Direct ventilation of the North Pacific did not reach the deep ocean during the last deglaciation

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[1] Despite its tremendous size, the deep North Pacific has received relatively little attention by paleoceanographers. It was recently suggested that the deep North Pacific was directly ventilated by dense waters formed in the subarctic Pacific during Heinrich Stadial 1 (HS1) of the early deglaciation. Here we present new redox-sensitive trace metal data from a sediment core at 2393 m in the subarctic Pacific, in comparison with previously published data from elsewhere in the region. The combined picture shows no sign of ventilation during the early deglaciation in any available core from water depths of 2393 m and deeper, while the deepest core to display clear signs of enhanced ventilation during HS1 was raised from 1366 m water depth. Thus, it appears likely that, although the North Pacific was well ventilated to intermediate depths during HS1, the deep ocean did not receive a significant input of dense waters from a local source, but remained isolated from the surface waters above. Sample unit level copyright **Citation:** Jaccard, S. L., and E. D. Galbraith (2013), Direct ventilation of the North Pacific did not reach the deep ocean during the last deglaciation, *Geophys. Res. Lett.*, *40*, 199–203, doi:10.1029/2012GL054118.

1. Introduction

[2] The transition from the Last Glacial Maximum (LGM) to the warm climate of the Holocene was accompanied by an ~80 ppm rise in atmospheric CO_2 [*Monnin et al*., 2001] and a substantial reduction in the $^{14}C/^{12}C$ ratio in the atmosphere [*Hughen et al*., 2004], of which a significant fraction is thought to be related to the oceanic storage of carbon. Of particular interest is the time of Heinrich Stadial 1 (HS1, 17.5–14.7 kyr, also known as the 'Mystery Interval' [*Denton et al*., 2006]). HS1 was coincident with the first pulse of atmospheric CO_2 rise and ^{14}C drop, rapid deposition of opal in the Southern Ocean [*Anderson et al*., 2009] and a dramatic change in the Atlantic meridional overturning circulation [*McManus et al*., 2004].

[3] Recently, *Okazaki et al*. [2010] argued that, during HS1, the subarctic North Pacific circulation followed a different mode than during either the preceding glacial maximum or the warmer interval that followed, known as the Bølling/Allerød (B/A). In particular, they argued for a greater northward advection of salty subtropical waters to the subarctic gyre, overcoming the halocline [*Emile-Geay et al*., 2003], and forming "deep waters" during HS1. There are indeed many signs of increased ventilation recorded in sediments deposited within the upper portion of the North Pacific water column during HS1 [*Ahagon et al*., 2003; *Duplessy et al*., 1989; *McKay et al*., 2005; *Mix et al*., 1999; *Sagawa and Ikehara*, 2008]. However, a number of geochemical proxies, previously measured at multiple deep North Pacific core sites between 2710 and 3640 m, are inconsistent with local ventilation of the lower half of the ~5000 m deep water column at this time. Among these measurements, the high-resolution radiocarbon data of *Lund et al*. [2011] suggest that the waters at 2710 m were actually very poorly ventilated (i.e., ^{14}C-depleted) during HS1, although these authors note the potential input of ^{14}C-deprived carbon from geological reservoirs at this time.

[4] Here we present new sedimentary uranium (U) concentration data from 2393 m depth in the NW Pacific (13PC; 49.7181°N, 168.3019°E), providing a new constraint on the oxygenation state of waters lying near the vertical midpoint of the water column. Consistent with prior evidence from similar and greater depths, these new data show no hint of ventilation until after HS1, contrary to the direct ventilation hypothesis put forth by *Okazaki et al*. [2010].

2. Material and Methods

[5] Sediment core PC13 was raised from the Northern Emperor Seamounts, located in the open western subarctic Pacific, during Leg 6 of the R/V *Thomas Washington* Roundabout expedition in 1988 (Figure 1; 49.7181°N, 168.3019°E, 2393 m) [*Keigwin*, 1998]. The analytical procedure was described in detail in *Brunelle et al*. [2010]. Briefly, ^{230}Th was measured at the University of British Columbia by isotopic dilution using ^{229}Th spike on a single collector, sector field ICP-MS, following the procedure described by *Choi et al*. [2001]. Initial excess activities were obtained after corrections for: (1) the detrital ^{230}Th inferred from the ^{232}Th content of the sediment; (2) the decay since the time of sediment deposition estimated from the age model; and (3) the diagenetic addition of ^{230}Th derived from authigenic U [*François et al*., 2004]. Authigenic uranium concentrations were determined as the excess U relative to its detrital background using a $^{238}U/^{232}Th$ activity ratio for the lithogenic fraction of 0.7 [*Henderson and Anderson*, 2003].

3. Results and Discussion

[6] "Ventilation" involves the input of atmospherically-equilibrated waters to the ocean interior. Well-equilibrated waters typically have high concentrations of oxygen, ^{13}C and ^{14}C, and relatively low concentrations of dissolved inorganic carbon (DIC). The modern North Pacific is strongly

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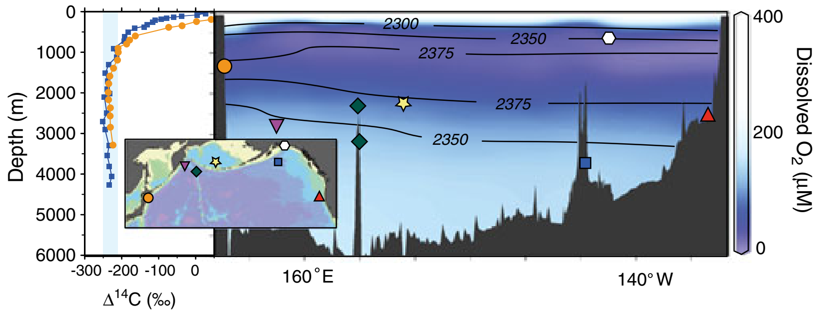

Figure 1. Dissolved oxygen (blue shading), inorganic carbon (DIC, black contours), and 14C (left panel) in the present-day subarctic Pacific. Solid symbols correspond to the locations of sediment cores MR01-K03-PC5 (orange circle), RAMA44 (purple triangle), 13PC, GGC-37 and ODP 882 (green diamonds), BOW 9-A and 17JPC (yellow star), ODP 887 and MD02-2489 (blue square), EW0408–85JC (white hexagon) and W8709A-13PC (red triangle). Dissolved oxygen concentrations are high at the surface, due to exchange with the atmosphere, and are very low between 400 and 1500 m depth. DIC reaches a maximum between 1000 and 2000 m, nearly coincident with the oxygen minimum. Radiocarbon profiles at two sites (colors and symbols correspond to map, shown as $\Delta^{14}C$ in ‰ relative to the preindustrial atmosphere) indicate very high values at the ocean surface, due to exchange with the atmosphere. Data from GLODAP [*Key et al.*, 2004] figure generated with Ocean Data View [*Schlitzer*, 2002].

stratified, limiting exchange between the ocean surface and the interior [*Warren*, 1983]. As a result, the decay of organic matter has depleted oxygen at intermediate depths, where the organic decay is most rapid relative to the ventilation rate (Figure 1). Bottom waters with low oxygen concentrations leave indications in underlying sediments by promoting the diagenetic (or authigenic) enrichments of some redox-sensitive trace metals, such as uranium (U) [*Barnes and Cochran*, 1990], which precipitates in suboxic sediments in association with the conversion of Fe (III) to Fe (II) [*Morford and Emerson*, 1999]. Meanwhile, high concentrations of DIC (relative to alkalinity) result in low $CO_3^{=}$ concentrations, inhibiting preservation of calcium carbonate ($CaCO_3$) microfossils. Thus, poorly-ventilated bottom waters are likely to show both sedimentary authigenic U enrichments and poor $CaCO_3$ preservation, while benthic foraminifera record low ^{13}C and ^{14}C.

[7] Figure 2 shows that, at 2393 m water depth in the NW Pacific, authigenic U and $CaCO_3$ suggest that poor ventilation reigned throughout the LGM and HS1, to finally disappear after ~15 ka, when stratification diminished in the Southern Ocean [*Burke and Robinson*, 2012]. Because authigenic U phases precipitate at some shallow depth within the sediment, they reflect the bottom water conditions at some time after the deposition of the sediment in which it is found; as a result, a temporal offset is expected on the order of 1000 years (~5–10 cm of sediment). Nonetheless, the timing of the authigenic U decrease is very similar within multiple deep cores from the region (Figure 3) and is also broadly coincident with the first sharp rise of $\delta^{13}C$ at 3300 m (Figure 2). This sequence of change was previously observed in North Pacific geochemical records from 3300 and 3610 m depth [*Galbraith et al.*, 2007; *Jaccard et al.*, 2009; *Keigwin*, 1998], and is supported by the new data, consistent with a poorly-ventilated deep ocean throughout this time interval that extended to within 2400 m of the surface. In contrast, bottom water oxygen concentrations appear to have been relatively high during HS1 at <1400 m depths on both sides of the North Pacific, including the Bering Sea [*Addison et al.*, 2012; *Caissie et al.*, 2010; *Cook et al.*, 2005; *Crusius et al.*, 2004; *Ikehara et al.*, 2006; *Ishizaki et al.*, 2009; *Jaccard and Galbraith*, 2012; *Shibahara et al.*, 2007]. We note that *Gebhardt et al.* [2008] inferred deep water formation in the NE Pacific during HS1 based on their interpretation of the planktonic $\Delta^{14}C$ record; however, this is inconsistent with the much higher-resolution planktonic-benthic data of *Lund et al.* [2011]. The general picture is therefore consistent with strong ventilation of intermediate depths of the North Pacific during HS1 [*Ahagon et al.*, 2003; *Okazaki et al.*, 2012; *Sagawa and Ikehara*, 2008], while the deep ocean below remained poorly ventilated [*Galbraith et al.*, 2007; *Jaccard and Galbraith*, 2012].

[8] Moreover, we would argue that the proxy data presented by *Okazaki et al.* [2010] (their Figure 2) do not indicate deep water formation. Two *Uvigerina* spp. (infaunal benthic foraminifera) $\delta^{13}C$ records from 1366 and 2391 m water depth show little change between the LGM and HS1 and might be expected to reflect porewater $\delta^{13}C$-DIC and carbon rain rate rather than bottom water $\delta^{13}C$ [*Corliss*, 1985; *McCorkle et al.*, 1990; *Zahn et al.*, 1986]. Consistent with this interpretation, the sense of change of $\delta^{13}C$ measured in epifaunal *Cibicidoides* spp., where available, is opposite (Figure 2) (see also *Galbraith et al.* [2007] and *Keigwin et al.* [1992]). Furthermore, the increase of dysoxic benthic foraminifera species following the LGM in 2391 m-deep core BOW-9A [*Okazaki et al.*, 2005] would appear more consistent with a decrease in ventilation during HS1, contrary to Okazaki *et al.*'s interpretation. Finally, the sedimentary $CaCO_3$ concentration in the same core [*Okazaki et al.*, 2005], and $CaCO_3$ flux determinations in nearby core 17JPC at 2209 m [*Brunelle et al.*, 2007] show low abundances of $CaCO_3$ that would be consistent with corrosive, CO_3-poor bottom waters, rather than well-ventilated $CO_3^{=}$-rich waters. Although this last observation could also reflect reduced export of $CaCO_3$ from the surface during HS1, low $CO_3^{=}$ concentrations are consistent with the $\delta^{13}C$ and benthic foraminiferal assemblages.

[9] In contrast to the geochemical and faunal data, the radiocarbon data compilation presented by Okazaki *et al.* do provide some support for better ventilation during HS1

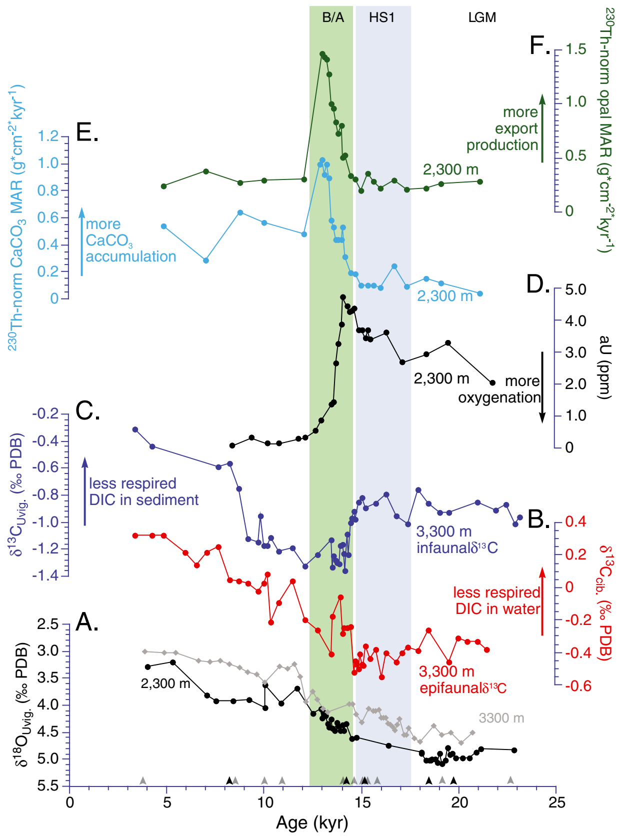

Figure 2. Multiproxy sedimentary records from the deep North Pacific spanning the past 25 kyr. (A) Benthic δ^{18}O from 13PC (black) and GGC37 (gray) [*Keigwin*, 1998], (B) epifaunal and (C) infaunal benthic δ^{13}C from GGC37 [*Keigwin*, 1998], (D) aU (*this study*), (E) ^{230}Th normalized opal flux, and (F) ^{230}Th normalized biogenic $CaCO_3$ flux [*Brunelle et al.*, 2010]. Higher aU concentrations preceding the B/A, characterized by consistently lower export flux from the surface ocean, can only be the result of decreased bottom-water oxygen concentrations associated with increased storage of respired carbon into the abyss. Black and gray triangles indicate ^{14}C ages at cores 13PC [*Brunelle et al.*, 2010] and GGC37 [*Keigwin*, 1998], respectively.

than during the BA at depths of less than 1400 m. However, we would argue that the data are perhaps best interpreted as a minimum of ^{14}C at these depths during the earliest deglaciation (19–17 ka), relative to the LGM and Holocene, rather than being particularly ^{14}C-rich during HS1. For example, the projection ages for these deep sites are not significantly different from modern values during HS1 (Figure 2) [*Okazaki et al.*, 2010], despite the fact that deep water is not forming in the modern subarctic North Pacific. The tiny handful of deeper measurements shown by Okazaki *et al.* (their Figures S5 and S6) do not show a trend that exceeds the error bars.

[10] To summarize, the assembled observations show good evidence for relatively strong ventilation during HS1 at depths of up to 1400 m, but fail to show clear signs at depths of 2393 m or greater. Thus, we argue that the well-ventilated waters penetrated to somewhere in the range of 1400 to 2400 m depth during HS1. Given that the North Pacific water column is more than 5 km deep, it seems more appropriate to refer to ventilation that reaches such depths an "expanded North Pacific intermediate water," following *Keigwin* [1998] and *Matsumoto et al.* [2002] (Figure 4). Thus, the deep waters below would have been ventilated by either Antarctic or North Atlantic waters throughout the deglaciation, in variable proportions.

[11] Nonetheless, the coupled ocean-atmosphere response highlighted by Okazaki *et al.*'s model study points to an intriguing mechanism of change: altering the intergyre exchange of the North Pacific by injecting more salty subtropical waters into the subarctic and developing a strong meridional overturning cell. Although models vary in their tendency to produce such an overturning [*Chikamoto et al.*, 2012], it seems feasible that this could have involved a switch from indirect ventilation, as occurs for the modern North Pacific intermediate water via the Okhotsk Sea [*Shcherbina et al.*, 2003], to direct ventilation in the open subarctic Pacific or Bering Sea. A strong North Pacific meridional overturning cell certainly could have penetrated to greater depths at more distant times in the past [*Motoi*

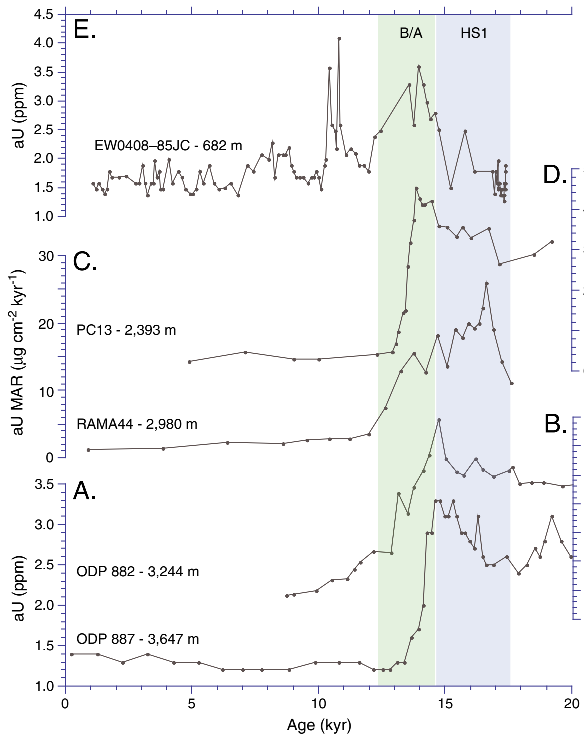

Figure 3. A comparison of authigenic U (A and B [*Galbraith et al.*, 2007], C [*Crusius et al.*, 2004], D (this study), E [*Addison et al.*, 2012]) records in the northern North Pacific. The cores from 2393 m water depth and deeper show elevated aU throughout the LGM and HS1, with declines of aU only occurring during the B/A. In contrast, site EW0408-85JC at 682 m water depth has negligible aU during HS1, but a significant accumulation of aU during the B/A. Authigenic U is expressed as mass accumulation rate (MAR - SedRate * DBD* aU; DBD dry bulk density) at RAMA44, since the record is characterized by a 10-fold decrease in sedimentation rate across the HS1-B/A transition, biasing its concentration profile.

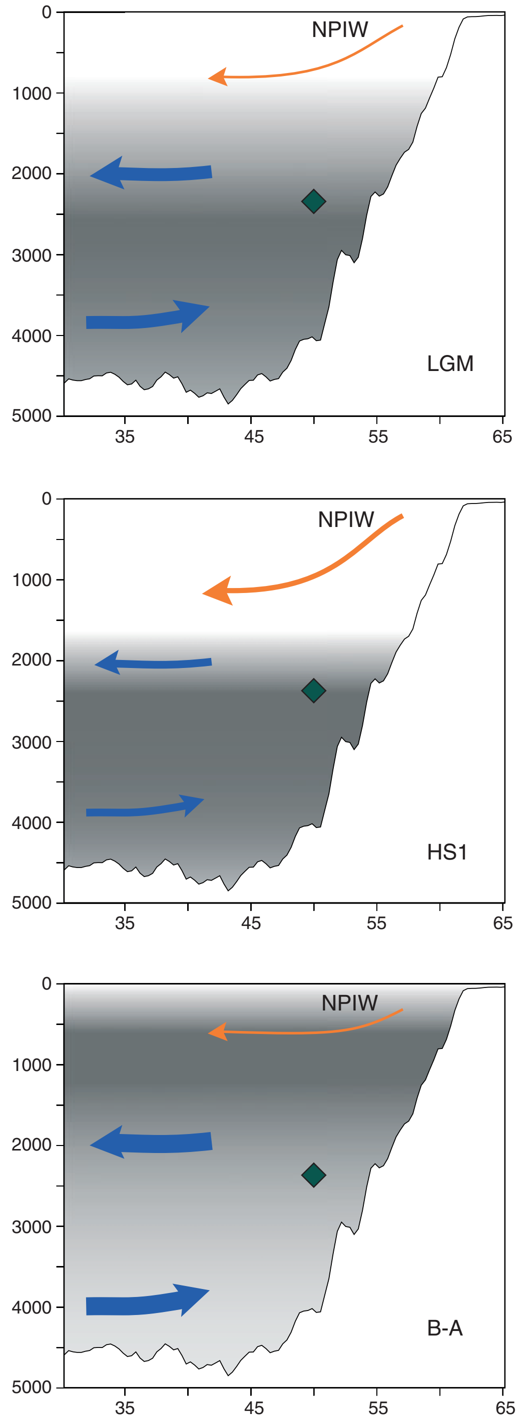

Figure 4. Schematic of the deglacial ventilation changes proposed here. Each panel represents a N-S cross-section of the North Pacific, where the "bottom" traces out the E-W average water depth. During the LGM (top), North Pacific Intermediate Water (NPIW) was reasonably strong and well ventilated, as argued by *Matsumoto et al.* [2002]. During HS1, the deep ocean may have been most poorly ventilated, while NPIW strengthened and expanded downward. During the B/A, the NPIW weakened and shoaled, the intermediate-depth hypoxic zone intensified and the deep ocean became better ventilated. The background shading is meant to suggest poorly ventilated waters, analogous to Figure 1. The green diamond displays the location of sediment core 13PC.

et al., 2005], and perhaps reached the lower half of the water column during previous intervals of Earth history.

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