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^{10}Be dating of late Pleistocene megafloods and Cordilleran Ice Sheet retreat in the northwestern United States

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ABSTRACT

During the late Pleistocene, multiple floods from drainage of glacial Lake Missoula further eroded a vast anastomosing network of bedrock channels, coulees, and cataracts, forming the Channeled Scabland of eastern Washington State (United States). However, the timing and exact pathways of these Missoula floods remain poorly constrained, thereby limiting our understanding of the evolution of this spectacular landscape. Here we report cosmogenic ^{10}Be ages that directly date flood and glacial features important to understanding the flood history, the evolution of the Channeled Scabland, and relationships to the Cordilleran Ice Sheet (CIS). One of the largest floods occurred at 18.2 ± 1.5 ka, flowing down the northwestern Columbia River valley prior to blockage of this route by advance of the Okanogan lobe of the CIS, which dammed glacial Lake Columbia and diverted later Missoula floods to more eastern routes through the Channeled Scabland. The Okanogan and Purcell Trench lobes of the CIS began to retreat from their maximum extent at ca. 15.5 ka, likely in response to onset of surface warming of the northeastern Pacific Ocean. Upper Grand Coulee fully opened as a flood route after 15.6 ± 1.3 ka, becoming the primary path for later Missoula floods until the last ones from glacial Lake Missoula at 14.7 ± 1.2 ka. The youngest dated flood(s) (14.0 ± 1.4 ka to 14.4 ± 1.3 ka) came down the northwestern Columbia River valley and were likely from glacial Lake Columbia, indicating that the lake persisted for a few centuries after the last Missoula flood.

INTRODUCTION

During the late Pleistocene, dozens of megafloods from glacial Lake Missoula in western Montana (United States) resulted from repeated breaching of the Purcell Trench lobe of the Cordilleran Ice Sheet (CIS). These floods traveled across eastern and central Washington State, ultimately draining into the Pacific Ocean (Fig. 1). In contrast to a model-based scenario positing a sequence of relatively small flood discharges eroding one of the many scabland channels impacted by glacial Lake Missoula outburst flooding (Larsen and Lamb, 2016; Perron and Venditti, 2016), field evidence and paleohydraulic calculations provide clear evidence of immense flood flows. The huge valley cross sections of the Rathdrum Prairie (Idaho) and Columbia Gorge were inundated, but not appreciably modified, by the largest of the Missoula floods, which had peak discharges of 10–20 × 10^6 m^3 s^{-1} or more (Baker, 1973; Benito and O'Connor, 2003; O'Connor and Baker, 1992; O'Connor et al., 2013), making these the largest known freshwater floods in Earth's geologic record. The specific routes taken by these floods depended on their peak discharge and the position of the Okanogan lobe of the CIS. When this lobe was at or near its maximum extent, it blocked the northwestern Columbia River in Washington, thereby forming glacial Lake Columbia and diverting the floods south across higher routes in eastern Washington. These floods, in part following channels cut by earlier Quaternary megafloods (Bjornstad et al., 2001), eroded the spectacular complex of anastomosing bedrock channels, coulees, cataracts, and immense gravel bars that compose the Channeled Scabland (Bretz, 1928) (Fig. 1).

Although the relative timing of flood-routing history is reasonably well known (Atwater, 1986; Baker et al., 2016; Waitt, 2016), there are few constraints on the ages of flood-related erosional and depositional features, limiting our ability to assess landscape evolution with respect to flood discharge and routes (Denlinger and O'Connell, 2010). The existing terrestrial chronology suggests that the last period of Missoula floods occurred sometime after 22 ka and ended sometime after 16 ka, with large uncertainties in this age range (Benito and O'Connor, 2003; Waitt, 2016). This chronology is based on seven maximum-limiting ^{14}C ages (Benito and O'Connor, 2003; Waitt, 2016), a floating varve chronology anchored by one ^{14}C age on reworked wood (Atwater, 1986), the Mount St. Helens ash set "S" volcanic ash with an imprecise age estimate (Benito and O'Connor, 2003; Clague et al., 2003), and the age of the Bonneville flood (from Lake Bonneville, ca. 18 ka; Oviatt, 2015). These dates and stratigraphic relations among deposits and flood features indicate that earlier floods were larger than later ones (Atwater, 1986, 1987; Benito and O'Connor, 2003; Waitt, 1985). Few ages, however, directly date the specific timing of flood events or of specific flood pathways.

To improve the flood chronology, we present 32 ^{10}Be ages from granitic boulders deposited by ice rafting or on flood bars or granitic bedrock associated with distinct flood pathways (Fig. 1). We also report 13 ^{10}Be ages on granitic boulders from terminal moraines deposited by the Purcell Trench and Okanogan lobes, which controlled flood origin and routing. Forty of these ages are new, to which we add five published but recalibrated ^{10}Be ages that date retreat of the Purcell Trench lobe (Breckenridge and Phillips, 2010). Our analysis does not include six ages apparently affected by prior exposure or post-depositional movement. ^{10}Be ages were calculated using the CRONUS-Earth web calculator (v. 2.0, http://web1.ittc.ku.edu:8888/2.0/) with a global production rate (3.92 ± 0.31 atoms g^{-1} a^{-1}) based on the nuclide and time-dependent scaling framework of Lifton et al. (2014). Other scaling schemes do not significantly alter the results or interpretations of our ages. Details of all sampled boulders

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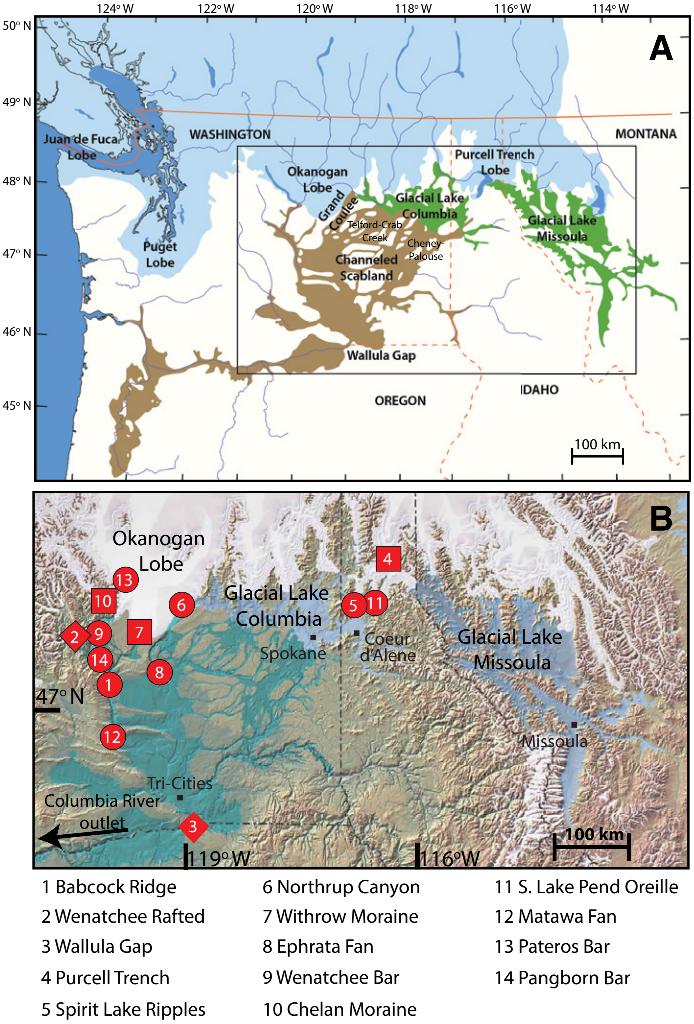

Figure 1. Maps of the Pacific Northwest (United States) during the late Pleistocene. A: Map of Pacific Northwest with blue regions representing maximum extent of Cordilleran Ice Sheet, green regions representing glacial lakes, and brown regions representing flood-inundated areas. Region outlined by black rectangle is area shown in panel B. B: Map showing sample locations (red symbols). Base map is adapted with permission from Ice Age Floods Institute (Richland, Washington, USA). Circles represent flood-deposited boulders; squares, glacier-deposited boulders; and diamonds, ice-rafted boulders. Individual site numbers are shown within each symbol and correspond to Figure 2 and to Figures DR1–DR49 (see footnote 1).

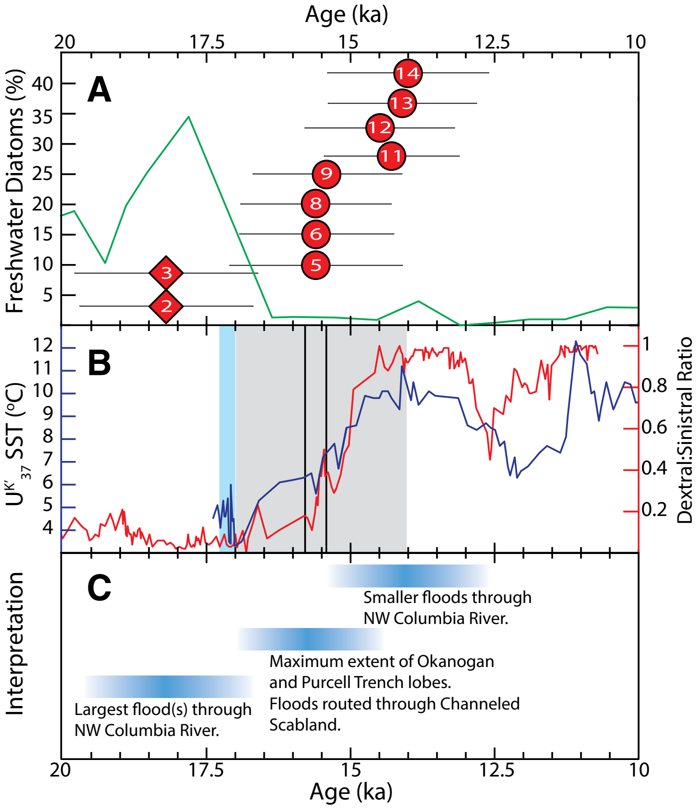

Figure 2. Summary of ^{10}Be surface exposure ages and their interpretation. A: ^{10}Be surface exposure ages from flood-deposited features (Fig. 1B; Figs. DR1–DR49 and Table DR1 [see footnote 1]) compared with diatom record from northeast Pacific. Circles represent ages on flood-deposited boulders except for Northrup Canyon (site 6), which is on bedrock; diamonds represent ages on ice-rafted boulders. All errors are reported at 1σ and include uncertainty in ^{10}Be production rate. Green line represents percent of freshwater diatoms from northeast Pacific and indicates pulses of large flooding events (Lopes and Mix, 2009). B: Mean ages for Withrow moraine of Okanogan lobe (site 7, 15.4 ka) and Purcell Trench Lobe (site 4, 15.7 ka) are shown as vertical black lines, and range of uncertainty for these two ages (1σ error) is shown as gray rectangle. Age and its uncertainty of maximum extent of Puget lobe (see text) is shown as blue rectangle. Proxy records of sea-surface temperatures (SST) from Santa Barbara Basin (offshore California) (red line: ratio of dextral to sinistral *Neogloboquadrina pachyderma*) (Hendy et al., 2002) and Gulf of Alaska (blue line: alkenone-derived paleotemperature [$U^{K'}_{37}$]) (Praetorius et al., 2015). C: General interpretation of flood and glacier events as constrained by new ^{10}Be ages.

and their ages are provided in the GSA Data Repository[1] and Tables DR1–DR3 therein.

RESULTS

We sampled boulders from three sites to constrain the age of one or more exceptionally large late Pleistocene floods. Three ice-rafted boulders near Wenatchee, Washington, lie 225–245 m above the Columbia River (420–440 m above sea level) and date to 18.2 ± 1.5 ka (site 2 in Fig. 1B; Table DR2). The general absence of ice-rafted erratics or other flood features at significantly higher elevations (Waitt, 2016) indicates that these samples represent the largest late Pleistocene flood(s) in the upper Columbia River valley. This age is similar to that of an ice-rafted erratic (18.2 ± 1.6 ka) at Wallula Gap (site 3 in Figs. 1B and 2A) that is just 25 m below evidence for the highest flooding (365 m above sea level) at this constriction (O'Connor and Baker, 1992). We also obtained an age of 23.0 ± 1.9 ka from a single ice-rafted boulder (site 1 in Fig. 1B) at a similar height above the Columbia River (219 m) as the 18.2 ± 1.5 ka erratics near Wenatchee (site 2). But additional samples are required to confirm whether this sample represents an older, similar-size flood or is from the ca. 18.2 ka flood but gives an older age because of ^{10}Be inheritance.

Blockage of the upper Columbia River by the Okanogan lobe created glacial Lake Columbia and diverted Missoula floods southward across the Columbia Plateau through the Channeled Scabland (Fig. 1). Grand Coulee was one of the primary flood routes during this time, and whether or not the upper portion of the coulee was open to its present depth affected the stage of glacial Lake Columbia and overall flood routing (Fig. 1A) (Atwater, 1986, 1987; Bretz, 1932). To constrain the timing of the opening of upper Grand Coulee, we obtained three ^{10}Be ages from exposures of granite bedrock near the mouth of Northrup Canyon (site 6 in Fig. 1B).

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[1] GSA Data Repository item 2017193, supplemental figures and information on age results, individual site maps, sampled boulders, and flood routes, along with ^{10}Be analytical data from this study, is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.

The Northrup Canyon cataract complex is adjacent to upper Grand Coulee and has a geomorphic position and elevation such that substantial flow into the canyon was unlikely if upper Grand Coulee was open and at its present depth (Bretz, 1932). The sampled granite was exhumed by flood erosion of the overlying Columbia River Basalt as the upper Grand Coulee and Northrup Canyon cataracts retreated headward toward the Columbia River (Bretz, 1932). Our ages thus indicate that the last major erosion in Northrup Canyon occurred at 15.6 ± 1.3 ka (Fig. 2A), indicating that upper Grand Coulee likely opened after this time.

To determine when the southern margin of the Okanogan lobe retreated from its maximum extent, we obtained four ^{10}Be ages on erratics from the Withrow moraine (site 7 in Fig. 1B), which marks the maximum position of the lobe. These indicate that onset of lobe retreat began at 15.4 ± 1.4 ka (Fig. 2B), which is slightly older than two ^{10}Be ages averaging 14.5 ± 1.2 ka from boulders on the crest of a lateral moraine deposited by the Okanogan lobe flowing down the Columbia River valley and up the Chelan trough (site 10 in Fig. 1B). Five ^{10}Be ages from a prominent lateral moraine marking the maximum late Pleistocene extent of the Purcell Trench lobe (site 4 in Fig. 1B) suggest that lobe retreat began at 15.7 ± 1.3 ka (Breckenridge and Phillips, 2010) (Fig. 2B), similar to our ages for onset of retreat of the Okanogan lobe from the Withrow moraine.

When recalculated using the CRONUS-Earth web calculator (v. 2.0), previously published ^{36}Cl ages from the Withrow moraine (Swanson and Caffee, 2001) are significantly older (22.3 ± 0.8 to 29.4 ± 0.8 ka) than our ^{10}Be ages (13.5 ± 0.4 to 17.1 ± 0.5 ka). Because recalculated ^{36}Cl ages from the Puget Lowland (western Washington; 22.3 ± 0.7 to 29.2 ± 0.7 ka) are significantly older than the well-established ^{14}C deglacial chronology (<17 ka), we conclude that the published ^{36}Cl ages are systematically too old, perhaps due to inheritance, although the boulders we sampled did not seem to have this problem. The Swanson and Caffee (2001) analysis was an early study, and subsequent considerable progress has been made in the application of ^{36}Cl. For example, some of the earlier works suffered from an incorrect estimation of Cl concentrations.

We dated several boulder bars at lower elevations, indicating that they were likely formed by later, smaller floods. Seven ^{10}Be ages on flood-transported boulders on the surface of the immense Ephrata fan just downstream from Grand Coulee (site 8 in Fig. 1B) give a mean age of 15.6 ± 1.3 ka (Fig. 2A). We also dated boulders from four flood bars in the upper Columbia Valley formed after retreat of the Okanagan lobe (Waitt, 2016) (sites 9, 12, 13, and 14 in Fig. 1B) that had average ^{10}Be ages ranging from 14.0 ± 1.4 ka to 15.4 ± 1.3 ka (Fig. 2A).

To determine the timing of the last of the Missoula floods, we sampled boulders on the floor of the Rathdrum Prairie valley just downstream from the point of release of Missoula floods (sites 5 and 11, Fig. 1B). We obtained three ^{10}Be ages on large boulders from the surface of megaripples near Spirit Lake (site 5) and one age on a boulder that is immediately adjacent to Lake Pend Oreille (site 11). Because these two sites are within 20 km of each other and are in positons where they would have been disrupted by subsequent flooding, we combine these ages (excluding sample RAT-04 as an outlier) to derive an average ^{10}Be age of 14.7 ± 1.2 ka (see the Data Repository; Table DR2).

DISCUSSION

Our new ^{10}Be ages establish a regional chronological framework for understanding late Pleistocene Missoula floods and their interaction with fluctuations of the southern margin of the CIS (Fig. 2C). Our oldest ^{10}Be ages (18.2 ± 1.5 ka) are on high-elevation ice-rafted erratics along the northwestern Columbia River and Wallula Gap. Their ages and position show that the largest late Pleistocene floods followed the Columbia River valley before blockage by the Okanogan lobe. This early phase of largest flooding is consistent with other evidence for early large floods from the upper Columbia River (Waitt, 1994, 2016) and the Columbia Gorge (Benito and O'Connor, 2003). The 18.2 ± 1.5 ka age for this flood and the similar ca. 18 ka timing of the Lake Bonneville flood (Oviatt, 2015), which had twice as much water as the largest Missoula flood (O'Connor, 1993), both correspond to a large low-salinity anomaly in the northeast Pacific at that time (Lopes and Mix, 2009) (Fig. 2A).

These ages also bear on the history of the Okanogan and Purcell Trench lobes of the CIS. In particular, the evidence that the largest late Pleistocene flood(s) came down the northwestern Columbia River at 18.2 ± 1.5 ka requires that the Okanogan lobe had not yet advanced across the Columbia River valley (Fig. DR50 in the Data Repository). But if these floods were from glacial Lake Missoula, the Purcell Trench lobe must have advanced to near its maximum position in the Clark Fork valley to create the lake by ca. 18.2 ka.

Our new moraine ages indicate that the Okanogan and Purcell Trench lobes began to retreat at 15.4 ± 1.4 ka and 15.7 ± 1.3 ka, respectively. Retreat of these lobes seems to be later than the retreat of the Puget lobe of the CIS to the west (Fig. 1A), based on our recalibration (IntCal13 calibration curve; Reimer et al., 2013) of the ^{14}C ages constraining the advance and retreat reported by Porter and Swanson (1998), which indicates that the Puget lobe began to retreat between 17.0 and 17.2 ka. This age is significantly older (at 1σ) than the ^{10}Be age constraints on retreat of the Okanogan and Purcell Trench lobes (Fig. 2B). We attribute this difference in timing to two independent controls on ice-margin retreat. A large increase in flux of ice-rafted debris in records from the northeast Pacific suggests rapid retreat of the marine-based Juan de Fuca lobe (Fig. 1A) at ca. 17 ka, which may have been induced by subsurface warming at the grounding line (Taylor et al., 2014). This dynamically triggered drawdown of the Juan de Fuca lobe then likely initiated retreat of the adjacent Puget lobe, which had a common catchment (Fig. 1A). In contrast, because the terrestrial Okanogan and Purcell Trench lobes were not influenced by marine-ice dynamics, their fluctuations would have largely been controlled by changes in surface mass balance. Our ages indicating onset of retreat at ca. 15.5 ka possibly indicate a surface mass balance response to the widespread increase of northeast Pacific sea-surface temperatures at this time (Fig. 2B) (Hendy et al., 2002; Praetorius et al., 2015; Praetorius and Mix, 2014), with the warming signal transmitted inland to the CIS margin by the atmosphere.

Advance of the Okanogan lobe to its maximum extent blocked the upper Columbia River and diverted Missoula floods southward, including through Grand Coulee (Waitt, 2016). One scenario permitted by our results is that Grand Coulee was partly filled with ice during the maximum extent of the Okanogan lobe, shunting flood flow into the Cheney-Palouse scabland tract southwest of Spokane (Fig. 2B) as well as onto the uplands to the east of Grand Coulee and into Northrup Canyon (Fig. DR50). This high-elevation glacial Lake Columbia would have persisted until Okanogan lobe ice vacated upper Grand Coulee associated with onset of ice-margin retreat at 15.4 ± 1.4 ka (e.g., Atwater, 1987), also marked by final erosion of the Northrup Canyon cataracts at 15.6 ± 1.3 ka. Another possible scenario is that the upper Grand Coulee cataract complex did not breach to the Columbia Valley until after 15.6 ± 1.3 ka, facilitated by Missoula flood diversion into an ice-free lower Grand Coulee during the maximum extent of the Okanogan lobe. While speculative, this second scenario is consistent with our ^{10}Be age of 15.6 ± 1.3 ka for the Ephrata fan downstream from Grand Coulee (site 8, Fig. 1B), which indicates substantial erosion of Grand Coulee at this time.

Regardless if the opening of upper Grand Coulee at 15.6 ± 1.3 ka was because of ice retreat (Atwater, 1987) or cataract retreat, subsequent Missoula floods would have preferentially followed Grand Coulee because of its much lower elevation divide with the Columbia Valley at ~460 m above sea level, compared to >700 m for glacial Lake Columbia outlets to the east. Consequently, the late-glacial floods carving the more-eastern Telford–Crab Creek and Cheney-Palouse scabland tracts (Fig. 1) likely pre-date the ca. 15.6 ka opening of upper Grand Coulee. They also likely post-date the ca. 18.2 ka down-Columbia floods because flood water would have preferentially followed the main Columbia Valley if not blocked by the Okanogan lobe.

Flooding into an ~460-m-elevation glacial Lake Columbia, probably from glacial Lake Missoula, continued after the opening of upper Grand Coulee, as shown by at least 14 flood beds within upper Grand Coulee (Atwater, 1987; Waitt, 1994). Floods from glacial Lake Missoula continued until 14.7 ± 1.2 ka, as indicated by our ^{10}Be ages on flood-transported boulders adjacent to the outlet at Lake Pend Oreille (sites 5 and 11, Fig. 2A).

The distinctive boulder-studded bars in the upper Columbia Valley formed after retreat of the Okanagan lobe are not evident upstream of the Okanogan River confluence with the Columbia River. They were likely deposited by outburst flood(s) from glacial Lake Columbia as the Okanogan lobe thinned and retreated. These geomorphic relations are consistent with the new chronology (Fig. DR50). Boulders on these glacial Lake Columbia outburst flood bars have average ^{10}Be ages ranging from 14.4 ± 1.3 ka to 14.0 ± 1.4 ka, likely a few hundred years younger than the youngest Missoula flood boulders of 14.7 ± 1.2 ka near the glacial Lake Missoula outlet and consistent with 200–400 glacial Lake Columbia varves overlying the last flooding into glacial Lake Columbia from upstream (Atwater, 1987).

In summary, our new chronological information suggests the following:

(1) Blockage of the Clark Fork river by the Purcell Trench lobe by ca. 18.2 ka, resulting in Missoula floods following the Columbia River valley.
(2) Blockage of the Columbia River valley by the Okanogan lobe before 15.4 ± 1.4 ka, which shunted Missoula flood water south across the Channeled Scablands.
(3) The final Missoula floods at ca. 14.7 ± 1.2 ka, signaling retreat of the Purcell Trench lobe from the Clark Fork valley, yet these floods entered a glacial Lake Columbia still impounded by the Okanogan lobe.
(4) Down-Columbia floods at ca. 14 ka from breakouts of glacial Lake Columbia, signaling the retreat and final damming of the Columbia Valley by the Okanogan lobe.

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