattens out and the bottom corners fill in, the curvature decreases, so the erosion rates will decrease. Erosion rates continue to decrease with time as a moraine flattens. Because of this, the erosion rate of moraines must be transient, with highest rates initially after deposition. All diffusion problems (e.g. temperature, hillslopes) respond this way (fast response at first, then slower response later) when adjusting to a non-equilibrium initial condition.*

# Response to Reviewer 1

Line 25: Reword “Requires careful consideration” to something less vague.

*Removed ‘careful’*

Line 31: “Target atoms”?

*Revised to “target nuclei”*

Line 34: Also Al-OOH (e.g. Graly et al., 2010 )

*Revised to “Fe- and Al-oxyhydroxides”, citation added*

Line 43: I might avoid implying that most previous work is flawed here. These issues have been discussed and debated since the inception of the method with the work of Pavich and Monaghan.

*Revised to “not all of which was possible in many previous studies”*

Line 58 (and elsewhere): A priori knowledge refers to knowledge derived from first principles, etc. Data from another study is not a priori knowledge.

*Revised to “previous knowledge” here and elsewhere.*

Line 60 (and elsewhere): Why “back-calculated”, why not simply “calculated”?

*We initially chose to use the phrase ‘back-calculated’ as to be up-front that we are rearranging equations to solve for delivery rate (i.e. the calculated flux will always be a ‘perfect match’ for a known erosion rate), since all other meteoric studies to date utilize these equations to solve for erosion rate. However, this is a matter of taste, and can also be described as “calculated”. We have since revised this to “calculated” here and elsewhere.*

Line 140: When you say “homogenized”, do you mean that two aliquots from the sequential extraction were mixed together? I assume you must, since nowhere in the results do we see data from the separate sequences. This needs to be more clearly stated.

*Correct -- the text now reflects this to be more clear.*

Line 156 (and elsewhere): I think "e.g. Willenbring and von Blanckenburg, 2010" would suffice. They were hardly the first or the only authors employ this concept of steady state (or the other concepts they receive sole credit for throughout the manuscript).

*Revised accordingly throughout the manuscript; added Brown et al., 1988 in this instance.*

Line 173: You may ignore the decay effect, but must you?

*No. Per Reviewer 2's comment on this matter, we now remove Eq.3 and include decay and inventory in Eq. 4 for applicability to older settings.*

Equations 3 and 4: I believe it is standard to use the interpunct for multiplication and a full line for division. Equation 4 is wrong. The density term from Eq. 3 has disappeared, and the water flux term should be added not multiplied. I sincerely hope this is a typographical error, not an error that was implemented in the Monte Carlo model. But the authors should certainly double check this.

*The multiplication of the water flux term is a nasty typographical error. It has been fixed. Likewise, the density term should not be in Eq. 3. Density is factored into the erosion rate, which was not described with units* ($g/cm^2/y$) *on line 163 previously! This has been fixed as well.*

Line 192: The authors need to explain how they treated inheritance (i.e. with an equation). The inherited fraction is also eroded and leached to depth, so it is not clear which approach was taken. I think inheritance should be included in equations 1-4, rather than tacked on separately without an equation.

*Inheritance (lowest concentration measured) was subtracted from all concentrations measured. We have added text that defines this explicitly when defining* $[10Be]_{reac}$, *as well as for the measured inventory, in this section.*

Section 3.3: This section, as written, belongs in results not methods. In its place, a proper description of the Monte Carlo methods is needed. As it is, I don't see what the Monte Carlo accomplished that could not be done with error propagation.

*This section has been moved to results -- in its place is a proper description of the Monte Carlo simulation, which we use to determine uncertainties for our calculated fluxes. Traditional error propagation could also accomplish this goal. However, we do not have great constraints on Kd and evaluating the equation over the entire range of possible values in this manner provides a more realistic estimate on the uncertainties.*

Line 205: I am confused to as which equation (1,3, or 4) was actually used to generate the results presented. It sounds like all of them where, though the caption in figure 3 indicates eq. 4 was. The methods here need to be far more clearly presented.

*In the interest of applicability of this method to both older and younger settings, we have removed Eq. 3 entirely and included inventory and decay in Eq. 4. We now explicitly state that this equation is used to generate the results presented.*

Lines 210-220: This topic needs to properly treated in the introduction. The delve into the literature to characterize the "debate" and the various approaches is not appropriate to the methods section.

*Agreed, majority of this section has been moved to the Introduction*

Section 3.5: The authors seem to take it as granted that paleomagnetic intensity exerts linear and predictable control on paleo 10Be flux. From what I can tell, this is far from certain. Looking at global datasets such as Frank et al. 2008, the two correlate but with significant deviation and scatter, including time periods (such as OIS 5e) where the correlation seems to break down entirely. I can't help but notice that the depositional fluxes derived from the two moraines are far closer to each other in raw form (Figure 3) than after paleomagnetic correction. What the authors seem to have done (line 259) is to simply use the average paleomagnetic intensity over the moraine age. But because erosion and leaching effects are cumulative, this should actually be weighted towards the more recent flux. If they wish to keep it all, the authors need to propagate the paleomagnetic flux correction through their model. This section also seems to mix introductory background with methods and results.

*The production rates dependence on paleomagnetic intensity is certainly not linear -- even if calculated from paleomagnetic stacks using the "Elsässer formula". However we avoid doing this by instead reconstructing paleo-production from the measured* $^{10}$*Be stack (from marine cores) from Christl et. al (2010).*

*The comment that before correction, the depositional fluxes are quite close to one another, yet deviate more after the correction however made us revisit the estimated time scale over which we have done this correction. This point is a great one that we agree with -- that one should weigh these corrections towards the most recent flux. We now normalize over 6 ka and 24 ka for Pinedale and Bull Lake moraines, respectively, based on the residence time for the soil from the surface to the e-folding depth (~20 and ~30 cm, respectively). This is a more realistic correction. Now, the corrected depositional fluxes for each moraine stay relatively close to each other (which one would expect for moraines so close to one another) and overlap within uncertainty.*

*After considering all reviewer comments and internal discussions, we have also decided to use the average transient erosion rate, recalculated from Schaller et al. (2009a), for all calculations, as it is more geologically correct than using the average between the constant and transient denudation rate model runs. Please see our note to the reviewers above with a detailed justification.*

Lines 269 & 276 / Table 1: The inventories should be reported at an appropriate precision and include propagated error calculations.

*This has been fixed.*

Line 278: I don't think the lowest concentration is the inheritance. The inheritance is the average of all of the values measured below the 60 cm (in this case).

*We chose to keep the lowest concentration as the inheritance to avoid negative inheritance-corrected* $^{10}Be_{met}$ *measurements at depth.*

Line 287 (and elsewhere): I personally find the need to call out other sections in advance to be a symptom of poor organization. The paper should flow naturally without the need to do this.

*After re-organization of sections as advised by both reviewers, we have greatly reduced section callouts throughout the manuscript.*

Line 293: Graly et al. 2010 tested this claim and found that grain size effects could explain subsurface maxima in none of the 29 soil profiles analyzed. A far better explanation is that 10Be is incorporated into the lattices of newly forming clays and oxyhydroxides at depth (e.g. Barg et al., 1997). Though in this case, the increase is fairly trivial and the depth and clay content small.

*This information has been added to the text as follows:*

> *"This subsurface maximum could be the result of smaller grain sizes within this horizon, as these grains have a higher surface area per unit mass and can exchange ions more easily (Brown et al., 1992; Willenbring and von Blanckenburg, 2010). An alternative explanation invokes enhanced* $^{10}Be_{met}$ *incorporation into the lattices of newly formed clays and oxyhydroxides at depth (e.g. Barg et al., 1997), though the increased clay content at this depth is not appreciably large."*

Section 5.1.2: This section would greatly benefit from having the Monte Carlo approach properly explained in the methods. As it is, the Monte Carlo is something of black box that gives surprising results on its own accord.

*We now include a paragraph introducing and summarizing the Monte Carlo simulation in the Methods section. We are also now explicit that the Monte Carlo simulation is used to determine the uncertainties on our calculated fluxes.*

Line 319: Remove “At first inspection, it appears that”.

*Removed*

Line 320: Remove “In either case”.

*Removed*

Line 322: This is a surprising and novel observation that deserves further depth of treatment. Could you possibly mix coarse sand and fail to mix silt and clay? In some cases, patterned ground will mix pebble and cobble sized clasts at the hexagonal boundaries, excluding smaller grain sizes. Some delving into the cryoturbation literature seems warranted. Likewise, the second explanation needs further treatment. It is true that you only need to mix a declining profile for the in situ, whereas everything drops in at the top for the meteoric. But could you really homogenize one but not the other from these initial shape considerations alone? The reactive flow explanation proffered seems a bit wanting as well. How would reactive flow transport everything to the top of the otherwise mixing layer? This section would be much richer if a numerical model/calculation could be provided for any of these possibilities.

*It is curious that smaller grain sizes wouldn’t be mixed, but larger grains would -- as finer grains are thought to have higher mobility than coarse grains and a tendency to migrate upward in a soil profile (e.g. Gray et al., 2020). A cryoturbation-related explanation would likely only explain a lack of mixing in the uppermost soil, however based on the in situ-produced 10Be data, we should expect a mixing signal down to ~40 and ~50cm for these profiles.*

*Reactive flow wouldn’t transport everything to the top of the “in situ mixed layer”, rather we are referring to a continual input of* $^{10}Be_{met}$ *at the surface overwhelming any potential “meteoric mixed layer”. In this case, even if there is mixing of these smaller grains going on in a similar fashion as the larger size fractions analyzed for in situ produced 10Be, before this mixed concentration can be set in stone, it gets ‘reset’ by the addition of newly-delivered* $^{10}Be_{met}$*, starting with the uppermost soil interval and then propagating to depth via reactive flow or possibly through macropore permeability. This requires reactive flow timescales to be much shorter than mixing timescales, which is a reasonable assumption given that typical soil mixing rates are low (cm’s per century [Kaste et al., 2007]) versus the rapid adsorption of beryllium (~1 day [Boschi and Willenbring, 2016]) and fast permeability rates (as a rough proxy for reactive flow rates; ~5 x 10^-3 m/s) for soils with these grain size distributions. We have revised the text* *to be more explicit about this. We are not certain how to numerically model such a scenario beyond back of the envelope style calculations by arbitrarily assigning diffusion and reactive flow rates (as described above), neither of which are known for this site. Modeling using an existing framework like Be2D or LSD Mixing Model would be fantastic, but is not possible at present due to a higher degree of model sophistication needed, which is beyond the scope of this work.*

*Please note that we have now decided to merge the Soil Mixing and Cosmogenic Nuclide Profile discussion sections for consistency and readability.*

Line 348: An 100% additive precipitation control on flux is almost certainly not possible, as some dry deposition will occur, and complete scavenging and thereby dilution is likely in the largest storms. However, I think this is the wrong framework to consider. The paleo-precip factor is from a glaciological model and therefore quite uncertain. Nor is there any certainty in assuming that the "Graly Curve" for the Pleistocene was the same shape as that of the modern. Only after several more studies of this nature, will these sorts of things start to flesh out. I would recommend simply comparing to the modern and mentioning the paleo-precipation estimate in the discussion. But the second line on figure 3 and the "uncertainty" term on Table 4 seem to attribute too much to something we still know too little about.

*Agreed, we have removed paleo-precipitation as an 'upper bound' in our calculations and instead mention the potential for paleo-precipitation rate to be higher in the text.*

Discussion: The deposition of recycled 10Be on dust is neglected in the analysis. Are there any estimates of Pleistocene dust flux in this region? If not, the uncertainty introduced by this unconstrained parameter should be at least mentioned. The authors don't make any mention of the fact that their two moraines differ by a statistically significant margin. As I mention above, the difference is almost entirely due to the paleo-flux correction. So, if they keep the paleo-flux correction, they need to come up with something that varies in opposition to paleo flux to explain their results.

*We mention on line 88 that eolian flux is insignificant, as determined by Sr isotope measurements of the moraine soils and dust sources from previous workers. Please see above for our new paleomag intensity normalization treatment.*

Line 636: "0Be"

*Fixed*

Table 4: There is uncertainty inherent in the Graly curve apart from the + 20% attributed to paleo-precipitation. I believe this is true of the Heikkila GCM output as well. Per above, I think that simply treating the paleo-precipitation model as an upper bound is an overly credulous approach.

*We have removed paleo-precipitation as an upper bound in the text, the table, and the MC simulation.*

Supplement: I don't know why this information needs to be supplemental. The paper is not over long and I see no reason why this information cannot be integrated into the main text.

*We have removed the section on paleo-precipitation rate, but have chosen to leave the Updated Independent Age Constraints section in the supplement as it is (necessarily) too detailed for the main text.*

References Cited: Barg, E., D. Lal, M.J. Pavich, M.W. Caffee and J.R. Southon 1997. Beryllium geochemistry in soils; evaluation of 10Be/ 9Be ratios in authigenic minerals as a basis for age models. Chemical Geology, 140: 237-258.

Egli, M., D. Brandová, R. Böhlert, F. Favilli and P.W. Kubik 2010. 10Be inventories in Alpine soils and their potential for dating land surfaces. Geomorphology, 119: 62-73.

Frank, M., B. Schwarz, S. Baumann, P.W. Kubik, M. Suter and A. Mangini 1997. A 200 kyr record of cosmogenic radionuclide production rate and geomagnetic field intensity from 10Be in globally stacked deep-sea sediments. Earth and Planetary Science Letters, 149: 121-129.

Graly, J.A., P.R. Bierman, L.J. Reusser and M.J. Pavich 2010. Meteoric 10Be in soil profiles – a global meta-analysis. Geochimica et Cosmochimica Acta, 74: 6814-6829.

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# Response to Reviewer 2

General technical comment: There are numerous grammatical errors throughout the text. I recommend the authors read through the text carefully and fix places where there are missing words, or verbose text that could be made more concise.

*With the helpful suggestions and guidance from the reviewers, we believe all grammatical errors are now fixed in the revised manuscript.*

Title: change “through a comparison of complimentary” to “by comparing complementary”

*A welcome change! Revised.*

Line 23: How do these compare to the model fluxes of Heikkila and von Blanckenburg for the study area? Are they wildly different, or in close agreement? Would be good to mention this in the abstract for those readers who might use the modeled fluxes.

*The calculated fluxes are higher than that estimated by Graly et al. (2011) for the Pinedale and Bull Lake moraines, respectively, and agree within uncertainty with that predicted by Heikkila and von Blanckenburg (2015). We feel this is a bit too specific for the abstract. Rather, we have revised the abstract text to note that a considerable discrepancy exists for both methods at this site, neither of which match the calculated fluxes within uncertainties.*

Line 24: Can the authors add the ages of these moraines to remind the reader over what timescale they are averaging over for the fluxes?

*Added*

Line 30: add uncertainty of +/-0.01 to (readers unfamiliar with 10Be might want to know the certainty of this half-life

*Added*

Line 31: be more specific about which particles (i.e. 14N and 16O)

*Added*

Line 34: Add both Al- and Fe-oxyhydroxides (Graly 2010 show that Al has a stronger relationship to 10Be concentrations)

*Added, along with citation.*

Line 43: I would cite Graly et al 2010 who did an extensive analysis of the controls on 10Be concentrations in soil profiles from around the world.

*Citation added.*

Line 68: If it is windy, this implies either removal or deposition of fine particles over time, which could influence 10Bem concentrations. Can the authors say anything about dust delivery to this site?

*We note that dust delivery is insignificant to this site, based on Sr isotope measurements of these moraine soils and dust sources from previous workers, on line 88.*

Line 93 and 99: can the authors give uncertainty estimates, as this should factor into the uncertainty of their 10Bem delivery rates?

*The model of Schaller et al., 2009a does not permit for uncertainties in the independent age constraints when calculating denudation rates. These uncertainties only matter for the recalculated independent age constraints, and thus in situ produced 10Be effective erosion rates, which indirectly affect meteoric 10Be delivery rates.*

Line 108: change studies' to study's; and sites to site's

*Fixed.*

Lines 123-124: Why do the authors want to compare the Schaller denudations rates with 10Bem erosion rates? The 10Bem erosion rates (calculated using equations of von Blanckenburg et al., 2012) are not always comparable to denudation rates (they would need 9Be concentrations to calculate these rates). One could perhaps evaluate the chemical weathering component as the difference between the erosion and denudation rates.

*We do not aim to compare the Schaller in situ denudation rates with meteoric erosion rates -- we instead do as described -- using the potential chemical weathering mass loss calculated by Schaller et al, 2009b to account for this component of the denudation rate of Schaller et al., 2009a in order to more properly compare "in situ-produced 10Be erosion rates" vs. meteoric 10Be erosion rates. Now that we use transient erosion rates for all calculations (see above), accounting for this potential chemical weathering mass loss is done so via the uncertainty for these transient erosion rates.*

Lines 128-130: Are there no major element data or weathering indices calculated for different depths within these profiles? In the introduction, the authors stated that they had all the data they needed to evaluate loss due to leaching and weathering.

*Major element data is available from Schaller et al., 2009b, however we are unable to determine if this potential mass loss occurred above or below the cosmic ray attenuation pathway. The weathering rate is based on weathering loss in profile and material removed by denudation --*

*with the rate based on the average of the four samples in the surface layer for each moraine (Schaller et al., 2009b). Since we do not know at which depths the material removed by denudation came from, we instead take this chemical weathering mass loss to be the uncertainty in the in situ-produced 10Be transient erosion rates used in all calculations.*

Lines 138-139: Please mention that the amorphous and crystalline oxide fractions were re-combined before the next steps.

*Added.*

Line 141: ~200 ul of 9Be carrier doesn't really provide any information because we don't know the concentration of the carrier solution. It's better to report the total mass of 9Be added to each sample.

*We now report the 9Be mass added in Table 1.*

Lines 142-143: Rather than repeating the previous sentence, say "The samples were then dried down and dissolved in an additional 1 mL 50% HF solution, repeated once."

*Revised.*

Line 161: what unit do the authors use for erosion rate?

*g/cm^2/y. This information has been added to the text, good catch.*

Line 165: rho is not used in equation (1), so the authors should introduce it in the next sentence, before equation (2). They also give the value for rho twice, but it is only needed once.

*This has been fixed.*

Equation (2): the authors should add in the correction for inherited 10Be into the equation.

*We instead now explicitly describe the inheritance correction before presenting these equations.*

Lines 172-173: It is best to include the decay effect in the equation. It might be negligible in this case, but may not be in older settings where this method may be applied in the future.

*Agreed, we have now removed Eq. 3. Eq. 4 now has density and inventory terms accordingly.*

Line 181: use 'calculation' rather than 'back-calculation'

*We initially chose to use the phrase 'back-calculated' as to be up-front that we are rearranging equations to solve for delivery rate (i.e. the calculated flux will always be a 'perfect match' for a given erosion rate), since all other meteoric studies to date utilize these equations to solve for erosion rate. However, this is a matter of taste, and can also be described as "calculated". We have since revised this to "calculated" here and elsewhere.*

Equation (4): This equation is dimensionally incorrect as written. By rearranging Eq. 3 of von Blanckenburg et al. (2012), the erosion term should be added to the discharge term, not multiplied. It is also unclear what units the authors used for the variables because a water flux in m/yr does not cancel out with the partition coefficient, which is in L/g, unless a density term is inserted.

*The multiplication of the water flux term is a nasty typographical error. It has been fixed. Additionally, while we report discharge units as m/y, our calculations actually use L/m$^2$/y. Great catches -- we have fixed these typographical issues and report units properly so everything in this section is consistent.*

Line 186: The authors previously defined [10Be]reac, so they don't need to re-introduce it here. The authors also don't use the term 'Nsurf', which is from the Willenbring and von Blanckenburg (2010) equations.

*This has been fixed.*

Lines 160-194: The text would read more clearly if the authors first introduce the equations and variables, and then parameterize the equation in a paragraph following the theory. If the authors change the format to theory first, followed application, it will be easier for the reader to follow the theory and then understand why and how each equation is applied.

*We chose to leave the format of this section as is. Aside from density in Eq. 2, we only directly parameterize Eq. 4, which already follows the theory at that point.*

Line 195: The calculated atmospheric 10Be flux estimates should be reported in the results section. It seems that the authors mix methods and results throughout the manuscript. These pieces should be separated.

*We have substantially re-organized the manuscript according to reviewer suggestions. Methods and results are now clearly separated -- moving much of the background information (e.g. comment below) to the Introduction aided this process.*

Lines 210-233: This is all background information that should go in the introduction. The authors should place this information into context. What do we know about 10Bem atmospheric fluxes in the study area (e.g. from previous estimates, if existing, or from the GCM/GISS -based models)? The authors should identify the knowledge gaps highlighted by this background information, then pose their questions and hypotheses, and then go into the methods.

*The majority of this information has been moved to the Introduction and, in some instances, rephrased to reflect existing knowledge gaps (e.g. without a local calibration like we carry out in this paper, we do not have any way of knowing which production rate estimation method is more correct -- which is troubling for a site with such a discrepancy).*

Lines 245-252: Similarly, the information about the variability in the geomagnetic field and its effect on 10Be atmospheric fluxes should e presented in the introduction, not the methods section. The authors should provide more detail on how the geomagnetic field strength influences the 10Be fluxes. Why is the modern solar modulation factor is much higher than the Holocene average? The authors should compare their Holocene-average flux of 0.92x106 at/cm2 yr to the value modeled by Heikkila and von Blanckenburg. If they are different, why? Could the dust flux make up an appreciable component of the Holocene-averaged flux? The authors should consider addressing this possibility in their flux reconstruction.

*The average Holocene flux depends on variations in both solar modulation and magnetic field strength, which results in a flux that differs from modern.*

*Dust flux is insignificant at this site (as noted on line 88). We have moved the majority of this information to the Introduction, and instead present the estimated flux for this site in the Results section, and then speculate on differences between methods and the calculated flux in the Discussion.*

Line 249: The authors should mention which Heikkila and von Blanckenburg flux map (i.e. the pre-industrial map).

*We are using the pre-Industrial modeled flux, but we use the Industrial as an estimate of uncertainty. Text has been added to be more clear about this.*

Line 280: The authors should include the inheritance correction in equations 1-4. Somewhere in the introduction, they should add that there is a high likelihood for inheritance since the concentrations were measured in reworked glacial till that may have been exposed to cosmic rays prior to burial.

*We have added text that defines this explicitly when defining $[10Be]_{reac}$, as well as for the measured inventory. We have also added a sentence to the Introduction explaining the likelihood for inheritance in these deposits, as follows:*

> *"We utilize bulk samples sieved to <2 mm for our analysis, extracted from the lower mineral soil developed on each moraine, both mixtures of reworked glacial till (composed of Archean granite, granodiorite, and dioritic gneiss) that have a high likelihood for inheritance from cosmic ray exposure prior to burial"*

Line 287: change parenthetical to: (e.g. Willenbring and von Blanckenburg, 2010)

*Fixed.*

Line 291: I believe the authors mean illuviation, rather than eluviation.

*Correct, this has been fixed.*

Lines 317-326: This paragraph raises a lot of questions about soil mixing, but leaves them mostly unresolved. Can the authors explore these questions in more detail? Because there is a low pH at the profile surface, can you estimate how much might be lost/mobilized down profile (e.g. based on Maher and von Blanckenburg, 2016 equations)? It appears that the grain size data in Tables 1 are from the <2 mm fraction only. How does the >2 mm size distribution change down profile? Could the relative abundances of pebble-sized clasts explain the difference between the in situ 10Be profile and the 10Bemet profile? It's possible that the fine fraction is relatively uniform down profile, but the coarse size fraction varies.

*The equations of Maher and von Blanckenburg (2016) are for non-eroding settings. We can reasonably assume steady state for these profiles so using an upper and lower bound for Kd is sufficient and achieves the same goal.*

*We do not have specific data on the GSD of the >2mm size distribution aside from it being assumed to be unweathered and representing ~50% of the total material (Schaller et al., 2009b) -- however, this wouldn't affect the in situ-produced 10Be profile any differently as those concentration measurements all came from the <2mm size fractions.*

Lines 346-347: Can the authors provide some suggestions for resolving the influence of precipitation on F10Bemet? If this is identified as one of the key uncertainties influencing F10Bemet estimates, then they should provide a brief outlook for future research into this topic.

*A hearty discussion on how to resolve this influence is beyond the scope of this work. However, new work by Deng and von Blanckenburg on this topic has just been published in EPSL and we cite and summarize in a few sentences here.*

Line 354: The authors do not make it exactly clear what two methods are being used to calculate the fluxes. Somewhere at the end of the introduction, the authors should state something along the lines of: "Here we estimate the atmospheric delivery flux of 10Bemet to the Wind River region using two methods: 1) . . ., and 2) . . .. Then we compare the results of these methods to determine the best estimate for the local flux, and gain insight into the key processes regulating 10Be accumulation and retention in soil profiles so we can improve soil residence time studies."

*We have revised a couple of sentences to this effect at the end of the Introduction.*

Supplementary material: In the paleo-precipitation rates section, the reported 10Be flux values are missing the 'x106' term. Instead, they are reported as 1.09 and 0.66 atoms cm2 yr-1, respectively, which is impossibly low.

*Good catch! We have since removed this section, however.*

Figure 2: It would help to show corresponding plots of grain size data for these profiles (e.g., wt% silt+clay). There is a typo after the semi-colon in the second sentence.

*The inclusion of these plots tends to make this figure too busy. Instead, we report this data in Table 1, and if curious, the reader can compare to the GSD plots of Schaller et al. (2009a,b). Typo has been fixed.*

Table 2: If the methodology for the in situ exposure age and denudation rate calculations are in the supplement, then Table 2 should also go into the supplement.

*Table 2 has been moved to the Supplement.*

Table 4: There are 10Bemet-derived erosion rates reported in this table, but neither the method nor the results are reported in the main text. The authors should add a section on the erosion rates and compare them to the in situ 10Be-derived erosion/denudation rates. This could make for an interesting comparison and ensuing discussion. The authors should also use numbers or letters for the superscripts in this table. Some of the chosen symbols could be confused with actual text.

*We have decided to remove this section of Table 4, as we choose not to discuss them in the main text -- erosion rates calculated from our study are circular, since we use them to calculate the* *depositional flux. They will always agree with the in situ derived rates. Any discussion therein is not warranted.*

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## Response to Reviewer 3

Line 34: Al-oxyhydroxides, too? See both Jungers et al., 2009 and Graly et al., 2011 in your references.

*Correct, this has been fixed; citations added.*

Lines 48-51: Consider rewording the sentence starting with " 10 Be met shares a…" To me it is a little confusing and I think I only understand it because I'm already familiar with the differences between in situ and meteoric 10 Be.

*This sentence has been reworded as follows:*

> *$^{10}Be_{in\ situ}$ shares a cosmic ray origin with $^{10}Be_{met}$ but differs in production method; $^{10}Be_{in\ situ}$ is produced within crystal lattices in surface rocks and soil, rather than in the atmosphere, with a well constrained total production rate of 4.01 atoms $g^{-1}y^{-1}$ at sea level, high latitude (Borchers et al., 2016), and is characterized by full retentivity and known production pathways with depth.*

Line 68: I think you mean a posteriori here since the knowledge is based on empirical evidence. Could just simplify it to "...utilize previously determined effective…" Same spirit goes for other instances of a priori later in manuscript.

*Great catch -- we have decided to change this to "previous knowledge" in all instances.*

Line 68: "...50-year…" There are small grammatical and punctuation errors peppered throughout the manuscript. Nothing that derails the reading, but the authors should do a couple proofreads. I'll point out ones that jumped out. Not really being a grump here - just want to help.

*Thank you -- we have carefully re-examined and edited the text for these errors thanks to suggestions and catches like these from all reviewers. It is a bit embarrassing!*

Line 68: When talking about precipitation here, you are really reporting an annual depth rather than rate (as written).

*We have added explicit units of m a$^{-1}$ here.*

Line 69: To me, the use of “proximal” here is confusing since that word has facies implications in geology. Just saying “nearby” might be clearer.

*Good call, this has been changed to “nearby” in all instances*

Line 78: Just to be clear, it sounds like you did not measure pH of your samples? I think it’s reasonable to use the nearby measurements, although in situ pH measurements would be nice considering the potential impact on 10 Be met mobility.

*pH was unfortunately not measured in these samples :-(*

Line 83: The suggestion here that the deepest samples are unweathered seems somewhat counter to the later argument that inherited meteoric concentrations are due to reworked material. Is there another model for inheritance that could work?

*Not that we are aware of. That the deepest samples are unweathered is actually an assumption of Taylor and Blum, 1995 and is in reference to the >2mm size fraction, which is not what is analyze for either in situ-produced nor meteoric 10Be.*

Line 92: I find “proximal” confusing again here, too (cf., Line 69). Do you mean nearby terraces or terraces that are proximal to the rangefront. Perhaps it doesn’t matter, but I’d encourage precision with the language in both cases.

*We have replaced proximal with nearby, as suggested.*

Line 95: The section that starts with “We recalculated…” seems like it should be part of the Methods section. There are several instances of methodology being presented either too early (such as here) or too late (such as the treatment of inherited concentrations), and I think that restructuring where these bits are presented would improve the clarity of the manuscript.

*Agreed, we have since restructured and re-organized this manuscript considerably based on all reviewer suggestions. This entire section is now in the Methods section.*

Line 102: Consider removing “...are likely…” All the moraines have experienced erosion since Deposition.

*Removed.*

Line 103: Stray hyphen in “...for-contiguous…”?

*Removed.*

Lines 105-110: It seems like the averaging times of the methods may also play a role in the different results.

*Indeed. We have added text to this effect.*

Line 113: “...were recalculated…” again suggests a section that may better fit in Methods. Some or all of the approach outlined in the Supplementary Materials could be integrated into the main text to good effect.

*This information has been reduced and moved to Methods -- we chose to keep the Supplementary Material related to this there as it is (necessarily) overly detailed for the main text.*

Line 116: I appreciate the consideration of transient denudation that you discuss here (in terms of a sensitivity analysis of your results), but you don’t clearly justify why you set up the transient denudation the way you do. Why waning instead of cyclical, for example? Just justify your approach with a sentence and/or reference.

*These scenarios are not prescribed by us, but rather by the model of Lal and Chen (2005) that Schaller et al. (2009a) uses. Nonetheless, we have added some additional text here describing the rationale they used in considering each scenario. As described in our note above, we have now chosen to use the average transient denudation rates (accounting for potential chemical weathering mass loss) for all calculations, instead of the average between the constant and transient denudation rates, as it is a more geologically sound approach. We now describe our rationale in the text.*

Line 130: “...erosion rate decrease…” From the original pub? Or is this the sum decrease of both recalculating and accounting for mass loss due to chemical weathering. Not immediately clear to me.

*We have removed this sentence from the manuscript.*

Line 147: “...minor adaptations…” Like what? You are so detailed in the preceding sentences, why not report your specific adaptations? Inquiring minds want to know!

*We have added this information to the text as follows:*

> *The Be in the water leach solution was extracted and purified by a form of the ion exchange chromatography procedure from von Blanckenburg et al. (2004) that was adapted for meteoric 10Be purification by passing the leachate through anion (2 ml of BioRad 1x8 100-200 mesh resin) and cation (2x 1 ml BioRad AG50-X8 200-400 mesh) exchange resins, precipitated at pH ~9 using NH4OH:H2O (1:1), washed twice with 2 ml ultrapure water with centrifugation in between, mixed with AgCl, centrifuged and dried overnight, and finally oxidized over open flame (>1000 °C; modified from Kohl & Nishiizumi, 1992).*

Line 157: "...residence time...less than the depositional age…" I wonder if you can quantify this in some way to show that it holds for your site (seems like it certainly does). Can a residence time be inferred from the difference between your modeled flux rates and a "naive" flux rate determined by just dividing total inventory by moraine age. The discrepancy between those two numbers may be telling you something about how much 10 Be met is being "lost" since deposition. Perhaps this isn't important, but it could be interesting in comparison to some of the diffusion modeling and other prior work that tried to quantify degradation rates for the moraines.

*We now calculate the residence time of the soil from the surface to the e-folding depth as 6 ka and 24 ka for the Pinedale and Bull Lake moraines, respectively, and use these timescales for paleomag normalizations.*

Line 163: Units for E?

*Added in (g/cm2/y).*

Line 165: No ro term in Equation 1. I would recommend going through equations carefully to make sure they are correct. I imagine this is in the realm of typos rather than anything that made it into your modeling.

*It is factored into the erosion rate (which we neglected to define the units of) -- this has been fixed.*

Line 175: Check unit analysis of Equation 3.

*Fixed.*

Line 186: There is no N surf in Equations 1 & 3.

*A remnant of an earlier draft of this manuscript -- this has been fixed to* $^{10}Be_{[reac]}$.

Line 195: Section 3.3 reads more like Results rather than Methods.

*This section has been moved to Results. In its place is a proper explanation of the Monte Carlo simulation.*

Line 196: Nice agreement between flux rates! Remarkable stability over these timescales. Encouraging for future application of this isotopic system if one's local flux rate is known. Good stuff.

*It was quite a welcome surprise to us! Even after using the transient erosion rates instead of the average between the constant and transient erosion rates for our calculations, the raw flux rates still agree remarkably well.*

Line 204: I feel like I've lost track of what equations you are now reporting the results from. Perhaps a small table could clarify the differences between the outputs of Equations 1 vs. 2 vs. 4?

*We have removed Eq. 3, revised Eq. 4 to include decay and inventory, and are explicit that this equation is used for results.*

Line 216: "...type of estimate…" not "...type of estimates…"

*Corrected.*

Line 253: Should this bit about rescaling other approaches go into Methods?

*Indeed -- it has been moved to Methods.*

Line 269: I think you really need to bring the discussion of potential inheritance into how you build your equations in your Methods. Can you just treat inheritance explicitly there? Then, in Results, you can certainly report apparent inheritance and discuss how that may occur.

*Inheritance is now directly factored into the equations and reported accordingly in the Methods section.*

Line 270: I believe there is a typo in your units for 10 Be inventory in Table 1. Check and correct.

*Fixed.*

Line 291: Think you mean “illuviation” not “eluviation” here. You are referring to removal of clay from above (eluviation) and the concentrating of clay in this horizon (illuviation).

*Indeed, good catch!*

Line 304: “...reworked till…” Just another flag to consider whether this idea of reworked till jives with the composition and state of weathering in your deepest samples.

*See response to line 83 comment.*

Line 320: “...different diffusion coefficients…” Seems like this would manifest itself in some way beyond just the 10 Be met depth profile. You’d see a trend in grain size with depth from the surface within the mixing layer or something. I think the difference between mixing timescales and the rate at which 10 Be met is being translocated from the surface is more likely. For that matter, the formation of distinct clay horizons in at least the Pinedale suggests that soil horizonation happens faster than mixing (as inferred from the 10 Be is profile). These are cool results with neat geomorphic and pedogenic process implications. Jungers et al., 2009, see a similar thing in hillslope soils of the Great Smoky Mountains.

*Great inference -- we agree that this is indeed a likely possibility and have added a couple sentences to this effect in the text. Please note that we have also decided to combine the Soil Mixing and Cosmogenic Nuclide Profile discussion sections for consistency and readability.*

Line 338: Where does the value of 128 cm/yr come from (in terms of both geography and a citation)?

*Citation added*

Table 1: Check units for inventories in the final column.

*Fixed.*

Nice work - this is very cool stuff!

*Thank you!*

# 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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**Abstract.** Meteoric $^{10}$Be ($^{10}$Be$_{\text{met}}$) concentrations in soil profiles have great potential as a geochronometer and a tracer of Earth surface processes, particularly in fine-grained soils lacking quartz that would preclude the use of *in situ*-produced $^{10}$Be ($^{10}$Be$_{\text{in situ}}$). One prerequisite for using this technique for accurately calculating rates and dates is constraining the delivery, or flux, of $^{10}$Be$_{\text{met}}$ to a site. However, few studies to date have quantified long-term (i.e. millennial) delivery rates, and none have determined a delivery rate for an eroding soil. In this study, we compared existing concentrations of $^{10}$Be$_{\text{in situ}}$ with new measurements of $^{10}$Be$_{\text{met}}$ in eroding soils sampled from the same depth profiles to calibrate a long-term $^{10}$Be$_{\text{met}}$ delivery rate. We did so on the Pinedale (~21-25 ky) and Bull Lake (~140 ky) glacial moraines at Fremont Lake, Wyoming (USA) where age, grain sizes, weathering indices, and soil properties are known, as are erosion/denudation rates calculated from $^{10}$Be$_{\text{in situ}}$. After ensuring sufficient beryllium retention in each profile, solving for the delivery rate of $^{10}$Be$_{\text{met}}$, and normalizing to the Holocene-average paleomagnetic intensity, we calculate $^{10}$Be$_{\text{met}}$ fluxes of 1.52 (+0.11/-0.21) x 10$^{6}$ atoms cm$^{-2}$ y$^{-1}$ and 1.31 (+0.43/-0.50) x 10$^{6}$ atoms cm$^{-2}$ y$^{-1}$ to the Pinedale and Bull Lake moraines, respectively, and compare these values to two widely-used $^{10}$Be$_{\text{met}}$ delivery rate estimation methods that substantially differ for this site. Accurately estimating $^{10}$Be$_{\text{met}}$ flux using these methods requires consideration of spatial scale as well as temporally varying parameters (i.e. paleomagnetic field intensity, solar modulation) to ensure the most realistic estimates of $^{10}$Be$_{\text{met}}$-derived erosion rates in future studies.

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## 1 Introduction

$^{10}$Be is a cosmogenic isotope with a half-life of 1.39 +/- 0.01 My (Chmeleff et al., 2010) and its meteoric form ($^{10}$Be$_{met}$) is produced in the atmosphere through spallation reactions as high-energy cosmic rays collide with target nuclei (i.e. $^{14}$N and $^{16}$O) in the atmosphere (Lal and Peters, 1967). $^{10}$Be$_{met}$ is then delivered to Earth's surface via precipitation or as dry deposition at a flux of 0.1 – 2 x 10$^{6}$ atoms cm$^{-2}$ y$^{-1}$ followed by dissolved export in runoff, or depending on retentivity, adsorption onto fine-grained, reactive surfaces, typically clays and Fe- and Al-oxyhydroxides in soil horizons at the Earth's surface (Graly et al., 2010; Willenbring and von Blanckenburg, 2010). $^{10}$Be$_{met}$ has been used as a tracer of Earth surface processes, including estimating erosion rates at the soil-profile and river-catchment scales, soil residence times, ages of landforms over millennial to million-year timescales, and paleo-denudation rates from marine sedimentary records (Pavich et al., 1986; McKean et al., 1993; Jungers et al., 2009; Willenbring and von Blanckenburg, 2010; von Blanckenburg et al., 2012; von Blanckenburg and Bouchez, 2014; Wittman et al., 2015; von Blanckenburg et al., 2015; Portenga et al., 2019; Jelinski et al., 2019). Prerequisites for interpreting the concentrations and isotope ratios (i.e. $^{10}$Be$_{met}$/$^{9}$Be) as erosion or denudation (the sum of erosion and weathering) rates, respectively, include knowing the delivery rate of $^{10}$Be$_{met}$ (Pavich et al., 1986; Reusser et al., 2010; Graly et al, 2011; Heikkilä and von Blanckenburg, 2015; Dixon et al., 2018, Deng et al., 2020) and quantifying the mobility or retention of beryllium in soils (e.g. Bacon et al., 2012; Boschi and Willenbring, 2016a,b; Maher and von Blanckenburg, 2016; Dixon et al., 2018), not all of which was possible in many previous studies. The potential ability of using $^{10}$Be$_{met}$ depth profiles to obtain quantitative data on soil ages, residence times, production and denudation rates in a similar manner as *in situ*-produced $^{10}$Be ($^{10}$Be$_{in\ situ}$) depth profiles could prove to be highly advantageous, as it is easier to measure (due to much higher concentrations than $^{10}$Be$_{in\ situ}$) and can be employed in a much wider range of environments, as there is no dependence on the existence of coarse-grained quartz as is required for the analysis of $^{10}$Be$_{in\ situ}$. $^{10}$Be$_{in\ situ}$ shares a cosmic ray origin with $^{10}$Be$_{met}$ but differs in production method; $^{10}$Be$_{in\ situ}$ is produced within crystal lattices in surface rocks and soil, rather than in the atmosphere, with a well constrained total production rate of 4.01 atoms g$^{-1}$y$^{-1}$ at sea level, high latitude (Borchers et al., 2016), and is characterized by full retentivity and known production pathways with depth. $^{10}$Be$_{met}$, in stark contrast, is potentially subjected to variable adsorption depths, incomplete retentivity, and heterogeneous internal redistribution.

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In this study, we compare the previously published $^{10}Be_{in\ situ}$ depth profiles of the Pinedale and Bull Lake terminal glacial moraines in Wind River, Wyoming (Schaller et al., 2009a,b) with new $^{10}Be_{met}$ concentrations from depth profiles from the same sample material to evaluate the long-term (i.e. millennial) delivery rate of $^{10}Be_{met}$ ($F_{(^{10}Be_{met})}$) to this site. This is the first study that evaluates $F_{(^{10}Be_{met})}$ for eroding soils as derived from the comparison of $^{10}Be_{in\ situ}$ and $^{10}Be_{met}$ depth profiles and erosion rates. We utilize previous knowledge of effective transient erosion rates from Schaller et al. (2009a), recalculated with revised parameters for *in situ* production of $^{10}Be$, to constrain and locally calibrate $F_{(^{10}Be_{met})}$ to these moraines while considering the extent of $^{10}Be_{met}$ retention post-delivery. We then compare the resulting calculated $F_{(^{10}Be_{met})}$, with uncertainties determined via Monte Carlo simulations, with the predicted $F_{(^{10}Be_{met})}$ of Graly et al. (2011) and Heikkilä and von Blanckenburg (2015), normalizing each result for paleomagnetic field intensity variations over the Holocene. We also explore the practical differences between these flux estimates and advocate for each approach to be carried out when estimating $F_{(^{10}Be_{met})}$ for use in erosion rate calculations in future studies.

## 2 Background

### 2.1 Study Area

The Fremont Lake area of the Wind River Mountains (Wyoming, United States) experienced multiple glacial advances during the Pleistocene, evidenced by several moraines of Pinedale and Bull Lake age (Fig. 1; modified from original mapping and descriptions by Richmond, 1973). The climate is cold, semi-arid, and windy, with a 50-year precipitation rate and temperature of 27.6 cm y$^{-1}$ and 2.1° C, respectively (WRCC, 2005), in the nearby town of Pinedale, Wyoming (~3.5 km southwest of the field area).

The Pinedale and Bull Lake age terminal moraines (hereafter referred to as Pinedale and Bull Lake moraines) analyzed in this study (Fig. 1) were formed by highland-to-valley mountain glaciers draining an ice cap accumulation zone that covered the mountain range. The Pinedale moraine is more steep-sided and boulder-strewn than the gently sloping Bull Lake

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moraine, each with a total height of ~30 m (see Figs. 1b, 1c of Schaller et al., 2009a for detailed moraine transects). The pH of the moraine soils is well characterized; both profiles have pedogenic carbonate below 1 m, fixing the pH at depth to ~ 8 (Chadwick and Chorover, 2001). Hall and Shroba (1995) report pH data on profiles adjacent to those analyzed in this study, with average pH ranging from ~5.5 on the surface to ~8 at depth.

The depth profile samples analyzed for $^{10}$Be$_{met}$ reported here are the same sample material analyzed for $^{10}$Be$_{in\ situ}$ by Schaller et al. (2009a). We utilize bulk samples sieved to <2 mm for our analysis, extracted from the lower mineral soil developed on each moraine, both mixtures of reworked glacial till (composed of Archean granite, granodiorite, and dioritic gneiss) that have a high likelihood for inheritance from cosmic ray exposure prior to burial. The same reported depths and grain size distributions apply for each sample at depth. The primary mineral content in the deepest (unweathered, >2 mm size fraction) sample is (in order of decreasing abundance): plagioclase, quartz, biotite, K-feldspar, hornblende, and magnetite (Taylor and Blum, 1995). Secondary clay minerals in the 2 μm size fraction include kaolinite, vermiculite, illite, and smectite (Mahaney and Halvorson, 1986), with total clay content ranging from 3 to 10 wt% and 9 to 30 wt% for the Pinedale and Bull Lake profiles, respectively. Major element data is reported in Schaller et al. (2009b). Sr isotope measurements of the moraine soils and dust sources showed insignificant dust fluxes in the depth profiles of the Pinedale and Bull Lake moraines (Blum and Erel, 1997; Taylor and Blum, 1997).

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### 2.2 Independent $^{10}$Be$_{met}$ Flux Estimation

Accurately estimating $F_{(^{10}Be_{met})}$ from field experiments is a topic of ongoing debate (e.g. Ouimet et al., 2015; Dixon et al., 2018), particularly in regard to the effect of precipitation rate on the flux (i.e. whether precipitation leads to additive or dilution effects on delivered $^{10}$Be$_{met}$, see *Willenbring and von Blanckenburg (2010)* and *Deng et al. (2020)* for extensive reviews). $F_{(^{10}Be_{met})}$ also varies through time, depending on solar and paleomagnetic field intensity, and has a spatial distribution primarily resulting from atmospheric mixing and scavenging. One means to estimate $^{10}$Be$_{met}$ production and delivery are $F_{(^{10}Be_{met})}$ estimates based on global atmospheric models (Field et al., 2006; Heikkilä and von Blanckenburg, 2015), which provide an estimate over large spatial scales. Another type of estimate is based on empirical, precipitationdependent field estimates of $^{10}Be_{met}$ inventories in dated soils (Graly et al., 2011) measured over annual time scales. The work of Ouimet et al. (2015) highlighted the necessity for local $F_{(^{10}Be_{met})}$ estimates that also integrate over millennial time scales against models such as these, as their comparison of $^{10}Be_{met}$ inventories and deposition rates from Pinedale- and Bull Lake-aged landforms in the Colorado Front Range showed that some were lower, and some exceeded, deposition rates from atmospheric models and precipitation collections.

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The $F_{(^{10}Be_{met})}$ map of Heikkilä and von Blanckenburg (2015) utilizes the $^{10}Be_{met}$ production functions of Masarik and Beer (1999) combined with the ECHAM5 general circulation model (GCM). Production rates were scaled to reflect the solar modulation and magnetic field strength for the entire Holocene (280.94 MV) using measured $^{10}Be$ concentrations in ice cores. The authors ultimately present a global grid of predicted "pre-industrial" and "industrial" (referring to simulated aerosol and greenhouse gas concentrations) Holocene $F_{(^{10}Be_{met})}$ with an approximate cell size of 300 km x ~230 km. GCMs such as this are useful for modelling atmospheric mixing of $^{10}Be_{met}$, particularly in the stratosphere, as well as the regional effect of climate and its influence on $F_{(^{10}Be_{met})}$ via atmospheric circulation and precipitation (Heikkilä et al., 2012). At this latitude (~42.9° N), the pre-industrial predicted $F_{(^{10}Be_{met})}$ of 1.38 x $10^6$ atoms cm$^{-2}$ y$^{-1}$ is nearly identical to that derived from the flux map of Field et al. (2006), which utilizes the GISS (Goddard Institute for Space Studies Model E) GCM to model production. While the pre-industrial modeled $F_{(^{10}Be_{met})}$ is more applicable for comparison for landforms of these ages, we utilize the industrial predicted $F_{(^{10}Be_{met})}$ of 2.37 x $10^6$ atoms cm$^{-2}$ y$^{-1}$ as an upper bound uncertainty on their estimate.

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On the other hand, the empirical, present-day estimates of $F_{(^{10}Be_{met})}$ from Graly et al. (2011) are based on measurements of $^{10}Be_{met}$ deposition rates from contemporary measurements of $^{10}Be_{met}$ in precipitation, corrected for dust and normalized to a modern (1951-2004) solar modulation value (700 MV). A first order estimate of the $F_{(^{10}Be_{met})}$ was empirically derived given latitude (L) and average precipitation rate (P) to the study area (Graly et al., 2011):

$$F_{(^{10}Be_{met})} = P \times (1.44 / (1 + EXP((30.7 - L) / 4.36)) + 0.63) \qquad (1)$$

A predicted $F_{(^{10}Be_{met})}$ of 0.55 x $10^6$ atoms $cm^{-2}$ $y^{-1}$ is calculated for these Wind River moraines using (Eq. 1), however in order to compare these two estimates with each other, as well as to our calculated $F_{(^{10}Be_{met})}$, we later normalize them all to a common paleomagnetic intensity datum (i.e. the Holocene).

## 3 Methods

### 3.1 Recalculating Previous Age Constraints

Ages for each moraine have been independently determined via multiple methods, with $^{10}Be_{in\ situ}$ surface exposure ages of boulders combined with $^{230}Th/U$ ages of nearby contemporaneous fluvial terraces yielding the most reliable average estimates of 21 ky and 140 ky for the Type-Pinedale and Bull Lake-age moraines, respectively (Gosse et al., 1995; Phillips et al., 1997; Easterbrook et al., 2003; Sharp et al., 2003). These ages closely correspond with global maximum ice volumes of marine oxygen isotope stages 2 and 6, respectively (Sharp et al., 2003). We recalculated the $^{10}Be$ boulder surface exposure ages used to constrain the timing of advancement of each moraine to its terminal position based on a recent revision of the $^{10}Be$ half-life, which affected the AMS standard values (Chmeleff et al., 2010), and the most recent nucleonic production rate of 3.92 atoms $g^{-1}$ $y^{-1}$ at sea level-high latitude (Borchers et al., 2016) (Table S1); the updated independent age constraints are 25 ky for the Pinedale moraine and remain at 140 ky for the Bull Lake moraine (see Supplementary Material for details).

### 3.2 Recalculating Previous Denudation Constraints

All moraine surfaces have been eroded to some extent after their deposition. To estimate the amount of erosion for our calculations, we utilize the previously reported denudation rates (comprising erosion and chemical loss by dissolution) for the Pinedale and Bull Lake moraines (Schaller et al., 2009a) from the same depth profiles and material analyzed in this study. The denudation rates of Schaller et al. (2009a) were calculated using a sea level, high latitude production rate of 5.1 atoms $g_{(qtz)}^{-1}$ $y^{-1}$ (Stone, 2000) and a decay constant of 4.62 x $10^{-7}$ $y^{-1}$. Denudation rates were recalculated using CRONUS v.3 (Phillips et al., 2016) with the updated half-life and production rate values (Table S1) and updated independent age

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constraints scaled to the sample altitude and latitude (Dunai, 2000) assuming two denudation rate scenarios: one of constant denudation since moraine deposition, and the other of transient denudation decreasing in magnitude since moraine deposition. Recalculated average denudation rates are 32.1 ± 2.7 mm ky$^{-1}$ and 12.4 ± 4.8 mm ky$^{-1}$ for the Pinedale and Bull Lake moraines, respectively, in the case of transient denudation, and are 15 mm ky$^{-1}$ and 7.5 mm ky$^{-1}$ for the Pinedale and Bull Lake moraines, respectively, in the case of constant denudation (Table 2). These recalculated denudation rates are determined from the best-fit Chi-Square solutions obtained from running Models 2, 4, 6, and 8 of Schaller et al. (2009a) with present-day parameters (See Supplementary Material for details). We consider the transient denudation rates to more closely approximate reality, as moraines, deposited as ~triangular landforms at the terminus of glaciers, initially experience faster denudation than that towards present day, where the moraines evolve to a concave-down parabolic geometry. As the curvature of the topography reduces over time, hillslope diffusion law dictates that the denudation rates will decrease as the moraine flattens.

To properly compare the transient denudation rates of Schaller et al. (2009a) with the $^{10}$Be$_{met}$-derived erosion rates using the methods of von Blanckenburg et al. (2012), the weathering component of denudation must be accounted for. For the Pinedale moraine, chemical weathering mass loss is estimated to be 16% of the denudation rate, while for the Bull Lake moraine, the chemical weathering mass loss accounts for 20% (Schaller et al., 2009b). If the weathering mass loss took place beneath the cosmic ray attenuation pathway, the recalculated average effective transient erosion rates are then 27.0 mm ky$^{-1}$ and 9.9 mm ky$^{-1}$ for the Pinedale and Bull Lake moraines, respectively. As there is no way to assess where this mass loss occurred, we instead utilize this degree of potential loss to place uncertainties (in addition to analytical uncertainties) on the effective transient erosion rates in all further calculations.

### 3.3 $^{10}$Be$_{met}$ Analysis

We analyzed approximately 1-2 g aliquots of the <2 mm grain-size moraine sediment fraction from the same ~10-15 cm depth intervals as Schaller et al. (2009a) analyzed for Be isotope abundance. We followed the sediment leaching procedure described in Ebert et al. (2012) and Wittmann et al. (2012), which was adapted from Bourlés (1988) and Guelke-Stelling and von Blanckenburg (2012), to extract Be isotopes from outer grain surfaces. Bulk samples underwent two steps to remove the

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adsorbed beryllium: a 24-hr agitation in 0.5 M HCl (to extract amorphous oxide-bound Be), and 1 M hydroxylamine-hydrochloride (to remove crystalline-bound Be). After each step, the supernate was separated from the sediment.

To measure the adsorbed $^{10}Be_{met}$, the two aliquots of leached material were homogenized with ~200 µl of $^{9}Be$ carrier (Table 1) and 2 mL HF was added to the acid sample solution. This solution was nearly completely dried down and then dissolved in 1 additional mL of 50% HF acid and dried down completely, repeated once. We then added 10 mL ultrapure (18 MΩ) water to the warm fluoride residue and leached it for 1 h on a warm hotplate. The water containing the Be was gently removed via pipette and dried down separately. The Be in the water leach solution was extracted and purified by a form of the ion exchange chromatography procedure from von Blanckenburg et al. (2004) that was adapted for meteoric $^{10}Be$ purification by passing the leachate through anion (2 ml of BioRad 1x8 100-200 mesh resin) and cation (2x 1 ml BioRad AG50-X8 200-400 mesh) exchange resins, precipitated at pH ~9 using $NH_4OH:H_2O$ (1:1), washed twice with 2 ml ultrapure water with centrifugation in between, mixed with AgCl, centrifuged and dried overnight, and finally oxidized over open flame (>1000 °C; modified from Kohl & Nishiizumi, 1992). $^{10}Be_{met}/^{9}Be$ ratios were measured at the Zurich AMS Lab (Kubik and Christl, 2010) (S555 standard, nominal $^{10}Be/Be = 95.5 \times 10^{-12}$), from which the $^{10}Be$ concentration ($^{10}Be_{reac}$ = $^{10}Be_{met}$) was calculated. Two carrier blanks analyzed with the samples register AMS $^{10}Be/^{9}Be$ ratios of $3.2 \pm 1.5\times10^{-15}$, and $2.2 \pm 1.5\times10^{-15}$ containing ≪0.1% of the $^{10}Be$ in analyzed samples.

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### 3.4 $^{10}Be_{met}$ Flux Calculations

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In an actively eroding setting, erosion rates can be calculated with knowledge of 1) the total inventory of $^{10}Be_{met}$ in the depth profile, 2) a known/estimated $^{10}Be_{met}$ flux to the location, 3) the $^{10}Be_{met}$ retention behavior, and 4) an assumption of approximate steady state conditions, which is only justified if the inventory of $^{10}Be_{met}$ is independent of the initial exposure age of the soil. Here, steady state means that $^{10}Be_{met}$ lost through erosion and decay equals the $^{10}Be_{met}$ gained from atmospheric flux (e.g. Brown et al., 1988; Willenbring and von Blanckenburg, 2010), a prerequisite of which is that the residence time of soil material containing meteoric $^{10}Be$ with respect to erosion is much less than the depositional age (Willenbring and von Blanckenburg, 2010). For an assumed steady state inventory, the inverse relationship between the local

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$$F({}^{10}Be_{met}) = E \times [{}^{10}Be]_{reac} + (I\lambda) \qquad (2)$$

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Where E is the erosion rate [g cm$^{-2}$ y$^{-1}$], $F({}^{10}Be_{met})$ is the atmospheric flux of $^{10}Be_{met}$ [atoms cm$^{-2}$ y$^{-1}$], I is the inheritance-corrected inventory of $^{10}Be_{met}$ [atoms cm$^{-2}$] in the depth profile, λ is the decay constant of $^{10}Be$ [y$^{-1}$], $[{}^{10}Be]_{reac}$ is the inheritance-corrected $^{10}Be_{met}$ concentration at the surface of the soil [atoms g$^{-1}$]. Inventories were calculated following Willenbring and von Blanckenburg (2010) using a depth-averaged regolith density (ρ) of 2.0 g cm$^{-3}$ for each profile (Schaller et al., 2009a,b), where z is the depth to the bottom of the soil column and $[{}^{10}Be]_{reac}(z)$ is the concentration of $^{10}Be_{met}$ at depth, minus inheritance:

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$$I = \int_0^z [{}^{10}Be]_{reac}(z)\rho dz \qquad (3)$$

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Both $^{10}Be_{met}$ and $^{10}Be_{in\ situ}$ depth profiles show indications of inherited nuclide concentrations at depth, likely due to incomplete glacial erosion resetting for each moraine (Schaller et al., 2009a). Higher concentrations at depth are observed for the Bull Lake moraine for both nuclide profiles (Fig. 1, Table 1), potentially due to the presence of pre-irradiated reworked till. We consider the lowest concentration observed for each depth profile as the inherited $^{10}Be_{met}$ concentration and subtract it from all measured concentrations.

**Deleted:** It is also possible to solve an equation for an erosion rate with only a $F({}^{10}Be_{met})$ estimate and a measured concentration of $^{10}Be_{met}$ at the soil surface. As with the inventory method above, this method also relies on the assumption that the system is at steady state. Here, the effect of decay may also be ignored, as it becomes increasingly insignificant with increasing erosion rates, as well as being minimal (1-4%) over the short lifespan of these moraines. Thus, $F({}^{10}Be_{met})$ may also be calculated by:→¶

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$$F({}^{10}Be_{met}) = E \times [{}^{10}Be]_{reac} \times \rho \qquad (3)$$

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Desorption of $^{10}Be_{met}$ can affect the inventory of $^{10}Be_{met}$ when erosion rates are low, water flux is high and soil chemistry favors mobility. Given that for these soil profiles pH ranges between 8 at depth and ~5.5 at the surface (Hall and Shroba, 1995), we must consider incomplete retention of beryllium and thus a reduced inventory and surface concentration used in (Eq. 2) (Bacon et al., 2012; Maher and von Blanckenburg, 2016). Applying a correction directly to the calculation of $^{10}Be_{met}$

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$$F_{(^{10}Be_{met})}\,(= E \times [^{10}Be]_{reac} + (I\lambda)) + Q \times [^{10}Be]_{reac} \div K_d \qquad (4)$$

$K_d$ is estimated as 1 x $10^5$ to 1 x $10^6$ L kg$^{-1}$ from the surficial pH of ~5.5 via Be sorption-desorption experiments from You et al. (1989). We estimate Q by proxy via the modern precipitation rate of 276 L m$^{-2}$ y$^{-1}$.

Utilizing (Eq. 4) and previous knowledge of the effective transient erosion rates, we calculate the loss-corrected $F_{(^{10}Be_{met})}$ to the locations of these moraines. To further account for the full range of possible $K_d$ values and transient erosion rates, we employ Monte Carlo simulations to determine the uncertainty of the calculated fluxes.

### 3.5 Monte Carlo Simulations

To assess the uncertainties of the calculated flux estimates, Monte Carlo simulations were used to solve for $F_{(^{10}Be_{met})}$ via (Eq. 4) over the entire range of possible values for each term (Table 3) for the Pinedale and Bull Lake moraines. This method is advantageous compared to traditional algebraic error propagation as it doesn't assume a Gaussian distribution, nor does it require an average $K_d$ value input for each moraine, which is difficult to estimate accurately. We carry out each Monte Carlo simulation over 100,000 iterations and report uncertainties representing the 95% confidence intervals of each simulation. The MATLAB code used for these simulations is available in the Supplementary Material.

### 3.6 Normalizing flux estimates for geomagnetic intensity variations over the Holocene

Geomagnetic field strength has varied considerably from the late Pleistocene to present and exerts the primary quantifiable influence on temporal variability in the production rate of cosmogenic nuclides in an inverse fashion (Pigati and Lifton, 2004). Relative paleointensity over the last 140 ky is, on average, ~20-40% of the current geomagnetic intensity depending on the methodology employed (e.g. Frank et al., 1997; Valet et al., 2005). The flux map of Heikkilä and von Blanckenburg (2015) accounts for paleomagnetic variations over the Holocene via the reconstruction method of Steinhilber et al. (2012),

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which effectively increases the production rate used in their model by 1.23 times the present-day rate by rescaling the modern solar modulation factor (Phi) and associated geomagnetic field intensity to that of the Holocene average (280.94 MV). As the estimations of flux from Graly et al. (2011) were normalized to reflect a solar modulation of 700 MV, we rescaled the modern Graly-derived $F_{(^{10}\mathrm{Be}_{met})}$ to the average Holocene solar modulation factor of 280.94MV used in the flux map of Heikkilä and von Blanckenburg (2015) via Masarik and Beer (2009) and Steinhilber et al. (2012), following the paleomagnetic and solar intensity normalization procedure of Deng et al. (2020).

To properly compare the model- and the precipitation-derived Holocene-average $F_{(^{10}\mathrm{Be}_{met})}$ estimates with those calculated in this study, we must also normalize for geomagnetic and solar intensity variations for the Holocene. We rescaled our calculated loss-corrected $F_{(^{10}\mathrm{Be}_{met})}$ for the Pinedale and Bull Lake moraines by first integrating the production rate relative to the modern using the transport-corrected $^{10}$Be marine core record of Christl et al. (2010) from 6 ky and 24 ky, respectively, and then normalizing these values over the Holocene, propagating the statistical uncertainties from the Monte Carlo simulations. These time intervals represent the calculated residence times of the soil profiles from the surface to the e-folding adsorption depth of $^{10}$Be$_{met}$ (20 and 30 cm for the Pinedale and Bull Lake moraines, respectively). This approach accounts for the cumulative effects of transient erosion and leaching by weighting geomagnetic intensity variations on $F_{(^{10}\mathrm{Be}_{met})}$ towards the present.

## 4 Results

### 4.1 Meteoric Cosmogenic $^{10}$Be Concentrations

The measured $^{10}$Be$_{met}$ concentrations are reported along with the previously published $^{10}$Be$_{in\ situ}$ concentrations (Schaller et al., 2009a) for the Pinedale and Bull Lake profiles (Table 1); $^{10}$Be$_{met}$ depth profiles are presented for the Pinedale and Bull Lake profiles in Figure 2. The Pinedale depth profile has $^{10}$Be$_{met}$ concentrations ranging from 3.57 (± 0.32) to 199.53 (± 5.26) x $10^6$ atoms g$^{-1}$. The highest nuclide concentration is measured at 10 cm, rather than at the surface. Below this maximum value, concentrations decrease exponentially until reaching an asymptote at ~ 3 to 6 x $10^6$ atoms g$^{-1}$ from 43 cm to

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the bottom of the profile (180 cm), the lowest of which we consider to be an inherited component. The Pinedale depth profile has an inventory of 6672 (± 122) x $10^6$ atoms cm$^{-2}$.

The Bull Lake depth profile has $^{10}$Be$_{met}$ concentrations ranging from 6.32 (± 0.25) to 415.48 (± 12.46) x $10^6$ atoms g$^{-1}$. The highest nuclide concentration is measured at the surface; below this, concentrations decrease in an approximately exponential fashion until the reaching an asymptote at ~ 6 to 8 x $10^6$ atoms g$^{-1}$ from 64 cm to the bottom of the profile (130 cm), the lowest of which we also consider to be an inherited component. The Bull Lake depth profile has an inventory of 19021 (± 318) x $10^6$ atoms cm$^{-2}$. The $^{10}$Be$_{met}$ inventory from the Bull Lake moraine is roughly 3 times higher than that of the Pinedale moraine.

### 4.2 $^{10}$Be$_{met}$ Fluxes

The loss-corrected F$_{(^{10}\text{Be}_{met})}$ as calculated from (Eq. 4) is 1.08 (+0.10/-0.16) x $10^6$ atoms cm$^{-2}$ y$^{-1}$ and 1.05 (+0.35/-0.40) x $10^6$ atoms cm$^{-2}$ y$^{-1}$ for the Pinedale and Bull Lake moraines, respectively (Table 3), where the Monte Carlo-derived uncertainties reflect the 95% confidence interval of all possible input parameters.

Retention calculations from (Eq. 4) and the Monte Carlo simulation indicate that the potential desorption loss at the surface of the Pinedale and Bull Lake profiles ranges from 0.4% to 4.9% and 0.8% to 15.4%, respectively.

These loss-corrected calculated fluxes are then normalized for paleomagnetic field intensity variations over the Holocene and compared in order to evaluate the F$_{(^{10}\text{Be}_{met})}$ to this area. The Holocene-average loss-corrected F$_{(^{10}\text{Be}_{met})}$ from this study are 1.52 (+0.11/-0.21) x $10^6$ atoms cm$^{-2}$ y$^{-1}$ and 1.31 (+0.43/-0.50) x $10^6$ atoms cm$^{-2}$ y$^{-1}$ for the Pinedale and Bull Lake moraines, respectively (Table 3).

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**Monte Carlo Simulation**

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The predicted Holocene-average $F_{(^{10}Be_{met})}$ of Graly et al. (2011) for this site is 0.83 x $10^6$ atoms $cm^{-2}$ $y^{-1}$ (Table 3). As the pre-Industrial flux map of Heikkilä and von Blanckenburg (2015) already presents a Holocene-average $F_{(^{10}Be_{met})}$ of 1.38 x $10^6$ atoms $cm^{-2}$ $y^{-1}$, no normalization for this method needs to be carried out.

## 5 Discussion

### 5.1 Cosmogenic Nuclide Profiles

An approximately exponential decrease in $^{10}Be_{met}$ with depth is observed for the Pinedale and Bull Lake moraines (Fig. 2). This trend can be explained most simply by the reactive transport of dissolved $^{10}Be_{met}$ with infiltrating water (e.g. Willenbring and von Blanckenburg, 2010) as exponential $^{10}Be_{met}$ profiles are predicted by reactive transport models (Maher and von Blanckenburg, 2016).

The maximum $^{10}Be_{met}$ concentration for the Pinedale moraine is measured at 10 cm depth, rather than the most surficial sample (3 cm). This peak concentration corresponds with the clay rich layer of the B-horizon in the soil profile (Table 1). This potentially indicates that this layer acts as a zone of illuviation, often observed in soil profiles that contain a mid-depth clay-rich horizon (e.g. Monaghan et al., 1992) formed by vertical transport of soil particles containing $^{10}Be_{met}$ (Jagercikova et al., 2016). This subsurface maximum could be the result of smaller grain sizes within this horizon, as these grains have a higher surface area per unit mass and can exchange ions more easily (Brown et al., 1992; Willenbring and von Blanckenburg, 2010). Alternatively, enhanced $^{10}Be_{met}$ incorporation into the lattices of newly formed clays and oxyhydroxides at depth (e.g. Barg et al., 1997) might explain this maximum. This phenomenon is not observed for the Bull Lake moraine; the highest clay content observed in the profile is in the Bk-horizon at a depth of 43 cm (Schaller et al., 2009a,b), however no increase or anomalous high $^{10}Be_{met}$ concentration is observed (Fig. 2, Table 1).

Peculiarly, the observed mixing depths for the Pinedale and Bull Lake moraines as determined from the $^{10}Be_{in\ situ}$ depth profiles of Schaller et al. (2009a) (~40 and 50 cm, respectively) are not observed for the $^{10}Be_{met}$ depth profiles (Fig. 2). A couple of viable reasons for a lack of a mixing signal in the $^{10}Be_{met}$ depth profiles exist. The different grain sizes analyzed

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here and in Schaller et al. (2009a) might exhibit different diffusion coefficients, however an observable trend in grain size with depth within the $^{10}$Be$_{\text{in situ}}$ mixing layer would likely be observed if this were the case. Another possibility is that the advection of $^{10}$Be$_{\text{met}}$ from the surface swamps the effect of mixing that is apparent in the $^{10}$Be$_{\text{in situ}}$ depth profiles. This could indicate that continual $^{10}$Be$_{\text{met}}$ delivery and reactive flow resets the $^{10}$Be$_{\text{met}}$ profile at timescales much shorter than that of physical mixing. Profiles with a relatively low surficial pH (<5) might be particularly susceptible to this phenomenon due to incomplete retention or differential mobility of $^{10}$Be$_{\text{met}}$ (Kaste and Baskaran, 2011), although the profiles analyzed here are not likely to show appreciable (>15%) $^{10}$Be$_{\text{met}}$ loss at depth due to retention issues. Nonetheless, the formation of a clay horizon in the Pinedale moraine may indicate that soil horizonation happens more rapidly than soil mixing, as inferred from the $^{10}$Be$_{\text{in situ}}$ depth profile (Schaller et al., 2009a), suggesting that $^{10}$Be$_{\text{met}}$ advection from the surface is a more likely explanation.

### 5.1.1 $^{10}$Be$_{\text{met}}$ Retention

A range of possibilities exist for retention effects and associated surficial $^{10}$Be$_{\text{met}}$ loss for these profiles. For the highest Kd estimate, at 1 x $10^6$ L kg$^{-1}$, potential loss is as low as 0.4% and 0.8% for the Pinedale and Bull Lake profiles, respectively. On the other hand, for the lowest Kd estimate, at 1 x $10^5$ L kg$^{-1}$, $^{10}$Be$_{\text{met}}$ loss due to desorption could be as great as 4.9% and 15.4% at the surface of the Pinedale and Bull Lake profiles, respectively. Despite this, the Monte Carlo simulations indicate a low probability for loss to this degree, particularly for the Pinedale profile, as evidenced by the relatively shallow tail for each histogram (Fig. S1), with $F_{(^{10}\text{Be}_{\text{met}})}$ results within the 95% confidence interval. While the possibility of desorption cannot be ruled out, we note that $^{10}$Be$_{\text{met}}$ mobilization to depth does not have an appreciable effect on $F_{(^{10}\text{Be}_{\text{met}})}$ in the vast majority of simulations. Even in the worst-case scenario, the magnitude of the potential loss does not substantially affect our calculated $F_{(^{10}\text{Be}_{\text{met}})}$ estimates within uncertainties.

### 5.2 $^{10}$Be$_{\text{met}}$ flux estimation; sources of variability

The calculated, loss- and paleointensity-corrected $F_{(^{10}\text{Be}_{\text{met}})}$ of 1.52 (+0.11/-0.21) x $10^6$ atoms cm$^{-2}$ y$^{-1}$ and 1.31 (+0.43/-0.50) x $10^6$ atoms cm$^{-2}$ y$^{-1}$ for the Pinedale and Bull Lake moraines, respectively, are higher compared to that estimated by Graly et

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Analysis of the $^{10}$Be$_{\text{in situ}}$ depth profiles and calculated denudation rates of Schaller et al. (2009a) indicate that there is an inherited nuclide concentration at depth, likely due to incomplete glacial erosion resetting for each moraine, that is higher for the Bull Lake moraine (~ 1.2 - 1.8 x $10^5$ atoms g$^{-1}$) compared to the Pinedale moraine (~ 0.3 – 0.6 x $10^5$ atoms g$^{-1}$) (Fig. 2; Table 1). The authors prescribe this observation to the presence of pre-irradiated reworked till in the Bull Lake moraine. The existence of appreciable $^{10}$Be$_{\text{met}}$ concentrations at depth is also observed for the $^{10}$Be$_{\text{met}}$ depth profiles analyzed in this study, with higher concentrations observed for the Bull Lake moraine (Fig. 2; Table 1), mimicking the trend seen in the $^{10}$Be$_{\text{in situ}}$ depth profiles. We also consider this incomplete resetting and presence of reworked till to be the predominant source of $^{10}$Be$_{\text{met}}$ at depth, as appreciable $^{10}$Be$_{\text{met}}$ mobilization to depth is unlikely for these profiles, as further explored below. ¶

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The observed mixing depths for the Pinedale and Bull Lake terminal moraines as determined from the $^{10}$Be$_{\text{in situ}}$ depth profiles of Schaller et al. (2009a) are between ~40 and 50 cm. The $^{10}$Be$_{\text{met}}$ concentrations gathered from the meteoric depth profiles presented in this study do not show a similar homogeneity with depth near the surface. At first inspection, it appears that these profiles do not exhibit the same mixing signal as those measured for $^{10}$Be$_{\text{in situ}}$, nor any mixing signal at all. In either case, either the different grain sizes analyzed here and in Schaller et al. (2009a) exhibit different diffusion coefficients, or the advection of $^{10}$Be$_{\text{met}}$ from the surface swamps the effect of mixing that is apparent in the $^{10}$Be$_{\text{in situ}}$ depth profiles. If the latter is the case, it could indicate that continual reactive flow resets the... [2]

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al. (2011), at 0.83 x $10^6$ atoms $cm^{-2}$ $y^{-1}$, and agree within uncertainty with that predicted by Heikkilä and von Blanckenburg (2015), at 1.38 x $10^6$ atoms $cm^{-2}$ $y^{-1}$ (Table 3). The considerable discrepancy between the predicted $F_{(^{10}Be_{met})}$ of each method arises primarily from differences in how each methodology treats the influence that precipitation rate has on the flux to a given area and, in particular for this study, how large of an area is covered. The 310 km x 228 km flux map grid cell of Heikkilä and von Blanckenburg (2015) covers the entirety of the Wind River Range and the surrounding, relatively low-lying flatlands (Fig. 1), where precipitation estimates vary considerably, by over an order of magnitude (WRCC, 2005), due to elevation and topographic effects on precipitation (Hostetler and Clark, 1997). For example, if one were to estimate $F_{(^{10}Be_{met})}$ from Graly et al. (2011) via (Eq. 1) to nearby Fish Lake Mountain contained within the same grid cell, with a modern precipitation rate of 128 cm $y^{-1}$ (WRCC, 2005), the $F_{(^{10}Be_{met})}$ would be 2.5 x $10^6$ atoms $cm^{-2}$ $y^{-1}$, substantially higher than that predicted from Heikkilä and von Blanckenburg (2015). Considering this alone, it is not surprising that such a discrepancy exists between methods, nor is this a unique occurrence (e.g. Jungers et al., 2009; Schoonejans et al., 2017; Dixon et al., 2018; Deng et al., 2020).

Each approach has its own set of shortcomings, precluding agreement between each approach in sites such as this. The flux map of Heikkilä and von Blanckenburg (2015) has a coarse resolution and does not handle short wavelength orographic effects well, along with being model based and requiring many assumptions on atmospheric scavenging. The formula of Graly et al. (2011), on the other hand, does not take atmospheric circulation into account, instead relying on data from sites with relatively high rates of precipitation to derive an empirical formula. Recent work by Deng et al. (2020) highlights the potential for precipitation estimates to differ from GCM-derived estimates due to short timescale additive effects (*sensu* Willenbring and von Blanckenburg, 2010). Further, they find that in the majority of studies globally, GCM- and soil-derived $F_{(^{10}Be_{met})}$ estimates agree within a factor of two. That the calculated fluxes of this study agree with the GCM-modelled pre-Industrial $F_{(^{10}Be_{met})}$ of Heikkilä and von Blanckenburg (2015) provides further evidence of this general observation. In any event, the strength of future $^{10}Be_{met}$ studies relies upon careful consideration of beryllium retention, spatial scale, and paleomagnetic intensity when determining $F_{(^{10}Be_{met})}$. As calculating a long-term delivery rate of $F_{(^{10}Be_{met})}$ for a particular site

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**Deleted:** A 100% additive precipitation-control on flux, if true, could lead to a higher predicted flux at sites with a higher time-integrated precipitation rate than historically recorded (up to 20% higher in this case, see *Supplemental Material*; Fig. 3) from the method in Graly et al. (2011). Regardless, t

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**Deleted:** back-using $^{10}Be_{in\text{-}situ}$ and $^{10}Be_{met}$ is both costly and time-intensive, it is especially prudent to estimate $F_{(^{10}Be_{met})}$ using both methods compared here for robust $^{10}Be_{met}$ erosion rate calculations in the future.

## 6. Conclusions

In this study, we compare new meteoric $^{10}Be$ and previously published *in situ*-produced $^{10}Be$ depth profile measurements from the well-characterized Pinedale (~21-25 ky) and Bull Lake (~140 ky) moraines of Wind River, Wyoming. Our ability to utilize previous knowledge of transient erosion rates from the $^{10}Be_{in\ situ}$ depth profile measurements of Schaller et al. (2009a), recalculated with revised parameters, allows us to calculate loss-corrected Holocene average $^{10}Be_{met}$ fluxes of 1.52 (+0.11/-0.21) x $10^6$ atoms $cm^{-2}$ $y^{-1}$ and 1.31 (+0.43/-0.50) x $10^6$ atoms $cm^{-2}$ $y^{-1}$ to the Pinedale and Bull Lake moraines, respectively. Comparing these fluxes to two widely-used independent estimation methods reveals that the empirical flux estimate of Graly et al. (2011), after normalizing for Holocene paleomagnetic intensity, at 0.83 x $10^6$ atoms $cm^{-2}$ $y^{-1}$, is lower than the calculated fluxes, and the modeled Holocene flux estimate of Heikkila and von Blanckenburg (2015), at 1.38 x $10^6$ atoms $cm^{-2}$ $y^{-1}$, agrees within uncertainty to the calculated fluxes. We find that loss of $^{10}Be_{met}$ in these profiles due to pH-influenced mobility/dissolution effects exerts a relatively minor potential control (biasing from 1% up to 15%) on flux calculations. Inspection of the $^{10}Be_{met}$ depth profiles and their near-surface concentrations suggest that soil mixing to depths of 40 and 50 cm, as observed for the Pinedale and Bull Lake $^{10}Be_{in\ situ}$ depth profiles, respectively, is not represented by the finer grain sizes analyzed in this study. The lack of a mixing signal may be most simply explained by a swamping effect from continual delivery and advection of $^{10}Be_{met}$ from the surface that occurs over more rapid timescales than soil mixing. These differences in the depth-concentration relationships between $^{10}Be_{met}$ and $^{10}Be_{in\ situ}$ might open up a new area of research to study particle movement in soils.

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## Author Contribution

TC is a current Ph.D. student at Stanford University and conducted the majority of the work during 2018-2019 under the supervision of JWK, who contributed to several drafts of the original manuscript as well as preparation of the meteoric data set. MS and JDB contributed via $^{10}Be$ data acquisition, interpretation, and discussion; MC and PWK contributed via AMS

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measurements at ETH-Zurich. FvB assisted in interpretation of the comparative data set and associated discussion of meteoric $^{10}$Be flux estimates, mobility/retention, and paleomagnetic field intensity normalization.

## Competing Interests

The authors declare no competing interests for this manuscript.

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## Figures

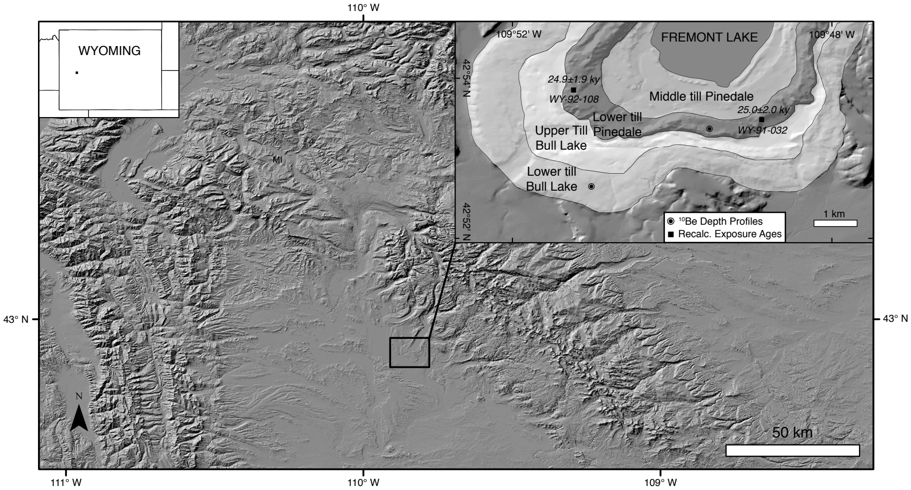


**Fig. 1)** Hillshade map of the Wind River range, derived from a 10 m digital elevation model (DEM); regional map encompasses the entirety of the meteoric $^{10}$Be flux map grid cell of Heikkila and von Blanckenburg (2015). Inset (upper left) shows location of regional map within Wyoming. Inset (upper right) shows locations of depth profiles analyzed for cosmogenic nuclide concentrations from the terminal Pinedale and Bull Lake moraines in the Fremont Lake area (after Richmond [1973] and Schaller et al. [2009a]). Also shown are the locations of boulder surface exposure dates for the Pinedale moraine (WY-92-108 and WY-91-032 of Gosse et al., 1995) that were recalculated using revised parameters (Table S1) to establish an updated independent age constraint for this moraine.

**Deleted:** Table 2

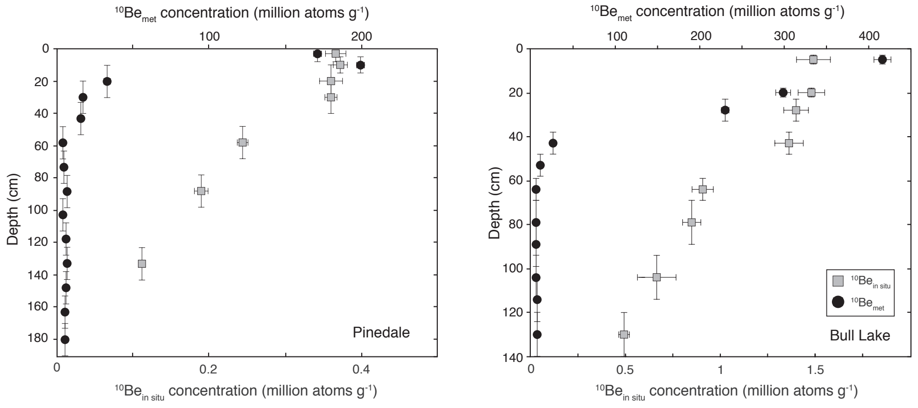
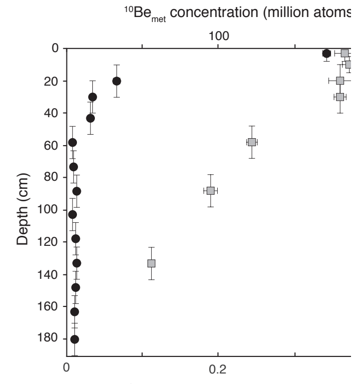


**Fig. 2)** (Left) Depth profile for the Pinedale moraine; $^{10}Be_{met}$ concentrations were measured from the <2 mm grain-size fraction of 14 samples from the same depth profile as analyzed for $^{10}Be_{in\ situ}$ in Schaller et al. (2009a). (Right) Depth profile for the Bull Lake moraine; $^{10}Be_{met}$ concentrations were also measured from the <2 mm grain-size fraction of 11 samples from the same depth profile as analyzed for $^{10}Be_{in\ situ}$ in Schaller et al. (2009a). The $^{10}Be_{met}$ concentration at 94 cm was not measured.



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**Deleted:** **Table 1.** $^{10}$Be Concentrations and GSD[a] in Depth Profiles from Pinedale and Bull Lake Moraines ... [4]

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**Deleted:** AT-FL-4A ... [34]

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**Deleted:** [a]Grain size distributions and *in situ* $^{10}$Be concentrations from *Schaller et al. (2009a)* ... [36]

**Deleted:** [b]See Schaller et al. (2009a) for the grain size fraction analyzed for each sample ... [37]

**Deleted:** [c]Corrected for blank, reported error includes analytical uncertainties (1σ) ... [38]

**Deleted:** [d]Average of $^{10}$Be$_{met}$ concentations from directly above and below this depth ... [39]

**Deleted:** ¤Average of multiple aliquots analyzed in Schaller et al. (2009a) ... [40]

**Table 1.** $^{10}$Be Concentrations and GSD[a] in Depth Profiles from Pinedale and Bull Lake Moraines

| Sample[b] | Depth (cm) | Sand (wt %) | Silt (wt%) | Clay (wt %) | *In situ* $^{10}$Be concentration[c] (10$^5$ atoms g$^{-1}$) | Meteoric $^{10}$ sample weig (g) | (mg) | (10$^6$ atoms g$^{-1}$) | cm$^{-2}$) |
|---|---|---|---|---|---|---|---|---|---|
| | | | *Pinedale moraine (2262 m asl, 42° 53′ 26″ N, 109° 49′ 34″ W)* | | | | | | |
| 04-WRMP-014 | 3 ± 2 | 75 | 18 | 6 | 3.67 ± 0.14 | 4.5747 | 0.2146 | 171.283 ± 5.142 | 1027 ± 30 |
| 04-WRMP-013 | 10 ± 5 | 68 | 22 | 10 | 3.73 ± 0.09 | 3.1697 | 0.2146 | 199.526 ± 5.986 | 2793 ± 84 |
| 04-WRMP-012 | 20 ± 10 | 70 | 23 | 7 | 3.60 ± 0.15 | 6.4287 | 0.2146 | 33.007 ± 3.183 | 660 ± 64 |
| 04-WRMP-011 | 30 ± 10 | 74 | 22 | 4 | 3.60 ± 0.08 | 6.1094 | 0.2148 | 16.819 ± 1.541 | 336 ± 31 |
| 04-WRMP-010 | 43 ± 10 | 76 | 19 | 5 | - | 5.1606 | 0.2144 | 15.357 ± 1.189 | 399 ± 31 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 04-WRMP-009 | 58 ± 10 | 82 | 15 | 3 | 2.44 ± 0.07 | 5.6470 | 0.2146 | 3.966 ± 0.336 | 119 ± 10 |
| 04-WRMP-008 | 73 ± 10 | 85 | 12 | 3 | - | 5.4438 | 0.2142 | 4.673 ± 0.382 | 140 ± 11 |
| 04-WRMP-007 | 88 ± 10 | 81 | 16 | 3 | 1.89 ± 0.09 | 5.6027 | 0.2140 | 6.699 ± 0.563 | 201 ± 17 |
| 04-WRMP-006 | 103 ± 10 | 82 | 15 | 3 | - | 6.0067 | 0.2103 | 3.569 ± 0.322 | 107 ± 10 |
| 04-WRMP-005 | 118 ± 10 | 71 | 23 | 6 | - | 3.0500 | 0.2127 | 6.207 ± 0.284 | 186 ± 9 |
| 04-WRMP-004 | 133 ± 10 | 71 | 24 | 5 | 1.11 ± 0.03 | 3.1070 | 0.2134 | 6.489 ± 0.302 | 195 ± 9 |
| 04-WRMP-003 | 148 ± 10 | 74 | 21 | 6 | - | 2.9340 | 0.2128 | 5.656 ± 0.249 | 170 ± 7 |
| 04-WRMP-002 | 163 ± 10 | 72 | 22 | 6 | - | 2.8869 | 0.2107 | 5.531 ± 0.240 | 166 ± 7 |
| 04-WRMP-001 | 180 ± 10 | 72 | 23 | 6 | - | 3.0824 | 0.2135 | 5.098 ± 0.236 | 173 ± 8 |
| | | | | | | | | ∫ | 6672 ± 122 |
| *Bull Lake moraine (2285 m asl, 42° 52′ 39″ N, 109° 51′ 00″ W)* | | | | | | | | | |
| AT-FL-4L | 5 ± 2 | 69 | 22 | 9 | 14.9 ± 0.9 | 1.0174 | 0.4125 | 415.475 ± 12.464 | 4155 ± 125 |
| AT-FL-4K | 20 ± 5 | 51 | 29 | 20 | 14.8 ± 0.7 | 1.0793 | 0.2139 | 298.813 ± 8.965 | 8964 ± 269 |
| AT-FL-4J | 28 ± 5 | 52 | 34 | 14 | 14.0 ± 0.6 | 1.0824 | 0.2140 | 230.442 ± 6.913 | 3687 ± 111 |
| AT-FL-4I | 43 ± 5 | 47 | 23 | 30 | 12.3[¤] ± 0.7 | 1.0593 | 0.1963 | 26.590 ± 0.798 | 798 ± 24 |
| AT-FL-4H | 53 ± 5 | 50 | 28 | 22 | - | 1.0176 | 0.2141 | 11.433 ± 0.343 | 229 ± 7 |
| AT-FL-4G | 64 ± 5 | 54 | 26 | 20 | 9.08 ± 0.56 | 1.0109 | 0.2144 | 7.083 ± 0.382 | 156 ± 8 |
| AT-FL-4F | 79 ± 10 | 60 | 24 | 16 | 8.50 ± 0.48 | 1.01 | 0.2141 | 6.639 ± 0.236 | 199 ± 7 |
| AT-FL-4E | 89 ± 10 | 62 | 24 | 14 | - | 1.0722 | 0.2142 | 6.318 ± 0.246 | 126 ± 5 |
| AT-FL-4D | 94 ± 10 | 75 | 17 | 9 | - | - | - | 6.723[d] | 134[d] |
| AT-FL-4C | 104 ± 10 | 64 | 26 | 10 | 5.98[¤] ± 1.00 | 1.0164 | 0.2144 | 7.129 ± 0.428 | 143 ± 9 |
| AT-FL-4B | 114 ± 10 | 60 | 25 | 15 | - | 1.0283 | 0.2142 | 8.021 ± 0.241 | 160 ± 5 |
| AT-FL-4A | 130 ± 10 | 60 | 25 | 15 | 4.93 ± 0.28 | 1.0294 | 0.2143 | 8.449 ± 0.253 | 270 ± 8 |
| | | | | | | | | ∫ | 19021 ± 318 |

[a] Grain size distributions and *in situ* $^{10}$Be concentrations from *Schaller et al. (2009a)*

[b] See Schaller et al. (2009a) for the grain size fraction analyzed for each sample

[c] Corrected for blank, reported error includes analytical uncertainties (1σ)

[d] Average of $^{10}$Be$_{met}$ concentations from directly above and below this depth

[¤] Average of multiple aliquots analyzed in Schaller et al. (2009a)

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**Table 2.** Parameters for Recalculated *in situ* $^{10}$Be Exposure Ages and Denudation Rates
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**Deleted:** *Nucleonic scaling factor* ... [50]

**Deleted:** *Stopped muonic scaling factor* ... [51]

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**Deleted:** [1]For denudation rate recalculations only; $^{10}$Be exposure age recalculations are scaled ... [57]

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**Deleted:** [1]For a full explanation of range allowed in and resolution ... [71]

**Table 2.** Recalculated Chi-Square Solutions for Different Denudation Rate Simulations of Schaller et al. (2009a)[a]

| Type of Denudation | Model | Age (ky; *fixed parameter*) | Average Denudation (mm ky$^{-1}$) | Inherited $^{10}$Be concentration ($10^5$ at g$^{-1}$) | Mixing Depth (cm) | Diffusivity *k* ($10^{-3}$ m$^2$ y$^{-1}$) | Maximum Height (m) | Slope Angle (degrees) |
|---|---|---|---|---|---|---|---|---|
| | | *Pinedale moraine (2262 m asl, 42° 53′ 26″ N, 109° 49′ 34″ W)* | | | | | | |
| Constant | 2 | 25 | 15 | 0.2 | 0 | | | |
| Transient | 4 | 25 | 29-35 | 0.2 | 0 | 20 | 30 | 25,30 |
| | | *Bull Lake moraine (2285 m asl, 42° 52′ 39″ N, 109° 51′ 00″ W)* | | | | | | |
| Constant | 6 | 140 | 7.5 | 1.4 | 0 | | | |
| Transient | 8 | 140 | 6-21. | 1.2-1.8. | 0 | 0.3-10 | 35,40,50,60 | 5,10,15,<br>20,25,30 |

[a]For a full explanation of range allowed and resolution of each parameter, see Table 3 of *Schaller et al. (2009a)*

**Deleted:** **Table 4.** Calculated $^{10}$Be$_{met}$ erosion rates for different flux estimates, raw and corrected for Holocene paleointensity variations ... [72]

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**Deleted:** Bull Lake (This Study) ... [75]

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**Deleted:** " *using measured $^{10}Be_{met}$ seafloor accumulation record of Christl et al. (2010)* ... [80]

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**Deleted:** ꜝ *uncertainty represents the 'industrial' modeled flux of Heikkilä and von Blanckenburg (2015)* ... [82]

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**Table 3.** $^{10}$Be$_{met}$ flux estimates, raw and normalized for Holocene paleointensity variations

| Method | F($^{10}$Be$_{met}$) uncorrected (x 10$^{6}$ atoms cm$^{-2}$y$^{-1}$) | Valid over time scale (ky) | $^{10}$Be$_{met}$ correction factor relative to Modern | $^{10}$Be$_{met}$ correction factor relative to Holocene | F($^{10}$Be$_{met}$) corrected to represent Holocene (x 10$^{6}$ atoms cm$^{-2}$y$^{-1}$) | Transient Erosion Rate (g cm$^{-2}$ y$^{-1}$)[e] |
|---|---|---|---|---|---|---|
| Pinedale (This Study) | 1.08 (+0.10/-0.16) | 6 | 0.88[a] | 0.71[a] | 1.52 (+0.11/-0.21) | 0.0064 (+0.0006/-0.0010) |
| Bull Lake (This Study) | 1.05 (+0.35/-0.40) | 24 | 0.99[a] | 0.80[a] | 1.28 (+0.43/-0.50) | 0.0025 (+0.0009/-0.0010) |
| Graly et al. (2011) | 0.55 | 0.005 | 0.82[b] | 1.06[c] | 0.83 | - |
| Heikkilä and von Blanckenburg (2015) | - | 10 | 1.23[c] | - | 1.38 (+ 0.99)[d] | - |

[a] *using measured $^{10}$Be$_{met}$ seafloor accumulation record of Christl et al. (2010) from 6 ky and 24 ky to present for the Pinedale and Bull Lake moraines, respectively*

[b] *using the paleomagnetic scaling method of Masarik and Beer (2009)*

[c] *using the paleomagnetic reconstruction method of Steinhilber et al. (2012)*

[d] *uncertainty represents the 'industrial' modeled flux of Heikkilä and von Blanckenburg (2015)*

[e] *calculated for a soil density of 2000 kg m$^{-3}$*

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