

Meltwater, mud, and the Mississippi: Upper Mississippi River Valley slackwater sediments reveal shifting deglacial meltwater sources associated with the Marquette Readvance of the Laurentide Ice Sheet
Penprase et al. (2025)

We thank both reviewers for their detailed and insightful comments on this manuscript. The suggestions for revisions and ways to improve the manuscript allow for greater clarity in the presentation of our findings and increase accessibility for readers.

We present the reviewer comments in their original format with our response in blue text, with changes to the manuscript noted in blue and **bold**.

RC1 Comments

This is a well-written manuscript on an interesting topic related to meltwater and glacial advances in the Upper Mississippi River Basin.

We send our thanks to the reviewer for their constructive comments towards our shared goal of better understanding proglacial lake chronologies and landscape evolution along the southern Laurentide margin.

I do have a few significant concerns and comments (I am also attaching a PDF with detailed comments).

We extract the major comments from this PDF (excluding minor grammar or text edits) and include them and our responses at the end of this document.

Overall, I would say these are moderate revisions, many of which can be addressed with changes in wording and better explanations. But some of the interpretations may need to be made more lightly, until additional data can be collected in the future.

One of the most significant concerns is that the discussion and conclusions of the manuscript are based solely on one core (the new data). I do think that the geochemical approach is well done and that the contrasting provenance between the sources is quite good. However, the fact that all the geochemical data is from only one 4 m core (and only the lower 2m of it), is somewhat concerning. There should be a caveat about this in the discussion that more cores are needed in the future to test these ideas.

We recognize this potential shortcoming in our dataset. In the revised manuscript, **we will add text highlighting potential shortcomings for our study based on the limited dataset. In this text, we will also add greater context for our study to bolster our conclusions by pointing to several studies along the Mississippi River that have previously related slackwater sediments to glacial meltwater routing and serve as valuable additional context for our sediment core and conclusions.**

Secondly, the chronology is based solely on 2 OSL ages (with 1.5 ka error). Although the ages do seem reasonable, it is not clear how the water content estimates were made. The data Table 3 indicates a water content of 25 % was used, but the methods are unclear as to how this was made from its burial history and the in-situ measurements. Please provide more detail on how calculated. Overall, is the precision of these OSL ages good enough to make a correlation to the Marquette Readvance? Is the Marquette Readvance the same as the Lakeview Phase that deposited the Miller Creek Fm. in NW Wisconsin (see Syverson et al., 2011. Wisconsin Stratigraphy Lexicon)?

The OSL ages presented in this manuscript were the wettest samples that were processed by the laboratory from this study area, with other samples from other parts of the watershed taken at similar depths measuring in-situ H₂O contents of 15% and lower. Given the anomalously low moisture content measured, it was assumed to not be representative of the annually averaged soil moisture for the site/region, but since we didn't have any other data, we used a soil moisture that was still high, but more realistic for the site (25% gravimetric soil moisture compared to the 27-31% measured values). Uncertainty on soil moisture was assumed to be +/- 30% of the value. Our use of a standardized 25% assumed moisture content for the duration of sample burial is within the 30% uncertainty for measurement. Moreover, the use of a standardized sediment moisture content for these samples results in a minor difference in the calculated ages (2-5%) as is well within the uncertainty of the OSL ages (12-13% RSE).

To provide additional precision on the age constraints presented in this study, we will add new text to our discussion section discussing age constraints for our dataset by incorporating published OSL and ¹⁰Be ages from local terraces from Penprase et al. (2025). These data provide limiting age constraints on sediment deposition prior to slackwater sediment inundation. Based on these previously published ages, we are confident that these sediments were deposited after ~12.3 ka (¹⁰Be upper regional terrace abandonment age) but before ~10.6 ka (¹⁰Be lower regional terrace abandonment age). With this additional geochronological context for our study, we are confident with our association between this sediment core and postglacial meltwater rerouting in the upper Mississippi River valley. The Lake View and Marquette periods were roughly the same time period and therefore likely correlative. **However, based on information available in existing literature and informed by comments from the other reviewer, in the revised manuscript we present a modified chronology that is more closely aligned with existing literature and events in the region.** This revised chronology is informed by the comments and suggestions of both reviewers, with a few modifications and additional references to the literature to bolster these deviations. **We will update manuscript text and figures to reflect this modified chronology.**

We hypothesize that the basal sandy sediments below are likely older and (1) deposited during aggradation up to the watershed's high terrace level, (2) followed by downcutting (abandonment age ~12.3 ka from Penprase et al. (2025), *Geology*) but likely ~13.4 ka associated with Agassiz floods), (3) inundation by meltwater + slackwater deposition, and (4) then abandonment again (abandonment age ~10.6 ka from Penprase (2025), *Geology*). **We will update the manuscript to add this clarification of our hypothesized origins of the basal sediments.** As a result of this proposed origin of the basal sediments, we believe the slackwater sediments would have been deposited after the ~13.4 ka Agassiz floods, which triggered incision but then inundation and

slackwater accumulation at the mouth of the Whitewater River. The timing of this could still align with the Lockhart and Moorhead phases. **Our new chronology is as follows:**

Phase A — ~20 ka to between 14.1 ka and 12.9 ka (below 385 cm) Local Provenance, pre-NW and NE sourced meltwater floods, no slackwater deposition at sampling location.

The basal sediments are associated with the aggradational phase of the Mississippi River starting at ~20 ka (Penprase et al. 2025). These sediments were then incised by fluvial incision with an abandonment age of ~12.3 ka from Penprase (2025), *Geology*, but likely within 14.1 to 12.9 ka (and likely near 13.4 ka) due to Agassiz floodwaters. This incision formed the terrace surface atop which the slackwater sediments were deposited. The terrace formation terminates Phase A.

Phase B — 14.1 ka-12.9 ka (385-315 cm): Lockhart Phase of Agassiz, deposition of predominately Agassiz-derived slackwater sediments

Meltwater inundation and slackwater deposition begins atop the terrace surface. Sediments are delivered to the Upper Mississippi River from the NW and associated with the Lockhart Phase of Agassiz.

12.9 to between 11.7 and 11.4 ka: no meltwater input; no slackwater sed deposition

There was no meltwater outflow to the Upper Mississippi River valley between 12.9 and 11.7 ka as outflow was rerouted to the north via the Mackenzie River and east via the St. Lawrence River (Fisher, 2003; Murton et al., 2010; Leydet et al., 2018; Keigwin et al., 2018; Wickert et al., 2023). See additional text from lines 335 and 347 of the original manuscript for additional discussion and references for this period of no meltwater input. We associate this with the Moorhead phase of Agassiz (12.5-11.7 ka).

Phase C — ~11.6 (or 11.4 ka) until 10.6 ka (315-212 cm): Superior and Agassiz meltwater

Southward routing of glacial melt resumes due to the Marquette and Lake View advances, which block eastern outlets. Both Lake Agassiz and Lake Superior (Duluth) outflows are routed towards the upper Mississippi valley. These slackwater sediments contain a combination of Agassiz- and (dominantly) Superior-sourced materials. Age ranges in the Gribben forest bed lead to some ambiguity on when to start this period (11.6 vs 11.7 ka). Since the age of the dated wood from the trees is unknown, the likely true age of this bed is towards the low end of the radiocarbon ages presented in Lowell (1999). So, we go with 11.6 ka, which aligns with the $d^{18}O$ record.

The 11.4 age is referring to this: "Increased meltwater must have entered Lake Agassiz following a readvance to the Marks moraine in the Superior basin, which was co-eval with the Marquette advance in the eastern Superior basin (e.g., Lowell et al., 1999). The unexpectedly high elevation of red varves from cored lakes in northwest Ontario (Fig. 5G: red varves) that date to 11,490 cal yr BP are difficult to explain (Breckenridge et al., 2021)."

Phase D — 10.6 ka: eastward meltwater routing resumes and end of slackwater deposition

Reviewer 2 suggested “10.06 ka at 247 cm depth (i.e. $11.56 - 1.5 = 10.06$ ka) for when major element contributions from Lake Superior last peaked at the core site”. However, this wouldn't make sense given the regional geochronology.

Based on the regional chronology, we find 10.3 ka age on wood in gravels at the base of Lake Pepin. (Blumentritt et al. 2009), 10.8 ka age from ^{14}C at the base of Lake St. Croix (Blumentritt et al. 2009) and 10.6 ka age from ^{14}C at the base of the Brule Spillway.” (Breckenridge 2013). These are minimum-limiting ages on lacustrine sediments that post-date southward meltwater routing. Therefore, deglacial meltwaters must have been rerouted eastwards significantly before the 10.0 ka date proposed by the reviewer.

We use 10.6 ka as the likely age of eastward drainage rerouting based on Wickert et al. (2023); Karrow et al. (2000); Fisher (2003); Breckenridge (2007); and Derouin et al. (2007), along with dated constraints from within the Whitewater tributary watershed the core was taken from, as presented in Penprase et al. (2025). We mark this as when waters from Lakes Superior and Agassiz once again are routed away from the Mississippi and slackwater deposition ends.

Third concern: the geochemical data is all on the bulk sample and not a grain size fraction. Thus, it is not clear to what degree the changes in the geochemistry are from source area shifts or from grain size partitioning from the sorting process (with more Si in the sand fraction and more Fe, Ni, Cu in finer fractions --- which is common). It would be important to show the grain size data (if you have it) in the graph next to the elemental data. Please add more on potential pitfalls with the methods related to this. Although the provenance idea may well be the correct interpretation, it is certainly likely that there is also a strong effect from mineral partitioning with grain size. It would be a good test to run a sample with different grain size fractions to prove the case that the elemental trends would hold even if narrow grain size fractions were used rather than bulk core. If unable to do this, then there should be a statement about the possibility that grain size may significantly affect the elemental data and complicate source area interpretations. The provenance data is really nice overall, with a strong contrast between the sources but want to consider and rule out other possibilities.

We, unfortunately, only have qualitative grain size data and are unable to add quantitative grain size data to our plots. In line with this suggestion we will follow the reviewer's recommendation and **add more text highlighting possible uncertainties in using bulk versus grain size fraction geochemical data and the possibility of grain size impacting source area interpretations**. However, despite these potential impacts, based on sedimentology of underlying terrace and material from within our core, we do express confidence that our core slackwater sediments are distinct (i.e. non-local) and the differences in the geochemistry are not solely due to grain size changes.

Fourth, a good core description is needed and would be appropriate to put in the Appendix. The photos of the core are great. However, this doesn't replace the need for a standard core description --- especially since only one core is presented here. Please add.

We will add a detailed sediment core description to the Appendix/Supplement.

Minor issues or suggestions:

-- use "southern Laurentide Ice Sheet" in title and other areas

We will update the text to be consistent and use “southern Laurentide Ice Sheet” throughout the manuscript.

-- inconsistent use of LGM term; may want to use last glaciation or Wisconsin Episode in some areas or better define LGM

To address this comment and remove ambiguity, we will update the manuscript to remove usage of the LGM term and move forward instead with “last glaciation”.

-- OSL ages could be rounded to one decimal perhaps, given the errors involved

In line with this suggestion, in the revised manuscript we will round our OSL ages to one decimal place.

--- some sentences have strange or contradictory wordings; the writing is generally good, but some sentences are confusing and long-winded with too many thoughts and might be better to split into two sentences

We will review the manuscript text and shorten and split sentences throughout to help with readability. We will also identify and revise word choices to help with readability.

Line 3: "well-dated paleoceanographic records" --- make new sentence

Per the reviewer’s recommendation, we will split this sentence to have a new sentence starting with “Well-dated paleoceanographic records...”.

Line 12: use "Mississippi River"

We will change this to “Mississippi River”

Fig. 1 --- show outline of glacial Lake Duluth ? was it present at the time ?

While we understand the motivation behind this suggestion, because of meltwater routing that allowed for Agassiz sediments to be delivered to the Superior Basin, we choose to designate the “Superior Basin” on our maps and within our text, rather than “glacial Lake Duluth” because the Superior Basin in a more broad sense served as a point of origin for sediments routed down the Mississippi River, rather than glacial Lake Duluth. Thus, we focus our figures and text on the Superior Basin and not Lake Duluth to aid in clarity. To add information for readers to reference on lake shoreline changes, we will add a sentence citing Breckenridge (2013), where readers can refer to paleoshoreline maps and lake extents.

Some additional papers to perhaps cite or investigate:

We will explore these papers and add them where appropriate in the text. We thank the reviewer for these suggestions.

Flock, M.A., 1983. The late Wisconsinan Savanna Terrace in tributaries to the upper Mississippi River. *Quaternary Research*, 20(2), pp.165-176. [This paper notes red and gray fine-grained beds in the terrace from perhaps Lake Superior and Lake Agassiz sources --- with late glacial age]

Johnson, M.D., Addis, K.L., Ferber, L.R., Hemstad, C.B., Meyer, G.N. and Komai, L.T., 1999. Glacial Lake Lind, Wisconsin and Minnesota. *Geological Society of America Bulletin*, 111(9), pp.1371-1386. [another example of glacial lake studies in the region]

Hobbs, H.C. and Breckenridge, A., 2011. Ice advances and retreats, inlets and outlets, sediments and strandlines of the western Lake Superior basin. Field Guide.
[https://doi.org/10.1130/2011.0024\(14\)](https://doi.org/10.1130/2011.0024(14)) [more details on controversy of Marquette Advance]

Curry, B.B., Hajic, E.R., Clark, J.A., Befus, K.M., Carrell, J.E. and Brown, S.E., 2014. The Kankakee Torrent and other large meltwater flooding events during the last deglaciation, Illinois, USA. *Quaternary Science Reviews*, 90, pp.22-36. [slackwater lake sediment records on the Illinois River valley]

Hajic, E.R., 1993. Geomorphology of the northern American Bottom as context for archaeology. *Illinois Archaeology*, 5(1), pp.54-65. [C14 ages on red clay beds in St. Louis region]

Grimley, D.A. , A.C. Phillips, and S.W. Lepley, 2007, Surficial Geology of Monks Mound Quadrangle, Madison and St. Clair Counties, Illinois: Illinois State Geological Survey, Illinois Preliminary Geologic Map, IPGM Monks Mound-SG, 1:24,000 [red clay beds in the American Bottoms of the St. Louis area --- Miss. Valley --- occur at the Holocene-Pleistocene contact and are similar in age to the red clay beds noted in this manuscript]

Porter, D.A. and Guccione, M.J., 1994. Deglacial flood origin of the Charleston alluvial fan, Lower Mississippi alluvial valley. *Quaternary Research*, 41(3), pp.278-284. [similar timing to the dated events in Minnesota - any relation ?]

Syverson, K.M., Clayton, L., Attig, J.W. and Mickelson, D.M., 2011. Lexicon of Pleistocene stratigraphic units of Wisconsin. *Wisconsin geological and natural history survey technical report, 1*, p.180. [might be good to correlate unit and phases to the names used in this report --- such as Miller Creek Fm. and Lake View Phase]

Line Items from PDF:

For clarity and simplicity only include reviewer comments in this document. Any direct text edits made in the PDF (deletions, capitalization, grammar, etc.) will be addressed in the revisions.

Title: deglacial and readvance seem like opposing thoughts ... can the title be simplified a bit ? I am confused by the title..., Remove "Meltwater, mud, and the Mississippi"

We will clarify this. Based on suggestions from the other manuscript reviewer, we will move forward with the title "*History of late-glacial meltwater routing to the upper Mississippi River basin as recorded in a tributary river slackwater sequence*".

19: where does 20 ka come from ? Citation needed, This first sentence is hard to follow --- how does "routing" remap a network ? Please break into two sentences to be more clear on the meaning.

Per the reviewer's recommendation, in the revised text we will remove references to "LGM" and instead use the terminology "last glaciation". This will address the confusion over the 20 ka referenced here. Additionally, we will update our word choice from "remap" to "reroute" to aid in clarity and break this sentence into two.

75: citations?

We will add additional references of past studies using field observations and isotopic data to this sentence, as aided by references provided by both this and the other reviewer and through a review of existing literature on this topic.

77: I disagree with the assumption that these meltwater floods caused slackwater sedimentation. The slackwater sediments were deposited during times of river aggradation (likely during glacial advance or during moraine formation), whereas the meltwater floods caused incision in both the main valley and tributary valleys.

This is a complex point that we intend to clarify in the text during the revision period. We suggest that while the reviewer is correct that meltwater floods would have resulted in incision, due to their low bed-load supply, we propose that the high suspended-sediment content in these meltwater floods resulted in simultaneous sediment deposition of fine-grained slackwater sediment at inundated tributary mouths. Thus, we assert that these sediments are, in fact, the result of meltwater floods because of this high sediment load and that there was simultaneous incision into the mainstem river bottom and inundation of tributaries and associated deposition atop existing terrace surfaces during these floods. **We will clarify discussion text to elucidate this point. We will also add additional text citing several studies observing slackwater sediment deposition in a similar depositional environment to our study area, including:**

- Baker et al. (1983) (<https://doi.org/10.1002/9781444303773.ch18>),
- Wiman et al. (2023) (<https://doi.org/10.1177/03091333231208612>),
- Patton et al. (1982) (in ISBN 9780367460587),
- Smith (1993) ([https://doi.org/10.1130/0016-7606\(1993\)105<0077:MFDAMI>2.3.CO;2](https://doi.org/10.1130/0016-7606(1993)105<0077:MFDAMI>2.3.CO;2)),

81: make separate sentence

Will do.

83: make separate sentence

Will do.

104: should this be 34.0 ka or is it rounded ?

It is rounded.

174: are these depths in the C horizon of the soil profile ?

Based on our geochemical data in Figure 4, we see that our ~150 cm sample is still in the weathered horizons, while our ~250 cm sample is in the C horizon. For the section of our core we describe in our geochemical analysis (below 250 cm depth), we believe this is a C1 and C2 profile, where the slackwater sediments are within the C1 horizon and C2 is the underlying locally derived sands. **We will clarify which soil horizons each of our OSL samples came from in our sediment description, to be added to the appendix.**

176: are these [sediment description] in the supplemental ?

See note above; **we will add a core sediment description to our appendix.** So, not yet but we will address this.

200: how were the interpreted moisture contents over the burial history determined ?

This is determined based on the likely depositional setting for our samples. In this case, we are assuming these samples were part of a fluvial terrace post-deposition and leading up to sampling. The OSL ages presented in this manuscript were the wettest samples that were processed by the laboratory from this study area, with other samples from other parts of the watershed taken at similar depths measuring in-situ H₂O contents of 15% and lower. Given the anomalously moisture content measured, it was assumed to not be representative of the annually averaged soil moisture for the site/region, but since we didn't have any other data, we used a soil moisture that was still high, but more realistic for the site (25% gravimetric soil moisture compared to the 27-31% measured values). Uncertainty on soil moisture was assumed to be +/- 30% of the value. Our use of a standardized 25% assumed moisture content for the duration of sample burial is within the 30% uncertainty for measurement. Moreover, the use of a standardized sediment moisture content for these samples results in a minor difference in the calculated ages (2-5%) as is well within the uncertainty of the OSL ages (12-13% RSE). **We will clarify this in the OSL table caption.**

223: perhaps would be more objective to call it NW source rather than Agassiz ? or it Agassiz justified ?

We agree with the reviewer that the use of Agassiz is perhaps not justified, as while the water is derived from Agassiz, the sediments are Des Moines and Red River lobe derived from within the modern Minnesota River basin. Therefore, we will move forward with “NW” and “NE” descriptors throughout our manuscript, instead of “Agassiz” and “Superior”.

Table 3: should there be an error bar associated with the water contents ? why is the moisture content used lower than that measured ? and not proportionally adjusted (should upper value at 1.5 m be lower than the 2.5 m value ?) how calculated moisture content?

Please see our response above to the reviewer’s comment on Line 200, where we discuss how the moisture content of our OSL samples were determined.

230: need error bars here...

We will add error bars for our OSL sample depth in the revised manuscript.

247: but one of the OSL ages is in the highly weathered zone ---

We will address the weathering of the sediment core in our sediment descriptions and add clarifying text in our OSL methods that one sample came from the weathered zone. We additionally will add text discussing the weathering of the sediments within this zone.

Figure 5: can you put a grain size curve next to this as well to see how much could be a result of grain size partitioning ?

See note above about grain size. We unfortunately do not have quantitative grain size data but will follow the reviewer’s suggestion to **add more caveats about the pitfalls of bulk versus grain size fraction geochemical data to the revised text and the possibility of grain size impacting source area interpretations.**

293: +/- 1.5 ka

Will add.

297: the correlation of this is somewhat questioned by Hobbs and Breckenridge

We will clarify this text after reviewing the additional texts suggested by this reviewer and Breckenridge (2013), which discusses this correlation between the Lake View and Marquette periods and update the text accordingly.

309: perhaps round ages and errors to single decimal ?

Will do.

317: do you have % sand, silt, clay for this core ?

See notes above about grain size.

318: in what way other than grain size ?

This determination is based on similarity between these sediments and locally-derived sediments. We will clarify this in the text and add additional text in our sediment description to show how we think this transition is due to provenance and not solely grain size. To do this, **we will add more descriptive sedimentological terms, including noting the similar high quartz-grain content, similar grain size, and similar bedding structure between other locally-derived sediments and the bottommost sediments in our core to help clarify the similarities.**

319: in what way ?

Same response as Line 318.

Figure 7: shouldn't lake levels also change in Lake Agassiz and Lake Superior as the glacier advances and due to isostatic rebound ?

Due to the short timescales of this study and scale of our maps, the shifts in lake levels due to rebound are relatively negligible. In Breckenridge (2013), which maps Superior Basin shorelines, warping is small, even between Epi-Duluth and Duluth phases. Therefore, the rerouting should be dominated by ice advance and retreat. Further, the focus of this figure is on the meltwater routing, rather than the specific morphologies of the lakes. Modeling results from Hu and Haseloff (2025) (<https://doi.org/10.1029/2025GL115184>) corroborate these observations. **We will add text to the manuscript highlighting these points and their relation to lake levels.** However, in the figure, for clarity we keep lake levels of the Superior Basin similar throughout to highlight the shifts in meltwater routing, rather than introducing additional visual complexity with lake level changes (particularly since the details and nuances of lake level changes are not discussed in the main text and the focus of this paper is not on lake level changes but instead on meltwater routing).

331: change wording here...the core was not "deposited"

Will clarify to “deposited the remaining sediments in the core”.

332: was capitalized in paragraph above

We will correct this.

375: why so ?

This is based on additional age constraints from Penprase et al. (2025), which provide terrace deposition and abandonment ages in line with this assertion. The additional geochronological context we will provide in the revised version of this manuscript will also help elucidate our logic here. **We will add additional text here to clarify this point.**

377: what is a "Readvance ice retreat" ?

We are referring to the retreat of the ice associated with the Marquette Readvance event of the Superior Lobe. **We will clarify the text here.**

390: these are seen also in the St. Louis region (see Hajic et al. / Grimley et al. references)

We will incorporate these and additional references provided by the reviewer to bolster connections between our sediment core and the St. Louis region to help bolster and clarify this section.