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The timing of Missoula floods: Implications for the age of Grand Coulee (eastern Washington, USA)

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ABSTRACT

The Channeled Scabland of eastern Washington (USA) was formed by outburst floods from glacial Lake Missoula. Despite chronological advances, the timing of erosion in the main flood channels is unresolved. In particular, it is still uncertain whether upper Grand Coulee, the largest canyon in the Channeled Scabland, was incised during or prior to the last glaciation. We report ^{10}Be exposure ages from erratics in upper Grand Coulee, glacial Lake Columbia, and surrounding flood routes. Flood-transported boulders on the high-elevation east rim of Grand Coulee date to ca. 17–15 ka. Ages from boulders on the floor of Grand Coulee indicate later flooding at ca. 14 ka, which post-dated canyon incision and occurred after inundation of the Telford-Crab Creek scabland at ca. 15–14.5 ka. Prior hydraulic modeling and dating suggest the entrance to Grand Coulee was blocked by rock and that canyon incision was incomplete at ca. 17 ka; hence, we interpret the 17–15 ka exposure ages on the east rim to coincide with flow over a retreating cataract during canyon incision. Our results indicate incision of Grand Coulee was completed between 17 ka and 14 ka. The short duration of canyon incision suggests that glacial Lake Missoula generated some of the most erosive outburst floods in Earth's history.

INTRODUCTION

The Columbia Plateau in eastern Washington (USA; Fig. 1) was carved into a nexus of basalt-floored channels by Pleistocene outburst floods from glacial Lake Missoula (Bretz, 1923; Bretz et al., 1956; Baker, 1973; Lehnigk et al., 2024). Periodic failure of the Purcell Trench lobe of the Cordilleran ice sheet released at least 100 Missoula floods (O'Connor et al., 2020) between ca. 17 ka and 13 ka (Balbas et al., 2017; all exposure ages from Balbas et al., 2017, have been recalculated to be directly comparable with our ages, as described in the Supplemental Material[1]). Early Missoula flood(s) flowed down Columbia valley, but the Okanogan ice lobe then advanced across Columbia valley, where it impounded glacial Lake Columbia and blocked down-valley floods until at least ca. 14–15 ka (Balbas et al., 2017). When ice blocked Columbia valley, Missoula floods flowed into glacial Lake Columbia, which overtopped at whichever divide was lowest at the time, diverting water across the Columbia Plateau (Fig. 1A). The floods deeply incised Grand and Moses Coulees (Bretz, 1932; Hanson, 1970; O'Connor et al., 2020; Waitt, 2021) and eroded loess and scoured bedrock in the Cheney-Palouse and Telford-Crab Creek scabland tracts (Fig. 1B).

The largest canyon, upper Grand Coulee, formed by headward retreat of an ∼200 m-high cataract driven by floods that were diverted out of Columbia valley (Bretz, 1932; Lehnigk and Larsen, 2022). Canyon incision was completed when the cataract retreated entirely through the drainage divide separating Grand Coulee and Columbia valley, after which Grand Coulee became the lowest-elevation spillway (∼471 m; Fig. 1B) from glacial Lake Columbia, and hence the preferred route of Missoula floods (O'Connor et al., 2020). Cataract retreat removed the entirety of the Columbia River basalt in the upstream 15 km of Grand Coulee, exposing granitic rock (Bretz, 1932). Glacial striae on a granitic inselberg indicate the Okanogan lobe advanced into a fully incised Grand Coulee during the last, Marine Isotope Stage (MIS) 2, glaciation (Waitt et al., 2021), timing that is consistent with ^{36}Cl exposure ages from glacial erratics deposited on nearby Steamboat Rock (Keszthelyi et al., 2009). However, whether Grand Coulee was incised entirely during MIS 2 or reached its present depth during a prior glaciation is debated (O'Connor et al., 2020; Waitt et al., 2021).

OLD VERSUS RECENT INCISION

Evidence supporting pre–MIS 2 incision of Grand Coulee is based on the argument that Missoula flood beds should be thinner and finer-grained if deposited in a deep versus a shallow glacial Lake Columbia (Atwater, 1986). Glacial Lake Columbia would have been deep before upper Grand Coulee was incised but would have shallowed by ∼200 m following completion of cataract recession. Flood beds at the base of the Manila Creek section, which records deposition from 89 Missoula floods in glacial Lake Columbia, are thick and coarse-grained, leading to the inferences that glacial Lake Columbia was shallow at the onset of Missoula flooding and that upper Grand Coulee had completely incised prior to the last glaciation (Atwater, 1986).

Geomorphic evidence indicates a long-lived glacial Lake Columbia was graded to the ∼471 m elevation spillway into upper Grand Coulee, also indicating upper Grand Coulee was incised to its current elevation near the beginning of the last glaciation (O'Connor et al., 2020). Higher-level glacial Lake Columbia stages of 715–730 m, with Missoula floods temporarily raising stages to 750 m, are attributed to the Okanogan lobe advancing into and blocking the inlet to Grand Coulee (Waitt and Thorson, 1983; Atwater, 1986; O'Connor et al., 2020), rather than rock impounding a high-level lake, as well-developed shorelines are lacking at these higher elevations (Waitt, 2021).

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[1]Supplemental Material. Additional details on methods and samples. Please visit https://doi.org/10.1130/GEOL.S.26823814 to access the supplemental material; contact editing@geosociety.org with any questions.

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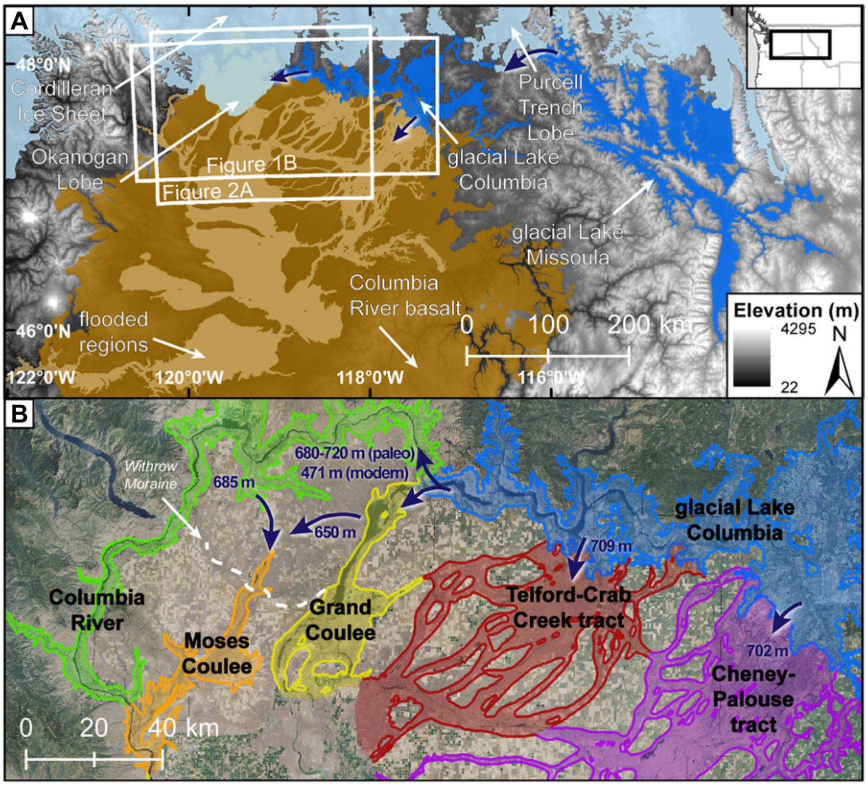

Figure 1. The study area (A) in the Channeled Scabland of eastern Washington (USA) showing the Columbia Plateau and Columbia River basalt (Burns et al., 2011), ice sheets, glacial lakes, and Missoula flood inundation (Ehlers et al., 2011). Inset: site location in the northwest United States. (B) Flood pathways, flow direction arrows, and glacial Lake Columbia spillover elevations (Waitt, 2021).

Evidence supporting MIS 2 incision of Grand Coulee is based on geological constraints and hydraulic modeling. Large flood bars downstream from Okanogan lobe moraine deposits show that Missoula flood(s) preceded blocking of Columbia valley by ice (Waitt, 2016). Exposure ages on high-elevation iceberg-rafted erratics deposited by those floods date to 16.9 ± 0.2 ka (Balbas et al., 2017; Fig. 2). Hydraulic models that route Missoula floods across the present-day topography predict that these erratics are not inundated because too much flow is routed through Grand Coulee, lowering flood stages downstream in Columbia valley (O'Connor et al., 2020; Denlinger et al., 2021). Only models where topography is reconstructed with rock filling a still-unincised upper Grand Coulee predict flood stages approaching the elevation of the erratics, indicating that incision of Grand Coulee was still incomplete at ca. 17 ka (O'Connor et al., 2020). The same hydraulic models predict a stage of ~730 m at the head of upper Grand Coulee, indicating water would have been diverted out of Columbia valley here prior to completion of coulee incision (O'Connor et al., 2020).

Further evidence for MIS 2 incision of upper Grand Coulee comes from a bar in Hartline basin (Fig. 2A) that contains gravel and sand clasts that were eroded from upper Grand Coulee and are nearly entirely composed of basalt, suggesting the cataract had not retreated far enough to unroof the granitic rock in the uppermost coulee when the bar was deposited (Waitt et al., 2021). Bretz (1932) described the weathering of the deposit as "almost perfectly fresh," implying deposition, and hence cataract retreat, during MIS 2.

Given the contradictory evidence, the enigmatic history of Grand Coulee continues to be debated (O'Connor et al., 2020; Waitt et al., 2021). Due to the huge volume of eroded rock, Bretz (1932) speculated that floods spanning two or more glaciations were required to incise Grand Coulee. In contrast, sediment transport constraints suggest upper Grand Coulee may have been eroded by only six floods (Lehnigk et al., 2024). Hence, determining when Grand Coulee formed yields insights on the history of outburst flooding on the Columbia Plateau, and, more generally, the time scales required for bedrock canyon formation by outburst floods.

SAMPLE COLLECTION AND ANALYSIS

We dated 28 granitic samples from Grand Coulee and adjacent flood routes using *in situ*–produced ^{10}Be. Exposure ages were calculated following the method of Balco et al. (2008). We report ages and internal uncertainties from our samples and recalibrated ages from Balbas et al. (2017) using production rate calibration data from Promontory Point, Utah (Borchers et al., 2015; Lifton et al., 2015), and Lifton et al. (2014) scaling. Sample information and analytical details are reported in the Supplemental Material.

EXPOSURE AGES AND INTERPRETATIONS

Grand Coulee and Ephrata Fan

Two high-elevation (>700 m) iceberg-rafted erratics deposited on the east rim scabland of upper Grand Coulee date to 15.2 ± 0.5 ka and 17.1 ± 0.5 ka (Figs. 2 and 3). We classify a nearby erratic with an age of 21.2 ± 0.5 ka as an outlier due to potential inherited ^{10}Be but note that this age agrees with the timing of marine freshwater pulses inferred to originate from glacial Lake Missoula (Lopes and Mix, 2009). The erratics could have been deposited either by broad, shallow floods when the cataract in upper Grand Coulee was still retreating toward Columbia valley or, alternatively, after upper Grand Coulee had completely incised, when the Okanogan lobe advanced into the coulee, forcing overflow from glacial Lake Columbia to drain around the ice (Lehnigk and Larsen, 2022). The short duration of Missoula flooding relative to the age uncertainties makes it difficult to distinguish between these possibilities based on ages alone. However, given that the 17.1 ± 0.5 ka age aligns closely with the 16.9 ± 0.2 ka age of the Wenatchee erratics (Balbas et al., 2017), which must have been emplaced by floods that occurred prior to incision of upper Grand Coulee (O'Connor et al., 2020), we infer that the erratics on the east rim were emplaced when cataract retreat through upper Grand Coulee was ongoing.

Ages of boulders on the Paynes Gulch bar on the floor of upper Grand Coulee, which were entrained from bedrock after floods eroded the overlying basalt, range from 12.7 ± 0.7 ka to 14.5 ± 0.6 ka with a mean of 13.6 ± 0.5 ka ($n = 9$). The exposure age of a bedrock sample on the floor of upper Grand Coulee is 13.3 ± 0.6 ka. Because the samples on the coulee floor originated from beneath ~200 m of Miocene-age basalt, they are unlikely to have inherited ^{10}Be. The spread in ages is potentially related to post-exposure erosion, such that the deposit age may be best characterized by the older ca. 14 ka ages. Two samples from flood-transported boulders on the Ephrata Fan, downstream of Grand Coulee ($n = 2$), when evaluated with samples from Balbas et al. (2017), yield a mean age of 14.5 ± 0.6 ka ($n = 9$) (Fig. 3) that constrains the minimum timing of unroofing of granitic rock in upper Grand Coulee.

The youngest and oldest high-elevation erratics on upper Grand Coulee's east rim pre-date deposition of the oldest Paynes Gulch bar sample by 0.7 ± 0.8 k.y. and 2.6 ± 0.8 k.y. (±1 standard deviation error propagation), respectively, indicating that upper Grand Coulee conveyed Missoula floods for less than a few millennia. Given our

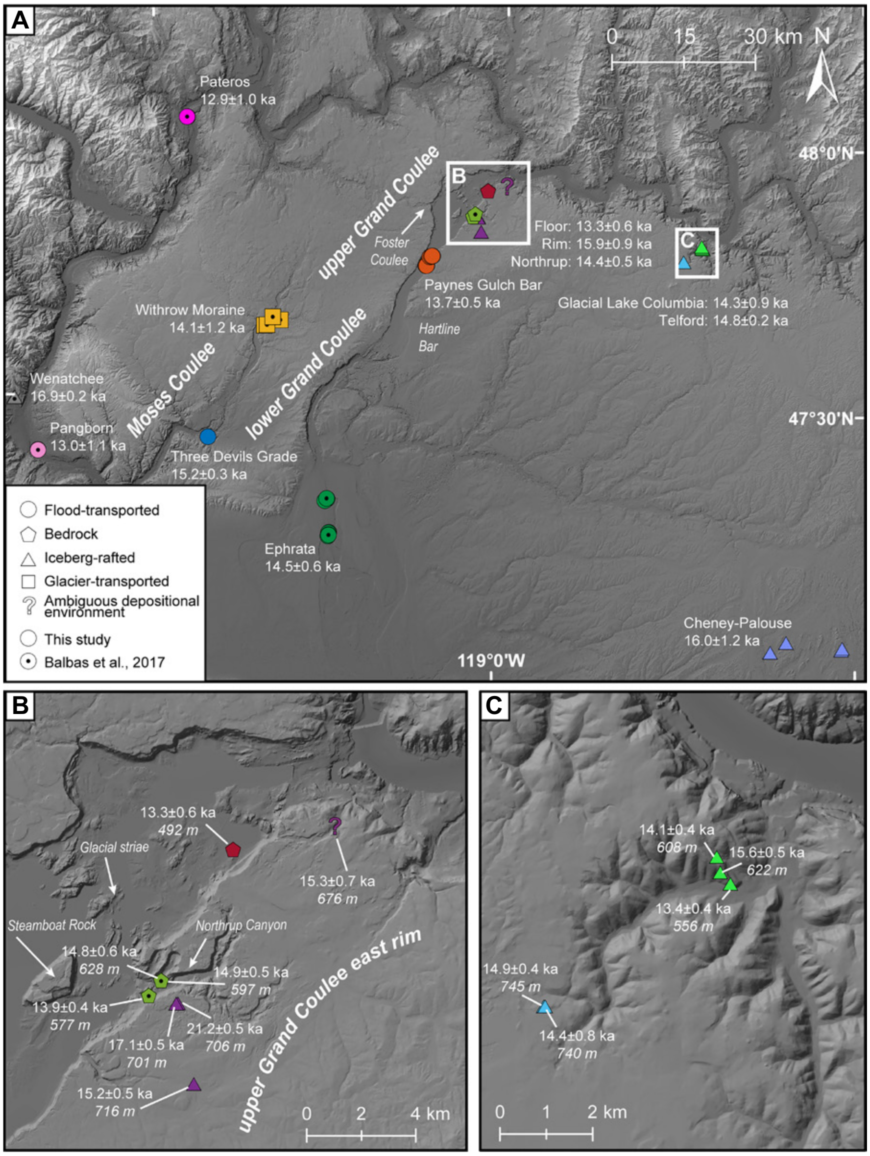

Figure 2. (A) Sample locations, elevations, and exposure ages in the Channeled Scabland, including ages from Balbas et al. (2017). Location shown in Figure 1A. (B, C) Ages of samples in upper Grand Coulee (B) and the Telford-Crab Creek scabland and glacial Lake Columbia (C).

interpretation that the erratics on the east rim were deposited during cataract retreat, the time scale for completing incision of upper Grand Coulee was similar. The ages on the coulee floor also indicate the Okanogan lobe had retreated from upper Grand Coulee, but still blocked Columbia valley, prior to ca. 14 ka, otherwise floods would have been routed down Columbia valley rather than through Grand Coulee. Small floods and the Columbia River itself would have flowed through Grand Coulee until re-opening of the Columbia valley by retreat of the Okanogan lobe (Atwater, 1987) at ca. 13 ka (Balbas et al., 2017; Fig. 3).

Telford-Crab Creek and Glacial Lake Columbia

Ages of two ice-rafted erratics at the head of the Telford-Crab Creek tract at elevations of 745 m and 740 m are 14.9 ± 0.4 ka and 14.4 ± 0.8 ka, respectively (Figs. 2B and 3). The elevations correspond to the stage of a flood-swollen glacial Lake Columbia (Waitt and Thorson, 1983; Atwater, 1986; O'Connor et al., 2020), and the ages are similar to the ca. 14–15 ka initiation of Okanogan lobe retreat from the Withrow moraine (Balbas et al., 2017). We interpret the ages to constrain the timing of Missoula floods overtopping glacial Lake Columbia and spilling into the Telford-Crab Creek tract when the entrance to an already-incised upper Grand Coulee was blocked by the Okanogan lobe. The maximum age of the glacial Lake Columbia high-stand (14.9 ± 0.4 ka) overlaps with, but postdates, the latest possible estimate of erosion through the upper Grand Coulee drainage divide of 15.2 ± 0.5 ka, which is consistent with prior interpretations that upper Grand Coulee was fully incised prior to subsequent closure by Okanogan lobe ice (Bretz, 1932; Atwater, 1987; Waitt et al., 2021). The ages also indicate that blockage of upper Grand Coulee by ice occurred within centuries or less following its incision. Ages from lower-elevation (556–622 m) ice-rafted erratics in the glacial Lake Columbia basin range from 15.6 ± 0.5 ka to 13.4 ± 0.4 ka and indicate lake stages exceeded the ~471 m elevation of the upper Grand Coulee threshold during this interval.

Cheney-Palouse

Ages of four ice-rafted erratics in the Cheney-Palouse tract (Fig. 2) range from 13.9 ± 0.6 ka to 17.8 ± 0.7 ka, spanning nearly the entire duration of flooding observed in other flood routes (Fig. 3), but more dates are needed to assess whether exposure age populations reveal the timing of distinct floods. Hydraulic modeling indicates the Cheney-Palouse scabland was likely inundated by Missoula floods for all ice margin scenarios and both prior to and after incision of upper Grand Coulee (Denlinger et al., 2021). Hence, though these ages do not constrain the timing of Grand Coulee incision, they are consistent with hydraulic predictions.

Moses Coulee

Two erratics from a Moses Coulee flood bar have ages of 14.9 ± 0.3 and 15.6 ± 0.4 ka (Fig. 3). The erratics are small (see the Supplemental Material) and hence are interpreted to constrain the minimum timing of Moses Coulee flooding because it is possible they were exhumed, but the oldest age overlaps with the 17.4–15.5 ka age range reported for Moses Coulee flooding (Gombiner and Lesemann, 2024). If Missoula floods inundated Moses Coulee (Hanson, 1970; O'Connor et al., 2020; Waitt, 2021), hydraulic modeling indicates floods of sufficient volume only enter Moses Coulee if Grand Coulee is not yet incised, because discharge through upper Grand Coulee lowers flood stages at Moses Coulee inlets (O'Connor et al., 2020). The only scenario in which hydraulic models predict Moses and Grand Coulees are completely and simultaneously flooded is when upper Grand Coulee is not fully incised and the Okanogan lobe blocks Columbia Valley downstream from Moses Coulee (Denlinger et al., 2021). The similar timing of flooding in Moses Coulee (17.4–15.5 ka; Gombiner and Lesemann, 2024) and on the east rim of upper Grand Coulee (17.1 ± 0.5 ka to 15.2 ± 0.5 ka; Fig. 3) is consistent with these hydraulic modeling results. It has been proposed that Moses Coulee floods originated subglacially (Gombiner and Lesemann, 2024), but there were likely many Missoula floods during the centuries between the blocking of Columbia valley and the closure of the Moses Coulee flood route by the advancing Okanogan lobe. Moses Coulee would have conveyed floods at that time if upper Grand Coulee had not yet incised (Baker, 1978; O'Connor et al., 2020); hence, the Moses Coulee flood chronology is consistent with our

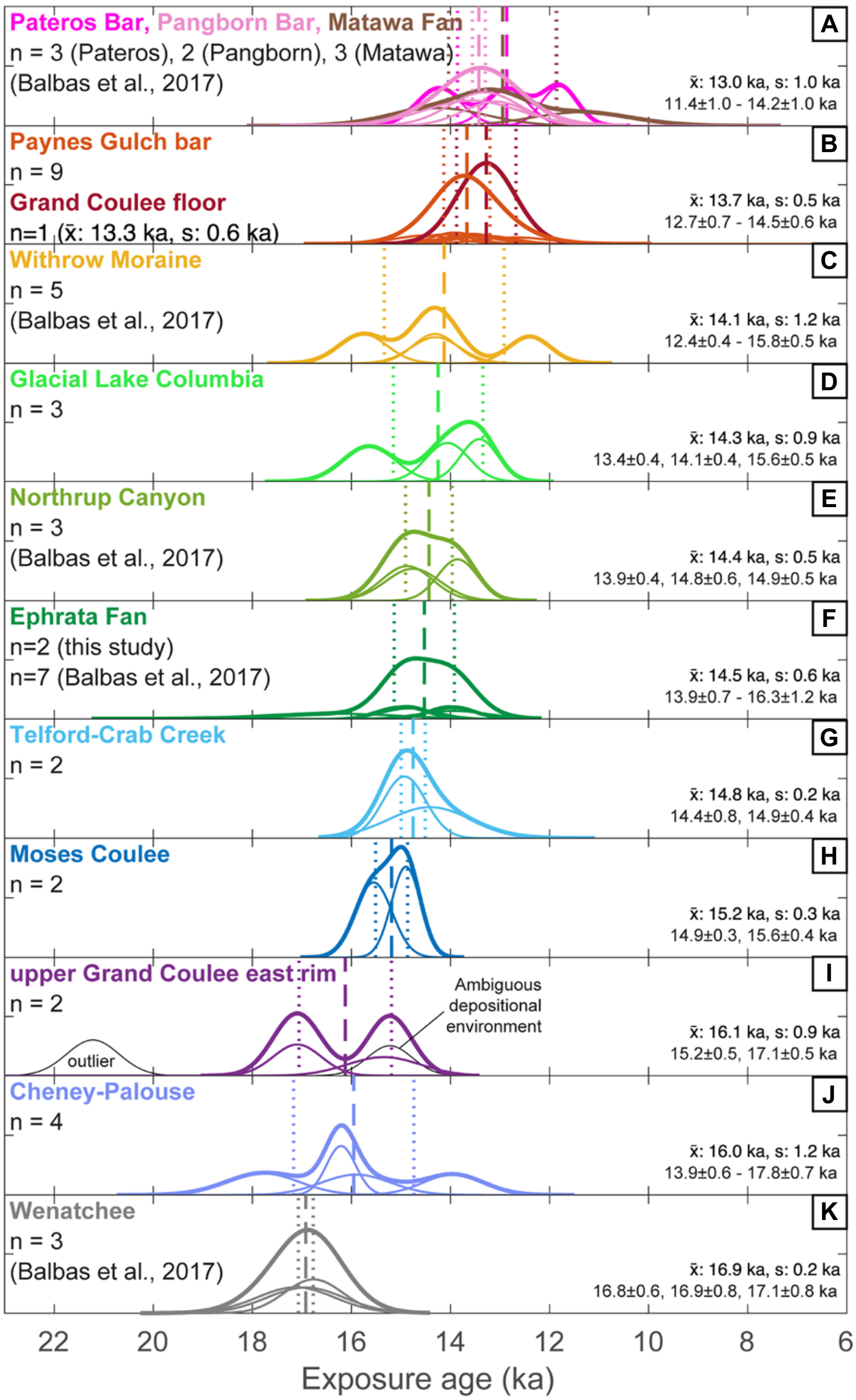

Figure 3. Chronology of flooding in the Channeled Scabland. Kernel density functions with probabilities ranging from 0 to 1 for individual samples (thin lines) and all samples from the same landform (thick lines), including the mean (dashed lines) and standard deviation (dotted lines). Outliers are shown in gray. The sample size (n), mean (x̄), standard deviation (s), and age range of individual ages are listed for each group of samples.

interpretation that incision of upper Grand Coulee was completed during MIS 2, rather than during a prior glaciation.

CONCLUSION

We interpret that our dating and results from prior work (e.g., Baker, 1978; Keszthelyi et al., 2009; Balbas et al., 2017; O'Connor et al., 2020; Denlinger et al., 2021; Waitt et al., 2021) indicate a sequence where (1) Missoula flood(s) flowed down Columbia valley before upper Grand Coulee was fully incised at ca. 17 ka; (2) the Okanogan lobe advanced across Columbia valley and impounded glacial Lake Columbia, diverting Missoula floods across the Columbia Plateau and incising upper Grand Coulee at ca. 17–15 ka; (3) the Okanogan lobe advanced into a fully incised Grand Coulee, raising the stage of glacial Lake Columbia and diverting Missoula floods into the Telford-Crab Creek tract at ca. 15.0–14.5 ka; and (4) flooding through a fully incised Grand Coulee deposited the Paynes Gulch bar at ca. 14 ka (Fig. 4).

Exposure ages indicate Missoula floods occurred from ca. 17 to 13 ka. The short duration of flooding and the uncertainty in exposure ages make it challenging to differentiate the timing of the closely sequenced events at Grand Coulee. However, our interpretation that the erratics on the east rim of upper Grand Coulee are related to cataract retreat at ca. 17–15 ka is supported by hydraulic modeling (O'Connor et al., 2020), sediment composition (Waitt et al., 2021), and relative weathering (Bretz, 1932) constraints. The Missoula flood record in glacial Lake Columbia (Atwater, 1986) can be reconciled with MIS 2 formation of upper Grand Coulee if incision was completed early in the flood sequence (O'Connor et al., 2020) by floods that pre-date the lake. Our findings suggest that the largest canyon in the Channeled Scabland was incised in a few thousand years or less, and the short duration indicates the Missoula floods were exceptional agents of landscape evolution.

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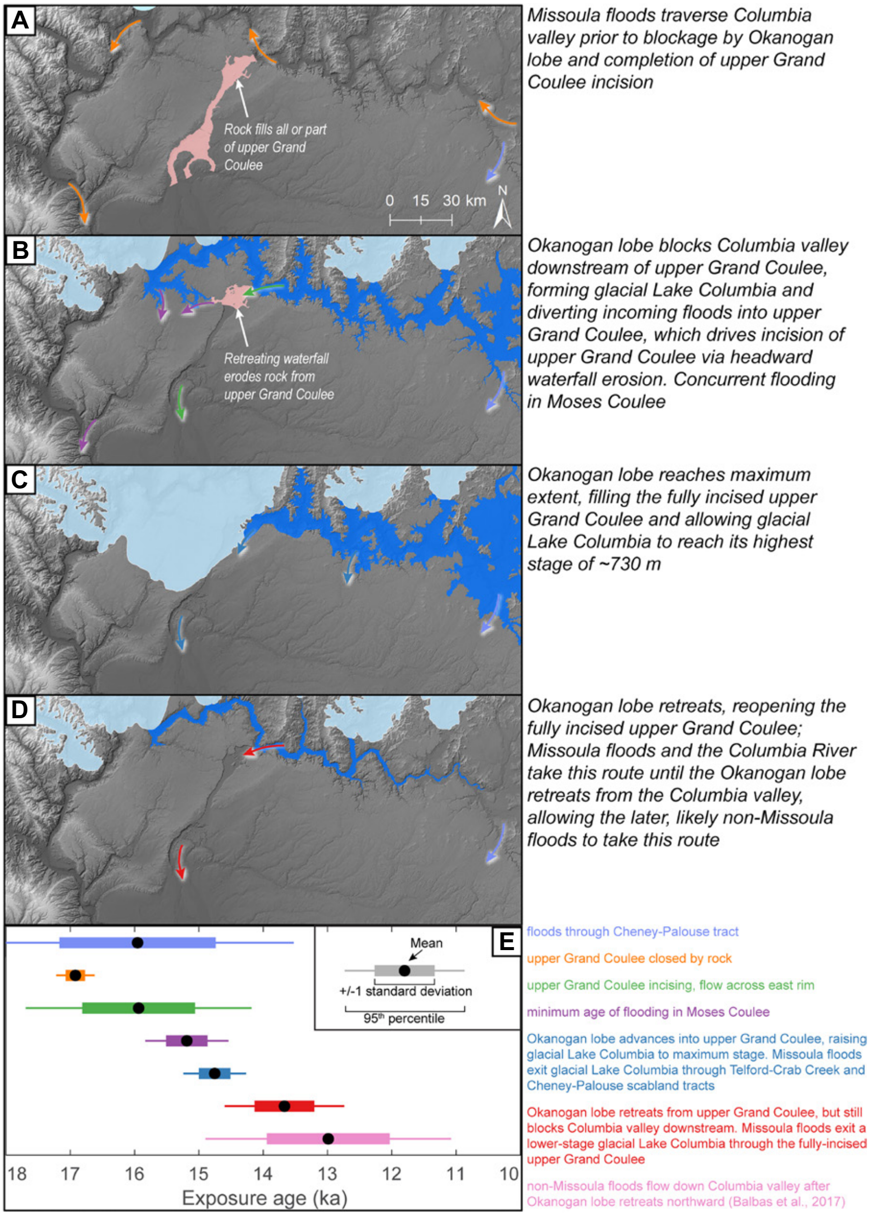

Figure 4. (A–D) Sequence of events inferred from exposure ages from this study and from Balbas et al. (2017), adapted from O'Connor et al. (2020). Colored arrows refer to events in panel E. (E) Timing of events related to incision of Grand Coulee in the Channeled Scabland.

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