A fresh perspective on the Cordilleran Ice Sheet

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The fate of Earth's cryosphere in the coming decades to centuries is a current topic of great debate within the climate science community and wider public arena. The advance and retreat of past ice sheets can shed new light on our understanding of the cyrosphere. The response of a temperate ice mass, like the Cordilleran Ice Sheet (CIS), to climate forcing contributes important clues to what scenario best fits the future. One such scenario involves the potential role of melting ice sheets (namely the Greenland Ice Sheet) injecting freshwater into the Atlantic Ocean, leading to deep-water shutoff and a frigid eastern North America and Europe. This scenario occurred repeatedly during the last glacial interval. Evidence has been easy to find for these freshwater events in the Atlantic, in the form of ice-rafted debris (IRD) layers and anomalous negative $\delta^{18}O$ values found in planktonic foraminifera (Hemming, 2004). Similar freshwater events in the Pacific Ocean have proven more elusive and have been largely overlooked, although the existence of glacial outburst flooding into the Pacific has been known for some time (Atwater, 1984; Bretz et al., 1956; Shaw et al., 1999). Consequently the effects of the impressive Lake Missoula floods events on the northeastern Pacific Ocean remain poorly understood.

Harlen Bretz (Bretz et al., 1956) identified evidence of catastrophic floods in the 1920s, based on morphological features in the Channeled Scablands, the Columbia Gorge, and the Willamette Valley (Fig. 1). These features included gigantic water-carved channels, enormous dry cataracts, overtopped drainage divides, and huge gravel bars (Bretz et al., 1956). Bretz, however, could not explain the source of such a large volume of water, and what followed was an acrimonious 40 yr debate over the origin of the Scablands. We now know that the floods were produced by melting the eastern lobes of the CIS—the much smaller, little-known western neighbor of the Laurentide Ice Sheet. The CIS initially grew in the north (Alaska) but spread south during the last (Fraser) glaciation, reaching its maximum extent (~4000 km wide) in southern British Columbia and northern Washington (Fig. 1; Booth et al., 2004).

Evidence for these outburst floods has been hard to find in the Pacific Ocean. First, a CIS meltwater signal could be difficult to detect relative to the Laurentide Ice Sheet. Estimated Laurentide Ice Sheet $\delta^{18}O_{ice}$ was probably ~−25 to −35‰ (Standard Mean Ocean Water, SMOW; Flower et al., 2004). These depleted values can be attributed to ice forming in a high-latitude, continental climate with a distal moisture source. Conversely, southern CIS ice formed from snow falling at significantly lower latitudes close to a maritime moisture source (Clague, 1981). The $\delta^{18}O$ of modern glacial ice in coastal southern Alaska is −17.8‰ at the Columbia Glacier and −22.6‰ (SMOW) at the Harvard Glacier (Kipphut, 1990). Finally, the environmental preferences of planktonic foraminifera make it unlikely that they would have inhabited a meltwater plume, unlike other marine plankton such as diatoms (Lopes and Mix, 2009; p. 79 in this issue) or dinoflagellates that are tolerant of low-salinity conditions.

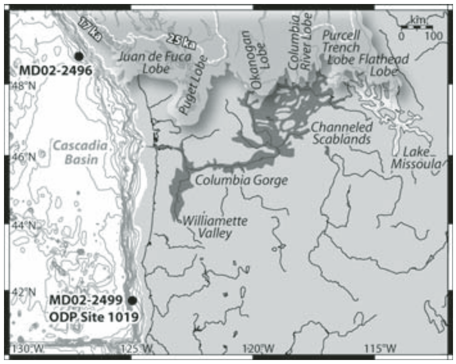

Figure 1. Map of northwestern American margin showing location of the southern lobes of the Cordilleran Ice Sheet at 17 ka, Lake Missoula (light shading), the Scablands (dark shading; Waitt, 1985), and locations of the deep sea cores. The maximum extent of the Cordilleran Ice Sheet at 25 ka (heavy dashed white line) and at 17 ka (3-dimensional white shading) is indicated (Clague and James, 2002). ODP—Ocean Drilling Program.

The new study by Lopes and Mix (2009) published in this issue of *Geology* finds evidence for the elusive low-salinity meltwater discharge from the eastern lobes of the CIS (Fig. 1). Freshwater diatoms transported by meltwater discharge are found in southern Oregon sediments starting at ca. 33 ka, ~2.5 k.y. before glacimarine sedimentation began on the continental slope of Vancouver Island (Cosma and Hendy, 2008). These results are important, first because they suggest that the continental side of the CIS advanced earlier than the marine border (with a caveat, however, that dating errors may allow for a synchronous advance). Second, outburst flooding maybe a long-standing feature of the CIS, with dammed glacial lakes similar to Lake Missoula appearing far earlier than previously believed.

Our present understanding of the CIS suggests that glaciers of the Coast, Selkirk, and Olympia mountains advanced during the Fraser Glaciation at ca. 30 ka, and by ca. 25 ka had coalesced to form the incipient CIS (Hicock and Armstrong, 1981). This initial expansion of glaciers was accompanied by an increase in glacial erosion and the deposition of large outwash sheets such as Quadra Sand (Clague, 1976). The glacial sequences in northern Washington and southern British Columbia were probably deposited under climatic conditions similar to temperate glaciers in the present-day Gulf of Alaska, as glacimarine sediment records suggest a significant meltwater discharge with a high suspended load (Domack, 1983).

The CIS advanced into the Pudget Lowland and Juan de Fuca Strait shortly after 21 ka (Porter and Swanson, 1998), while to the west it coalesced with a large independent glacier in Barclay Sound after overtopping Vancouver Island (Herzer and Bornhold, 1982). The CIS reached its maximum extent by 17.5 ka in Washington (Porter and Swanson, 1998). At this time, the CIS extended westward to the edge of the continental shelf in the Juan de Fuca Lobe, and south in several large lobes, including the Puget, Okanogan, Columbia River, Purcell Trench, and Flathead lobes (Fig. 1; Porter and Swanson, 1998; Waitt, 1985). In contrast to the well-constrained chronology of the western CIS, Fraser Glaciation timing east of the Cascades and Coast Mountains is poorly constrained, with an advance to within 100 km of the ice limit at 17.2 ka (Booth et al., 2004).

On the Eastern CIS, pro-glacial Lake Missoula formed at the leading edge of the CIS when the Purcell Trench Lobe blocked drainage to the northeastern Pacific (Porter and Swanson, 1998). Between 18.6 and 15.9 ka, repeated failure of the ice dam (~89 times; Atwater, 1984) resulted in 2500 yr of freshwater input to the northeastern Pacific Ocean. The timing (19–17 ka) of these ice dam failures closely corresponds to significant low-salinity anomalies inferred by Lopes and Mix (2009). Outburst floods containing fresh water and entrained sediment reached the northeastern Pacific via the Columbia River (Atwater, 1984), with the largest flood volume estimated at ~2,500 km^3 (Ostlund et al., 1987). Later floods were probably smaller in volume and more frequent. Large sediment loads from these floods were deposited over the southern Cascadia Basin, and the adjacent abyssal plain off the western North American margin (Brunner et al., 1999; Normark and Reid, 2003).

The timing of outburst flooding may have been different further north on the marine boundary of the CIS, where floods appear to be only associated with a fully developed ice sheet (Cosma et al., 2008). At ca. 19.5 ka, cyclic (~80 yr return interval) outburst flooding abruptly began at core MD02–2496 (Cosma and Hendy, 2008). Repeated cycles of sediment input are recorded in the ~2-cm-thick sediment layers on the continental slope off Vancouver Island. After 17 ka, outburst floods into the Pacific Ocean from Vancouver Island or nearby environments became intermittent and infrequent (Cosma and Hendy, 2008).

To the west, rapid invasion of the Juan de Fuca Strait by ocean water (Mosher and Hewitt, 2004) accompanied CIS retreat and ice-rafted debris deposition occurred at ca. 17 ka (Clague, 1981; Hendy and Cosma, 2008; Porter and Swanson, 1998). The retreating Juan de Fuca Lobe beheaded the Puget Lobe so that iceberg calving into Juan de Fuca Strait began on the northern margin of the Puget Lobe (Mosher and Hewitt, 2004; Porter and Swanson, 1998). Iceberg calving diminished as retreating ice grounded at the heads of fjords, and retreat slowed as downwasting dominated ice removal. Several small advances interrupted the retreat between 14.7 and 12 ka (the Sumas advances; Clague et al., 1997; Kovanen, 2002); however, their relationship with climate change remains controversial. Finally, outburst floods are believed to have swept over the Georgia Strait at ca. 11 ka as the CIS retreated across the Fraser Lowland (Blais-Stevens et al., 2003).

Challenges for the future include first improving the chronology of CIS reconstruction, particularly on the eastern lobes, and secondly placing this reconstruction within a robust global climate history. Transient responses to the Last Glacial climate, as well as rapid climate events, need to be considered in future studies of ice sheet response. The climate change during the Last Glacial is now known to contain numerous scales of change, from decadal to multimillennial, that can be broken into two patterns: "Greenland" or "Antarctic." Recent studies suggest ice sheet behavior in both hemispheres followed the Antarctic pattern (Hill et al., 2006); however, most dating techniques are insufficient on their own to confirm this result. Lopes and Mix (2009) indicate there is still much work to be done, both in the marine and terrestrial environments influenced by advance and retreat of the Cordilleran Ice Sheet.

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