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**.

COMMENTS ON PENPRASE ET AL. MANUSCRIPT egusphere-2025-3920

GENERAL COMMENTS

This paper presents some good data but is not ready to be published. Although well-written, with good goals stated (lines 53-58), the paper has numerous shortcomings, the most important being the tenuous chronology of the sequence and its questionable links with external events. With only one OSL date below the weathered zone, the age extrapolation below the OSL date could have a variety of interpretations. I don't think the authors have chosen the best correlation of sequence with events in the Agassiz and Superior watersheds; I've elaborated on this below in SPECIFIC MAJOR CONCERNS.

The author team sends our thanks to the reviewer for their detailed comments and attention to improving our study. The highlighted areas of concern give us specific targets to address towards the overall goal – which we share with the reviewer – of improving the deglacial chronology and our understanding of how these large lakes and their spillways evolved over time.

We recognize the reviewer's concern over the chronology of our sediments (as noted in by the other manuscript reviewer). T**o address this shortcoming, we plan to add additional text to the discussion that will bolster our geochronological interpretations by citing previously published OSL and ^{10}Be data for our study area from Penprase et al. (2025). These geochronological constraints indicate that the sediments in our core must have been deposited after ~12.3 ka (^{10}Be upper regional terrace abandonment age) but before ~10.6 ka (^{10}Be lower regional terrace abandonment age). These bracketing ages provide additional geochronological constraints for the older sediments below the weathered zone in our core, which (as noted by this reviewer) are currently less well-constrained with the included OSL samples in this manuscript. We believe this additional geochronological context will bolster our chronology and connections to external events.**

I think a different, and perhaps shorter, title would be better. Your paper is more than just the recognition of the Marquette readvance, so I'd omit that part. Although the 3 M words in the title Meltwater, Mud, and Mississippi) are cute, I wonder if they are worth including. What about something like "*History of late-glacial overflow from the Superior and Agassiz watersheds as recorded in a slackwater sequence in the Upper Mississippi River basin*"?

We appreciate the reviewer's comments on the manuscript title and **will revise the title of the manuscript to "*History of late-glacial meltwater routing to the upper Mississippi River basin as recorded in a tributary river slackwater sequence".*** We remove the word overflow from the reviewer's suggested title and instead use "meltwater routing" because it is possible some of the meltwater delivery is not associated with overflow events.

Attributions of previous research on paleohydrological changes related to LIS meltwater flows are not adequate and many important references about continental & marine events should be added; see some suggested additions in the section below on MINOR CONCERNS.

We will review current manuscript text to identify places where additional citations are required, particularly in discussion of paleohydrology and LIS meltwater flows. We will also add the additional citations recommended by both reviewers to the updated manuscript text and will respond to additional notes on specific suggested additions in the MINOR CONCERNS section below.

SPECIFIC MAJOR CONCERNS

75-79 I don't follow what you're describing. How does a tributary pond breach a hydrological barrier in the main Mississippi River channel?

We are referring to the origin of meltwater floods in this paragraph, not referring to tributary ponds. **To clarify this point and clarify confusion over tributaries and meltwater flooding, we will split this single paragraph into two paragraphs to more clearly describe geomorphic change, slackwater deposition, and their drivers.**

Our proposed text for the first paragraph will include information following this language: "These ice margin fluctuations significantly changed the Mississippi River system. When ice margins were close to the Mississippi, they directly discharged both water and bed-load sediment to the river. This caused the Mississippi to steepen and aggrade (Knox, 1996). Mainstem Mississippi River aggradation raised base level for tributary rivers, which aggraded in turn (e.g. Faulkner et al., 2016). When the ice sheet retreated, proglacial lakes formed in front of retreating ice lobes. Meltwater discharge increased but bed-load sediment was trapped in these lakes. To restore its sediment load, this meltwater entrained sediments from the upper Mississippi valley, causing the Mississippi River to incise. This change in inputs to the Mississippi River caused it to incise, thereby lowering base level for its tributaries, which incised in turn. This incision generated flights of terraces along the Mississippi River and its tributaries."

The next paragraph will address the floods:
"Although proglacial lakes caused rivers to incise by trapping coarse sediments, fine sediments were able to pass through these lakes. High melt-season outflows were able to

overtop the river terraces, depositing layers of slackwater sediments across them."

244 As you indicate, your OSL date at ~150 cm in the "visibly weathered" upper zone is not reliable. You might mention why you concluded this, such as the uncertainty of the value used for water content, root disturbance, etc. So, why did you not get an OSL date from the lower part of the core (e.g. 270-375 cm), where there are a number of changes in the elements and their trends shown in Figure 5?

We thank the reviewer for pointing out this concern, because this comment makes it clear that we did not explain well. We have no reason to doubt the luminescence age itself. Its location in the core, within the weathered zone, means that we cannot assess the provenance of the sediments from which it was taken. However, this weathering would not impact the luminescence signal preserved within the quartz grains used for the OSL dating. Therefore, this sample does serve as a bracketing upper age on deposition of the main study units. Because its age is indistinguishable from the deeper OSL age, it also suggests one main phase of deposition ca. 11.6 ka.

Section 5 I do not agree with many of your interpretations/correlations in this section that relate zones in the core to the time of specific events in the Lake Agassiz and Lake Superior basins. With only 1 date below the weathered zone, there is no chronological control below the 11.56 +/-1.5 ka at 247 cm depth. My comments below begin with a disagreement on the age of 11.7 ka that you assign to the blocking of the eastern outlets of Lake Agassiz by the Marquette glacial readvance in the Superior basin. Indeed, the ice may have been readvancing in the Superior basin then, as you note by dates on the Gribben Forest Bed, but others have concluded that the blocking of the Agassiz outlets was closer to 11.4 ka (e.g. Clayton, 1983; Fisher, 2020; Fisher & Breckenridge, 2022). The text and Figure 7 should reflect that. Why not begin the story by assigning the clayey sediment just above the locally-derived sandy zone (with a high Si element content) to the first overflow events from Agassiz & Superior? For these reasons, and others noted below, your Phase interpretations need to be changed. Some specifics and suggestions follow:

In the revision phase of the manuscript, **we will include new age constraints that bolster the dates of our sediment, including terrace abandonment ages that bracket the deposition of our sediments to after 12.3 ka (10.6–14.0 ka; Penprase et al. 2025) but before 10.6 ka (7.3–13.7 ka; Penprase et al. 2025). These additional constraints will provide chronological control below the 11.56 ka at 247 depth age noted by the reviewer. We will respond to each of the details mentioned by the reviewer in the preceding paragraph as they go into more detail about each in the paragraphs below.**

352-358 I disagree with the words "following the initiation of the Marquette Readvance". You've left out 2500 years of the early phases of Lake Agassiz (the Lockhart and Moorhead). The wording and interpretation in your Phases 2-4 should be changed, or at least an alternative chronology and correlation should be given.

To the point raised by the reviewer about "just assigning the clayey sediment to the early phases of overflow from Agassiz and Superior", we hypothesize that the basal sandy sediments below are likely older. **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 ^{10}Be 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 (^{10}Be upper regional terrace abandonment age) but before ~10.6 ka (^{10}Be 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. **Based on information available in existing literature and informed by comments from both reviewers and comments made by this reviewer below, 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.

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.

Based on the reviewer's comments, we will update the chronology presented in the paper, with a few modifications. In the table below, we summarize the original chronology presented in the manuscript and the new modified chronology. We discuss our deviations from the reviewer's suggestions in the text following the table.

361- It doesn't seem to me that there is any significant rise or trend in Lake Superior basin major elements in the core just above 350 cm (Fig. 5) as you state, so I wouldn't conclude that the interval above 350 relates to the Marquette readvance and its blocking of the eastern outlets of Lake Agassiz. However, there is a rise above 310 cm, which I'd argue is the first re-direction of Lake Agassiz overflow into the Superior basin and then into the Mississippi River watershed (i.e. the shift from the Lockhart Phase to Moorhead Phase of Agassiz). Then, around 280 cm, after a peak in Superior basin elements, more Ca-rich waters appear in the core which dates the return of Agassiz overflow thru its southern outlet (River Warren) into the Mississippi basin related to the Marquette ice blocking its eastward overflow into the Superior basin—this interval is also reflected by the low Superior element input that then gradually rises as the Marquette ice retreats (275-250). Following this, there is a diminished Superior element input to the core site that relates to the re-direction of overflow eastward thru the Great Lakes from the Superior watershed.

Using the 11.4 ka (vs 11.7 ka) age for the blocking of the eastern outlets of Lake Agassiz by the Marquette, and using the same assumption that you did about the OSL age of 11.56 +/- 1.5 ka being too old, one could use a date of 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, as shown in Fig. 5. Below would be my suggested interpretation of Phases at the core site based on the above comments. Whatever your conclusions are, the Phase zones should be shown on Figure 5.

Phase A--below 400 cm: dominated by local sand (high Si) = pre-Agassiz and Superior watershed meltwater contributions (~pre-14 ka).

Phase B—400-315 cm: blend of Ca (Agassiz) and Fe, Cu, Ni (Superior) contributions from 2 watersheds, beginning ~14 ka and ending ~12.9 ka; Lockhart Phase of Lake Agassiz.

Phase C—315-280 cm; decline in Ca (Agassiz), rise in Superior elements with a peak near the end about 280-285 just as Marquette ice invaded Superior basin; Agassiz overflow east into Superior; Moorhead Phase of Agassiz when its waters stopped overflowing south into the Minnesota-Mississippi River basin, 12.9 to 11.4 ka.

Phase D—280-270 cm: jump in Ca (Agassiz), drop in Fe, Cu, Ni (Superior) elements during time when Marquette readvance blocked E outlets of Agassiz for a few hundred years.

Phase E—270-250 cm; decline in Ca, increase in Fe, Cu, Ni as Marquette ice retreats and Agassiz waters resume overflow eastward into Superior basin; Emerson Phase of Lake Agassiz ~10.7-10 ka.

Phase F—250- ; LIS retreats in Agassiz and Superior basins and overflow to core site from them ends.

410-415 I don't think your conclusions here are the best fit with the major element concentrations shown in Figure 5—above is my interpretation, although there may be alternatives for part of the sequence. And, a more elaborate statement and expansion of your conclusions should be presented here, including some of the rationale and plot of your Phases on Fig. 5.

We thank the reviewer for these considerations, and will revise the manuscript with a broader set of possible interpretations of the sediment sequence in mind.

MINOR CONCERNS (with line references)

By definition, throughout the paper "glacial" Lake Agassiz, should not be Glacial Lake Agassiz.

In the manuscript we are referring to Glacial Lake Agassiz as a proper noun, rather than using "glacial" as a descriptive adjective. However, per the reviewer's suggestion, **we will update Glacial Lake Agassiz in the text to glacial Lake Agassiz.**

20 "remapped"?

We will update this to "reworked" for clarity.

20-21 Lots of needed references to the shaping of the landscape morphology in Canada such as by Fisher, Teller, etc.

We will add additional references to these lines, including the ones noted by the reviewer.

21 Curious short selection of references to how these meltwaters "impacted glacial climate"; Broecker et al, (1989 Nature) as a start and modellers and continental Quaternarists should be added.

We will add the additional reference to this line, including the one noted by the reviewer.

24 Lots of continental research exists that is related to the history of Lake Agassiz that spans hundreds of kilometers (e.g. Teller, Fisher, Breckenridge, Colman, Leverington, etc.)—some should be cited.

We will add additional references and text to these lines, including the ones noted by the reviewer.

25 Many “marine sediment cores” have been studied with this in mind from the North Atlantic to the Gulf of Mexico to the Arctic Ocean, and some should be cited here.

We will review the literature, including Wickert et al. (2013) and Carlson et al. (2007) to find appropriate references discussing previous work on marine sediment cores relevant to marine sediment cores discussed in this point by the reviewer and add the appropriate additional references and text to Line 25 and throughout the manuscript.

40 Fisher (2020 QSR) and/or Fisher & Breckenridge (2022 QSR) would be better to cite here or some of Teller’s articles.

We will update this reference.

44 other Gulf of Mexico studies should be mentioned (e.g. Aharon 2003 Paleoceanography; Broecker et al., 1989; Flower, etc.).

We will add additional references and text to these lines, including the ones noted by the reviewer. We will review the Aharon 2003 paper to determine its relevance to the study because the sediments in that study are very coastline-proximal and some interpretations in these papers are more difficult to interpret than those from farther out in the Gulf.

70-71 not sure this 10.6 ka age is what recent research has concluded, and 10.0 ka may be closer to the time

Please see our updated chronology and response to the reviewer’s comments on the sequence of events in the MAJOR CONCERNS section above. We derive this 10.6 ka age from Wickert et al. (2023), as well as more proximal papers on ice retreat through Lake Superior (e.g. Breckenridge and Johnson, 2009; Wickert et al., 2023; Karrow et al., 2000; Breckenridge, 2007).

74 “observations” à studies of stratigraphic records along the river

We will update the text to read “decades of field observations of river stratigraphic records, supported by isotopic….”.

84 need at least a couple of references of Canadian authors from the Canadian side where the bulk of research on Lake Agassiz has occurred.

To address this comment and point to the extensive work the reviewer is referring to while keeping the focus of this work aligned on the southward routing of glacial meltwater, **we will add the text “Comprehensive reviews of Lake Agassiz's lake levels and meltwater routing history are synthesized in Fisher 2020; Fisher and Breckenridge 2022”.** We will also expand our review of the literature into works by Teller, Leverington, Thorleifson, and Lewis, and cite these where appropriate in the manuscript.

85 Gran et al. (2013) citation needs full reference in References section.

We will update this reference in the references section.

98 other references might be worth including here and for following sentences (e.g. Flock, 1983 QSR; Curry et al. 2014 QSR)

We will add additional references to this line, including the ones noted by the reviewer.

103 downstream in? our study area (OR, downstream of our study area in . . . . ?)

We will update the text to say "...deposited ~800 km downstream of our study area in the Mississippi River valley".

Section 4.2 A standard (simple) stratigraphic section description would be helpful here, with OSL ages on it.

This was noted by the other reviewer and will be included in the Section 4.2 of the revised version of the manuscript.

240 gray clay laminae (vs "beds")

We will update the text to say clay laminae.

283 delete "with depth"

Will do.

299 use "reflect" for the second word "capture"

Will do.

318 "markedly different"—describe how

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 just grain size.**

319 ". . . these grains are markedly similar ?in appearance? to local . . . . ??? A little elaboration on how they are similar would be worthwhile (frosted? rounded? stained?).

We will add more descriptive sedimentological terms, including 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.

326 We correlate the locally derived fluvial . . . .

We will update this sentence with this rewritten structure.

361 AfteràAbove

We will delete after in this sentence and update it to read "Above 350 cm…".

382 Is the St. Croix route low enough at this time to allow overflow from Superior?

Work in Breckenridge (2013), which shows shorelines and 14C ages from the Brule Spillway provide evidence that there was Superior overflow into the St. Croix River between 11.6-10.6 ka. Therefore, we do believe that the St. Croix route was low enough at this time to receive water from Superior.