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Pleistocene megafloods in the northeast Pacific

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ABSTRACT

Massive discharges of freshwater from the glacial lake Missoula to the northeast Pacific Ocean are thought to have sculpted the Channeled Scablands of eastern Washington and debouched via the Columbia River near 46°N. The dynamics and timing of these events and their impact on northeast Pacific circulation remain uncertain. Here we date marine records of anomalous freshwater inputs to the ocean based on freshwater diatoms, oxygen isotopes in foraminifera, and radiocarbon data. Low-salinity plumes from the Columbia River reduced sea-surface salinities by as much as 6 psu (practical salinity units) more than 400 km away between 16 and 31 cal (calendar) ka B.P. Anomalously high abundances of freshwater diatoms in marine sediments from the region precede generally accepted dates for the existence of glacial Lake Missoula, implying that large flooding or freshwater routing events were common during the advance of the Cordilleran Ice Sheet and that such events require multiple sources.

INTRODUCTION

Megafloods were first recognized in the U.S. Pacific Northwest in the widespread erosion of the Channeled Scablands of eastern Washington (Bretz, 1925, 1969). The best-documented water source is glacial Lake Missoula (northeast Idaho, dammed by the southern margin of the Cordilleran Ice Sheet; Bretz, 1925; Benito and O'Connor, 2003). A more controversial view is that additional water sources in British Columbia, perhaps including subglacial lakes, contributed to intermittent flooding (Shaw et al., 1999; Lesemann and Brennand, 2007; contrasting with Clarke et al., 2005). Other sources of freshwater may include spillover events from Lake Bonneville in Utah, via the Snake River (O'Connor, 1993). Whatever the sources, the only major path for glacial floodwaters to reach the northeast Pacific Ocean is the Columbia River, which today accounts for 77% of the total runoff from western North America (Hickey et al., 1998).

Opinions have varied regarding the mechanisms for the Cordilleran megafloods. Originally, the erosion was thought to reflect a single major event (or perhaps a few events) from Lake Missoula, associated with the early retreat of the Cordilleran Ice Sheet (Bretz, 1969; Baker, 1973). Flood events were later described as a sequence of 40–90 smaller jökulhlaups events (Waitt, 1985).

The timing of the megafloods from Lake Missoula is constrained by the advance of the Purcell Lobe of the Cordilleran Ice Sheet to between 18.4 and 15.7 cal ka B.P. (Waitt, 1985; Clague and James, 2002). Some ^{14}C dates on charcoal fragments from the Columbia Plateau flooding are older than 19 cal ka B.P.; however, these dates were discounted because the materials could be reworked (Benito and O'Connor, 2003).

The total volume of freshwater associated with individual Cordilleran megaflood events is estimated as 2×10^3 km^3 (the volume of Lake Missoula; Clarke et al., 1984) to ~10^5 km^3 (including additional sources of meltwater; Shaw et al., 1999). Peak fluxes of $1–2 \times 10^6$ m^3/s are thought to have reached the Pacific through the Columbia River valley (Benito and O'Connor, 2003). Such flow rates are a factor of 1000–2000 greater than annual average flows of the modern Columbia River. In the long run, the integrated freshwater fluxes cannot exceed the regional water balance (precipitation minus evaporation, P – E, integrated over the full drainage including relevant portions of the Cordilleran Ice Sheet). Climate models reconstruct a slight regional decrease in P – E during the Last Glacial Maximum (Hostetler et al., 2006), so the high flux estimates require that the megaflood intervals were episodic, allowing time for recharge with estimates of average repeat times ranging from 10 to 60 yr (Waitt, 1985; Atwater, 1987; Booth et al., 2004).

In marine records, megafloods have been inferred from turbidites in the Cascadia Basin (Benito and O'Connor, 2003; Zuffa et al., 2000; Normark and Reid, 2003). Turbidite layers are difficult to date directly, however, because the dated materials (wood fragments) are reworked. Dates on foraminifera in hemipelagic layers between turbidite events are likely more robust, and suggest ages from ca. 30 to younger than 11 cal ka B.P. The younger turbidites (younger than 19 cal ka B.P.) are assumed to be related to the Lake Missoula floods, while the older ones (older than 19 cal ka B.P.) were not associated with any identified source and remain enigmatic (Zuffa et al., 2000). Some turbidite events are associated with great earthquakes in the Cascadia subduction zone (Goldfinger et al., 2003), so the link of turbidites to flood events is not unique. Better marine tracers are needed.

TRACKING FLOOD INTERVALS IN MARINE PALEOSALINITIES

The best hope for developing complete and well-dated chronologies for past flooding events is through measures of paleosalinity in continuously accumulating hemipelagic marine sediments. Driven by ocean currents, the modern Columbia plume from the Columbia enters the northeast Pacific Ocean and flows mostly to the north during winter and to the south during summer (Hickey et al., 2005), and can be recognized as a ~0.25–0.5 psu (practical salinity units) reduction in surface salinities relative to ambient oceanic salinities of ~33 psu as far as 600 km south of the Columbia mouth, and far as 400 km offshore (Hickey et al., 2005). Smaller regional rivers, such as the Umpqua, the Rogue, the Klamath, and the Eel Rivers, have no significant effect on offshore salinities (Fig. 1).

Core tops (n = 41) from the northeast Pacific (Lopes et al., 2006, updated here; Fig. 1; GSA Data Repository[1]) relate fossil diatoms to freshwater input. The percentage of freshwater diatoms, an unambiguous freshwater tracer that is transported seaward with the freshwater

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[1] GSA Data Repository item 2009018, table with freshwater diatom percentages and salinities for modern and past conditions, age models, turbidite dates, and foraminifera isotopic record, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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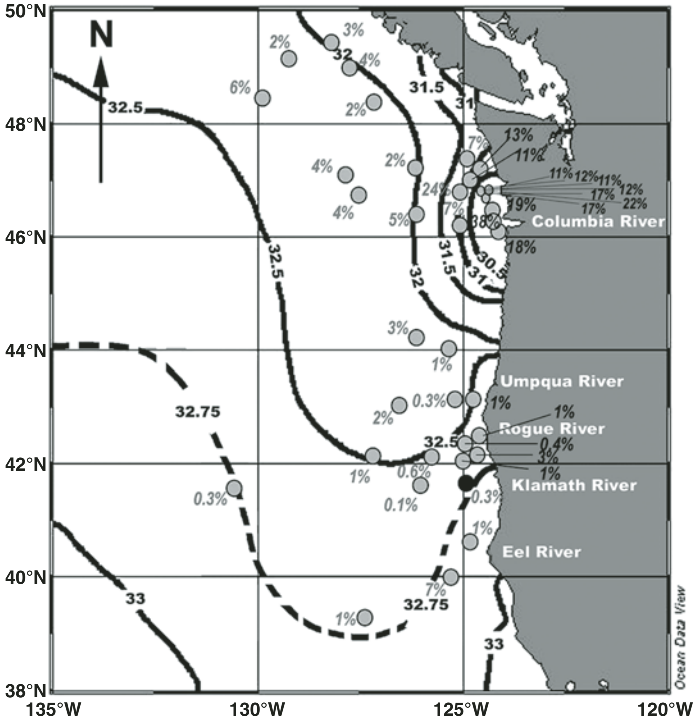

Figure 1. Spatial distribution of freshwater diatom percentages (relative to total diatoms) in core tops (gray dots) and annual sea-surface salinity (contours; National Oceanographic Data Center, 2001). Black dot indicates Pleistocene study sites (ODP 1019D and MD02–2499).

plume, mirrors modern annual salinities (National Oceanographic Data Center, 2001) because dilution with marine diatoms in sediments approximately parallels dilution with ambient saline ocean water. Sea-surface salinities (in psu) are estimated by S = 32.323 – 0.1231 × FD ($r^2 = 0.8$), where FD is freshwater diatom percentages relative to the total diatom flora (Fig. 2). Cross-validation follows that given in Kucera et al. (2005). Average prediction error (root mean square error of prediction) is 0.6 psu. At high salinities the prediction error is smaller (FD of 5% implies S of 31.7 ± 0.26) and at low salinities it is larger (i.e., FD of 40% implies S of 27.4 ± 1.0).

We estimate salinities over the past ~45 cal ka B.P. off northern California, near the southern limit of the modern Columbia River low-salinity plume, at Ocean Drilling Program (ODP) Site 1019 (41.683°N, 124.933°W, 978 m depth) and piston core MD02–2499 (41.683°N, 124.940°W, 904 m depth). Freshwater diatoms are virtually absent in modern core tops here (Fig. 1). Hole 1019D includes the late Holocene interval (0 to ca. 8 cal ka B.P.), which is missing in core MD02–2499. Hole 1019C was analyzed for oxygen isotopes in foraminifera and radiocarbon in planktic and benthic foraminifera (Mix et al., 1999).

Chronologies of the cores reflect 19 calendar-corrected radiocarbon dates and benthic foraminiferal oxygen isotope stratigraphy (Fig. 3; see the Data Repository). Sedimentation rates range from ~30 to ~50 cm/k.y. Sample intervals are 10–20 cm. Although individual samples are 1–2 cm thick, the bioturbation length scale of ~10 cm means that each sample likely integrates conditions over ~200 yr, which is excellent for dating intervals in which megafloods were prevalent, but unlikely to resolve individual events.

RESULTS AND DISCUSSION

The presence of abundant freshwater diatoms in marine sediments documents anomalously high freshwater inputs during most of

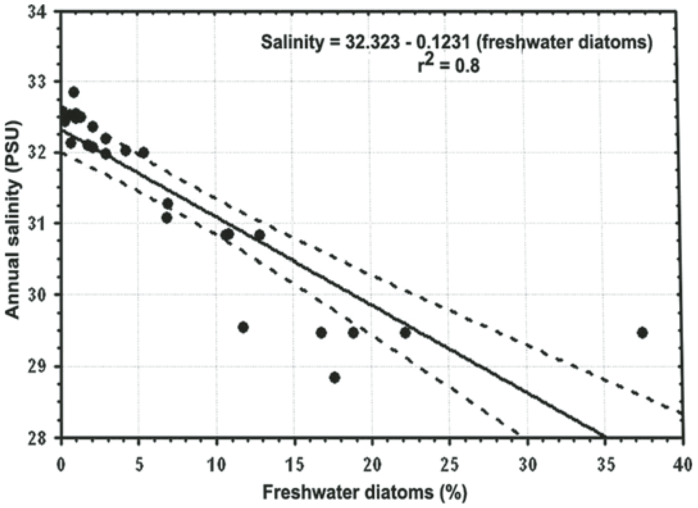

Figure 2. Calibration of paleosalinity estimates from modern (core top) freshwater diatom percentages, and sea-surface salinities (National Oceanographic Data Center, 2001).

marine oxygen isotope stage (OIS) 2. Peak abundances of freshwater diatoms occurred at this site at 17.5, 20, 23, 27, and 30.5 cal ka B.P., and reached values of >40% (Fig. 3). Application of the modern spatial calibration implies paleosalinity reductions of up to 6 psu relative to background values of ~32.5 psu; i.e., approaching values within the modern Columbia Estuary.

The species of freshwater diatoms present off northern California during OIS 2 suggest different freshwater sources and/or flooding mechanisms at different times. The younger events were dominated by planktonic freshwater diatoms (Fig. 3D), including *Aulacoseira granulata* and *A. islandica* and *Cyclotella ocellata* and *C. comta*, which are common in large lakes (such as Lake Missoula). The older events (older than 25 cal ka B.P.) include relatively high percentages of benthic freshwater diatoms (mainly *Surirella linearis*), consistent with a source dominated by either shallow lakes or running water (Fig. 3D).

Oxygen isotopes ($\delta^{18}O$) in the planktonic species *Neogloboquadrina pachyderma* (left coiling), when differenced against benthic foraminiferal $\delta^{18}O$ data (to minimize the isotopic influence of global ice-volume and temperature changes that covary in the benthic and planktic records) support anomalously low sea-surface salinities from ca. 17–24 cal ka B.P. (Fig. 3C), with a maximum $\delta^{18}O$ anomaly of –1.5‰. Assuming a modern $\delta^{18}O$ for Columbia River water of –10‰ to –14‰ Vienna standard mean ocean water (Kendall and Coplen, 2001), this $\delta^{18}O$ anomaly would imply a salinity reduction of 4–5 psu (larger if ice age cooling contributed to the stable isotope records, smaller if ice age freshwaters has lower $\delta^{18}O$). Planktonic foraminifera likely underestimate salinity changes, because they live either under low-salinity plumes, or intermittently during times of minimal plume influence (Ortiz et al., 1995).

The presence of a substantial low-salinity plume as far south as the California-Oregon border during marine OIS 2 requires a strong southward flow in the California Current, consistent with regional paleoceanographic reconstructions of the glacial maximum ocean (Ortiz et al., 1997). It is unlikely that freshwater diatoms and isotopically depleted surface waters during the last glacial interval reflect local river runoff from the Rogue and/or Klamath Rivers (as has been inferred for some components of clays and silts; VanLaningham et al., 2007). These local rivers do not carry significant water to the ocean at present. Regional reconstructions based on pollen (Worona and Whitlock, 1995) and diatoms (Bradbury et al., 2004) in lake sediments indicate that the local precipitation during OIS 2 was

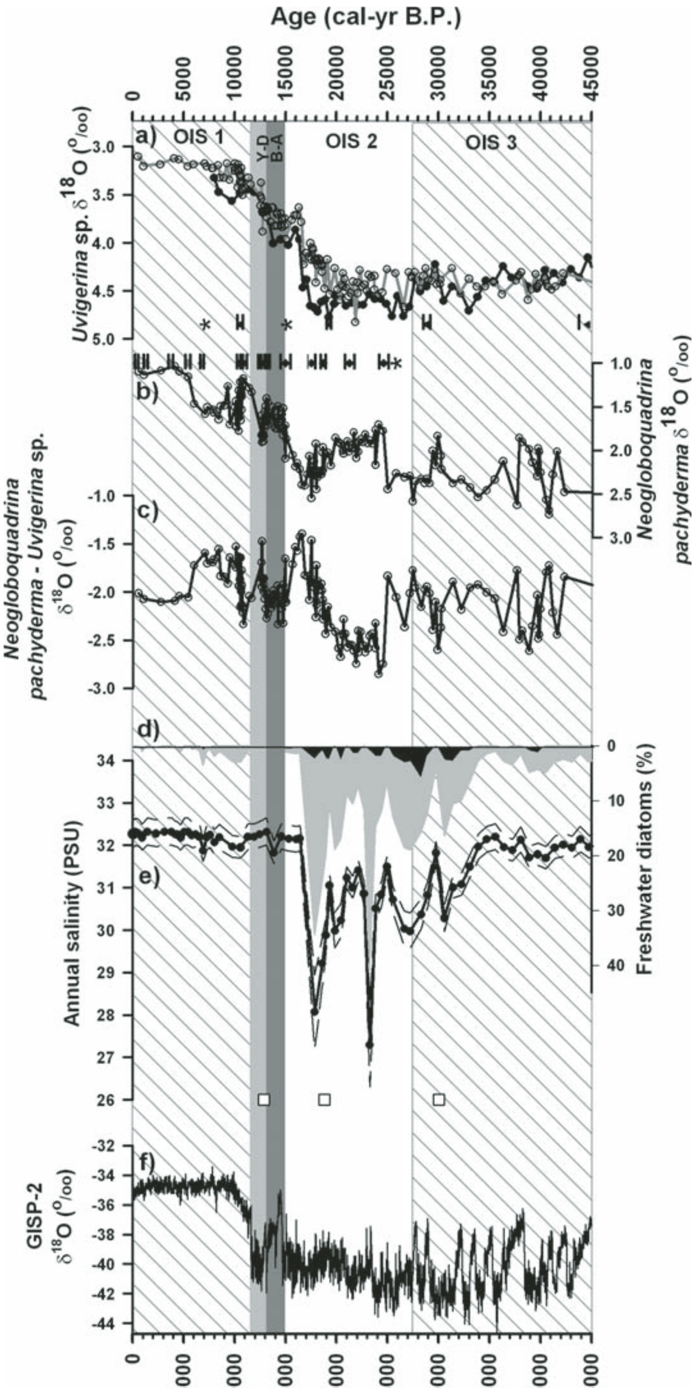

Figure 3. Downcore observations from cores MD02–2499 (closed circles) and Ocean Drilling Program (ODP) Site 1019 (open circles). A: Benthic *Uvigerina* sp. δ^{18}O record for MD02–2499 and ODP 1019C; calendar-corrected (cal) ^{14}C dates with ±1σ error bars for ODP 1019 (diamonds: gray is 1019D, black is 1019C; triangles are MD02–2499; stars are stratigraphic correlations). OIS—oxygen isotope stage. B: Planktonic left-coiling *Neogloboquadrina pachyderma* δ^{18}O at ODP 1019C. C: *N. pachyderma* δ^{18}O record minus *Uvigerina* sp. δ^{18}O record from ODP 1019C. D: Freshwater diatom percentages for MD02–2499 (gray filling is percent planktonic diatoms and black is percent benthic diatoms). E: Annual salinity reconstructions with envelope of estimation errors (long dashed lines). F: Greenland Ice Sheet Project 2 (GISP-2) δ^{18}O (Grootes et al., 1993). Squares represent turbidites from Zuffa et al. (2000).

about half that at present, and lake levels were low, implying that local river discharge from southern Oregon and northern California was reduced during the Last Glacial Maximum. It is also unlikely that the freshwater diatoms are eolian (Sancetta et al., 1992), because easterly winds required for such transport were confined to the region in Washington near the ice edge (Hostetler and Bartlein, 1999), far north of our study site. Although quantification of the intermittent flux of freshwater needed to drive the increase in freshwater diatoms in the marine sediments requires additional work on plume modeling, the massive changes in freshwater diatoms at our study site imply that the paleoevents must have been much larger than mean modern flows or historical flooding (especially considering the smoothing effects of bioturbation on intermittent events).

CONCLUSIONS

The younger age range of the low salinity anomalies inferred from freshwater diatom abundances off southern Oregon, from 19 to 17 cal ka B.P., is a close match to terrestrial dates of megafloods associated with glacial Lake Missoula (Booth et al., 2004), as well as with the age of the youngest turbidites in the Cascadia Basin that have been linked to the Missoula floods (after 19 cal ka B.P.; Zuffa et al., 2000). However, the full range of ages for the freshwater diatoms predates the existence of glacial Lake Missoula. Additional sources are needed for the older events we observed.

One possible source of the older events could be intermittent release of subglacially trapped waters (Shaw et al., 1999), as has been documented in Antarctica (Bell et al., 2007; Fricker et al., 2007), that can contain diatoms that concentrate beneath ice sheets after transport through ice (Burckle et al., 1997). Plausible outbursts of subglacial meltwater, however, are thought to be much smaller than the Missoula floods due to limitations on the possible volumes of subglacial waters and regional elevation gradients (Clarke et al., 2004, 2005). Another option is surge behavior during the growth phase of the Cordilleran Ice Sheet. This would leave little or no recognizable record on land, due to subsequent erosion during glacial advance. Finally, release of water from other lake systems could contribute to the offshore record. Lake Bonneville, for example, may have had spillover events as early as ca. 30 cal ka B.P. (Malde, 1968) and ca. 17.5 cal ka B.P. (O'Connor, 1993). Lamb et al. (2008) also reported the existence of older flooding events (ca. 45 ka ^{14}C) in the Snake River Plain (Idaho). Our finding of benthic freshwater diatoms in the pre-Missoula record argues for a source in shallow lakes or actively running waters. Whatever the sources, intermittent massive freshwater inputs to the northeast Pacific appear to have been a common feature of the full extent of marine OIS 2 (the broadly defined Last Glacial Maximum), and may have been common features during other ice age intervals, suggesting that the dramatic erosional features in the region may have a long history.

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