Late Glacial to Holocene radiocarbon constraints on North Pacific Intermediate Water ventilation and deglacial atmospheric CO₂ sources

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Radiocarbon reconstructions of past ocean ventilation rates constrain oceanic sources and sinks of CO₂ and mechanisms of subsurface hypoxia. Here, 14C in coexisting benthic and planktonic foraminifera from a sediment core 682 m deep off Southeast Alaska documents paleoventilation over the past ~17,000 years. A chronology based on calibrated planktonic foraminiferal dates, consistent with independent terrestrial dates for regional glacial retreat, yields deglacial projection ages moderately greater than those of the Holocene, suggesting comparatively limited ventilation. The observed Holocene increase of apparent ventilation at intermediate depths tracks inundation of the Bering Strait between ∼11,800 and 13,200 years ago, suggesting that flooding of continental shelves and export of low-salinity surface waters to the Arctic enhanced intermediate water formation in the North Pacific. An abrupt increase in the benthic– planktonic radiocarbon age gradient, implying homogenization of abyssal radiocarbon in deep and intermediate waters, aligns with the younger of two episodes of rapid rise of atmospheric CO₂ and depletion of atmospheric 14C during deglaciation (∼11,500–13,000 years ago), suggesting the North Pacific as a possible pathway for venting of oceanic CO₂ to the atmosphere during the second half of the deglacial transition.

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1. Introduction

Increases in atmospheric CO₂ content during the last deglaciation (Termination 1, ∼19,000–11,000 years BP) were accompanied by a decrease in atmospheric ∆14C, apparently unsupported by abrupt changes in 14C production rate (Monnin et al., 2001; Hughen et al., 2006; Broecker and Barker, 2007). Release of CO₂ from abyssal waters is hypothesized to explain the apparent introduction of aged carbon to the atmosphere (Toggweiler, 1999; Sigman and Boyle, 2000; Stephens and Keeling, 2000; Monnin et al., 2001; Skinner and Shackleton, 2004; de Boer et al., 2007; Broecker and Barker, 2007; Galbraith et al., 2007; Marchitto et al., 2007; Keeling, 2007; Pena et al., 2008; Stott et al., 2009; Bryan et al., 2010; Basak et al., 2010; Skinner et al., 2010; Burke and Robinson, 2012; Sarnthein et al., 2013). Evidence for two discrete events of 14C-depletion in some parts of the intermediate depth Indo-Pacific, apparently concomitant with the abrupt rises in atmospheric CO₂ (Marchitto et al., 2007; Stott et al., 2009; Bryan et al., 2010; Basak et al., 2010) supports this view. The site of release of this aged carbon is not well constrained, but is often presumed to originate around Antarctica; the effects may have been redistributed in the upper ocean via Antarctic Intermediate Water (AAIW). However, the evidence for such transport via intermediate waters is unclear (De Pol-Holz et al., 2010), and a volumetrically sufficient 14C-depleted glacial watermass has not been found in the deep ocean (Broecker and Clark, 2010; Lund et al., 2011). Simple models that predict the consequences of deep carbon storage are not consistent with evidence from the deepest Pacific (Hain et al., 2011).

The two most common approaches to reconstructing paleoventilation are: (1) 14C age differences between benthic and planktonic foraminifera, placed on a planktonic chronology assuming constant surface reservoir age (e.g. Broecker et al., 1990; Kennett and Ingram, 1995; van Geen et al., 1996; Mix et al., 1999; Keigwin, 2002; McKay et al., 2005; Broecker et al., 2008), and (2) benthic 14C anomalies relative to known ages and watermass trajectories, placed on a chronology derived by correlation of some measure of local climate change to the layer-counted
δ¹⁸O record of the Greenland ice cores (e.g., Marchitto et al., 2007; Bryan et al., 2010), or by independent dating, for example based on uranium decay series in favorable samples (e.g., Burke and Robinson, 2012) projected to the atmospheric Δ¹⁴C history. Here we employ both chronological strategies to evaluate radiocarbon data from jumbo piston core EW0408-85JC, along with its trigger core EW0408-85TC (59°33.32′N, 144°09.21′W, 682 m water depth) and an adjacent multicore EW0408-84MC2 (59°33.30′N, 144°09.16′W, 682 m water depth), recovered from the continental slope of SE Alaska, south of Kayak Island (Fig. 1). Modern sedimentation at this site is hemipelagic, but during the Last Glacial Maximum, the northwestern portion of the Cordilleran Ice Sheet or its outlet glaciers terminated in the ocean (Molnia, 1986); glacially-derived sediments dominate accumulation prior to ∼14,700 cal years BP (Davies et al., 2011), supporting high sedimentation rates that make this site well-suited for reconstruction of radiocarbon while minimizing the smoothing effects of bioturbation.

2. Methods

2.1. Physical properties

Physical properties data for the multicore, trigger core, and jumbo piston core from the site were analyzed shipboard on whole-core sections using the Oregon State University GEOTEK multi-sensor core logger (MSCL), and include gamma density, P-wave velocity, and magnetic susceptibility. These measurements are effectively smoothed by the detectors to ∼4 cm for the P-wave velocity data, and ∼6 cm for the magnetic susceptibility data. P-wave velocity values with amplitudes of zero were considered to be spurious due to poor transducer contact, and have been cleaned from the data set. All data are presented on a composite depth scale generated by alignment of the multicore, trigger core, and jumbo piston core physical properties data, described in Davies et al. (2011).

A computerized tomographic (CT) scan of EW0408-85JC was logged at the Oregon State University College of Veterinary Medicine using a Toshiba Aquilion 64 Slice. Scans were collected at 120 kVp and 200 mAs. The resulting images were processed with a “sharp” algorithm to generate sagittal and coronal images every 4 mm across the core. Down-core and across-core pixel resolution within each slice is 500 μm. The cores were scanned in ∼60 cm segments and then joined into a composite image using Adobe Photoshop software (Davies et al., 2011).

2.2. Radiocarbon

Radiocarbon analyses were performed at the UC Irvine Keck AMS facility. A total of 78 measurements were performed for 39 samples: 3 benthic/planktonic pairs from EW0408-85TC, and 36 benthic–planktonic pairs from EW0408-85JC (Fig. 2). Benthic and planktonic foraminifera were picked from the >150 μm sediment fraction of jumbo piston core EW0408-85JC. The two predominant planktonic species at this site, *N. pachyderma* (sinistral) and *G. bulloides*, were analyzed separately at 555 cmbsf. In this sample, the ¹⁴C age of *N. pachyderma* was 65 ± 50 years greater than that of *G. bulloides* (Davies et al., 2011). As this difference approximates the measurement uncertainty for the individual samples, these dates were averaged at 555 cmbsf. In this sample, the ¹⁴C age of *N. pachyderma* was 65 ± 50 years greater than that of *G. bulloides* (Davies et al., 2011). As this difference approximates the measurement uncertainty for the individual samples, these dates were averaged at 555 cmbsf. For all other depths the species were combined to increase sample size and thus reduce analytical
uncertainty. Benthic foraminiferal $^{14}$C analyses were run as mixed species, although care was taken to avoid agglutinated (none observed) and deep infaunal (Globobulimina spp and Chilostomella oolina; Zellers et al., 2009, 2011) taxa.

### 2.3. Stable isotopes

Stable isotopic measurements on planktonic foraminifera (Neo-globobuquadina pachyderma, sinistral) were carried out at the Oregon State University College of Earth Ocean and Atmospheric Sciences (OSU/CEOS) Stable Isotope Mass Spectrometer Facility. We performed 177 analyses of $\delta^{18}$O and $\delta^{13}$C across the last deglaciation interval at an average sample interval of 5 cm in the jumbo piston core; this data set as well as further details on our analytical methods are published in Davies et al. (2011).

### 3. Results and discussion

#### 3.1. Age models

To generate Age Model 1, raw radiocarbon dates from planktonic foraminifera were converted to calendar ages using the Marine13 database (Reimer et al., 2013) in the Bayesian radiocarbon chronology program BChron (Haslett and Parnell, 2008; Parnell et al., 2008) (Table A.1). A constant 1-σ $\Delta R$ of 470 ± 80 years reflects modern (pre-bomb) regional surface–ocean reservoir ages of 880 ± 80 years (McNeely et al., 2006). At depth, modern preanthropogenic reservoir ages near the sample site at an equivalent density horizon to 682 m water depth are 1390 ± 100 years (Sabine et al., 2005). The uppermost planktonic sample from the trigger core (22 cmbsf) yielded a raw radiocarbon age of 660 ± 250 (1-σ), while the coexisting benthic sample yielded a raw radiocarbon age of 1530 ± 45 years; the planktonic date implies negative calendar-corrected surface ocean ages. Excess $^{14}$Pb activity in adjacent multicore EW0408-84MC indicates that the dated level at 22 cmbsf was deposited within the past hundred years (Walinski et al., 2009). To explain the anomalously young planktonic date relative to known reservoir ages, we infer minor contamination of the planktonic foraminifera with bomb-derived (i.e., post 1962 AD) radiocarbon, and assume a core-top age equivalent to the year of coring (2004 AD, or −54 BP). Age Model 1 is derived from a Bayesian probabilistic model (BChron; Haslett and Parnell, 2008; Parnell et al., 2008) of the remaining calibrated planktonic foraminiferal dates, assuming constant reservoir ages with respect to a changing atmosphere (Fig. 3).

To generate tuned Age Model 2, 0 cmbsf was assigned an age reflecting the year of core collection, while the core bottom was assigned an age based on the oldest calibrated planktonic radiocarbon date, after applying the nominal modern reservoir age 880 ± 80 years of (Table A.1). Six correlation tie points of $\delta^{18}$O in planktonic foraminifera (Neo-globobuquadrina pachyderma, sinistral) to $\delta^{18}$O in the Greenland NGRIP ice core on the GICC05 chronology (Rasmussen et al., 2006) further constrained Age Model 2. We purposely selected tie points corresponding as closely as possible to those used previously to correlate Baja California core MV99-GC31/PC08 to the Greenland GISP2 chronology (Ortiz et al., 2004; Marchitto et al., 2007) to facilitate comparison of these two intermediate-depth sites (Table A.2; Fig. 4). No significant difference in the EW0408-85JC age-depth relationships resulted from correlating to GISP2 relative to the NGRIP Greenland ice core isotope data on their synchronized GICC05 chronologies (Rasmussen et al., 2006) (Table A.2; Fig. 3). Chronological uncertainties for the tie points in this age model reflect the resolution of the EW0408-85JC $\delta^{18}$O record, as well as the uncertainties on the layer-counted GICC05 chronology. A Monte Carlo approach (1000 simulations of the age model, calculated from starting depths and calendar ages selected randomly from within the 1-σ distribution of the sampling and chronological uncertainty) was then applied to generate a 1-σ uncertainty envelope for the tuned age–depth model (Table A.3).

We propose Age Models 1 and 2 as reasonable options, acknowledging that the assumption of constant sediment accumulation rates between tie points in Age Model 2 is probably not realistic. More detailed correlation to Greenland would require a $\delta^{18}$O reconstruction of higher resolution than recovered from this site. We evaluated an age model (not shown) based on interpolation of surface–ocean reservoir ages between points of correlation to Greenland (following a strategy similar to that of Skinner et al., 2010) but this approach yielded a result intermediate to those of Age Models 1 and 2, and would not change our general conclusions. We also considered tuning the age models based on radiocarbon “plateaus” with respect to depth (Lund and Mix, 1998; Sarnthein et al., 2007). Sedimentation rates are sufficiently variable on the continental margin that radiocarbon plateau tuning is not warranted here.

#### 3.2. Projection ages

Projection age calculation requires an independent chronology; here we evaluate the implications of Age Models 1 and 2. The projection method accounts for changes in atmospheric radiocarbon but not for the reservoir ages of the watermass source region(s) or changes in the mixing ratio of source regions with differing initial reservoir ages (Adkins and Boyle, 1997). Nonetheless, this method remains instructive where subsurface watermasses have experienced prolonged isolation from the atmosphere, as long as the potential mechanisms contributing to the projection age are considered in the interpretation. All projection ages were calculated here with respect to the IntCal13 atmospheric reconstruction (Reimer et al., 2013).

Benthic foraminiferal radiocarbon ages were converted into subsurface ocean $\Delta^{14}$C values ($\Delta^{14}$C<sub>deep</sub>) at site EW0408-85JC for Age Models 1 and 2 following standard methods (Stuiver and Polach, 1977) (Table A.3; Fig. 5). A Monte Carlo approach (1000
simulations for each dated sample including both chronological and radiocarbon analytical uncertainty) was applied to calculate a 1-σ uncertainty on the projection age intersection with the atmospheric calibration curve (Fig. 5). For Age Model 2, we also calculated apparent surface–ocean projection ages from planktonic $\Delta^{14}$C values (Table A.3). This calculation does not reflect time of isolation from the atmosphere, but it is useful in evaluating possible artifacts in the benthic age model. Planktonic $\Delta^{14}$C is enriched relative to the atmosphere younger than $\sim$8000 cal years BP on Age Model 2, resulting in negative projection ages; we reject this result as an artifact of tuning.

3.3. Northeast Pacific paleoventilation

Age Model 1 yields mean benthic projection ages for Holocene time ($\sim11,700$ cal years BP) of $1880 \pm 180$ years (±1-σ), and $2000 \pm 340$ years for the prior interval back to $\sim17,400$ cal years BP (Fig. 6). Relatively high benthic projection ages (i.e., >2000 years) occur intermittently during the glacial transition, with the highest values observed between $\sim14,600$ and $11,900$ cal years BP. The greatest benthic projection age of $2720 \pm 130$ years occurs at $12,290 \pm 105$ cal years BP and coincides with anomalously high benthic–planktonic $^{14}$C age differences of up to $1420 \pm 40$ years (Fig. 6), consistent with the presence of an aged watermass in the intermediate-depth North Pacific at that time.

In Age Model 2, the correlation to Greenland produces two distinct intervals of high benthic projection ages (Fig. 6). The older and larger excursion implies an increase in benthic projection ages to >3000 years between 15,770 ±60 and 14,800 ±60 cal years BP, with a peak of $3500 \pm 80$ years at $15,120 \pm 60$ cal years BP. In the younger excursion benthic projection ages are >2500 years between $14,030 \pm 500$ and $12,450 \pm 230$ cal years BP, with a peak of $3130 \pm 290$ years at $12,840 \pm 290$ cal years BP, similarly timed to, although larger in magnitude than, the large ventilation–age anomaly reconstructed on Age Model 1 and supported by the uncalibrated benthic–planktonic $^{14}$C data. These two events are reminiscent of (although not identical in timing to) benthic projection age anomalies inferred off Baja California and Oman based on an age model similarly tuned to the Greenland GISP2 ice core (Marchitto et al., 2007; Bryan et al., 2010)(Fig. 5; Fig. 6). Note, however, that the anomalously high benthic projection ages found by this method in the Gulf of Alaska site (and also in the Baja site) occur mostly in the intervals interpolated between the correlation points, and thus may be artifacts of this interpolation.

The planktonic foraminifera $^{14}$C data off Alaska, on Age Model 2, also produce anomalously high near-surface water projection ages, >2500 years, during the older of the two events (Table A.1;Fig. 6). If correct, this interpretation would imply that a hypothetical radiocarbon-depleted deep glacial watermass spread in essentially unaltered form to the high North Pacific, vented to the atmosphere here, and contributed to the abrupt drop in atmospheric $\Delta^{14}$C observed during Termination 1. However, such anomalously old apparent reservoir ages for planktonic foraminifera are inconsistent with other regional reconstructions based on plateau tuning (Sarnthein et al., 2007) and are implausibly of the same amplitude as the benthic events in spite of the dominance of watermass downwelling on this margin. Simple ocean models (Hain et al., 2011) suggest that such a scenario is unlikely; rapid dilution of intermediate-depth radiocarbon anomalies by strong ocean mixing near the sea surface and relatively rapid isotopic exchange of carbon with the atmosphere would almost certainly attenuate the surface ocean reservoir-age anomalies relative to those at depth.

Age Model 2 would imply rapid glacier retreat at $\sim15,000$ cal years BP, preceded by relatively constant sedimentation rates of $\sim150$ cm/ky within the glacial–marine unit and followed by an abrupt reduction to $\sim20$ cm/ky. This is inconsistent with cosmogenic isotope exposure dates and terrestrial radiocarbon constraints that suggest earlier glacier retreat (Briner et al., 2005; Shennan, 2009), as well as with sedimentological changes in core EW0408–85JC. The MSCL physical properties data sets, along with
ample, the abrupt warming associated with the onset of the Bølling
some climatic events in Alaska and Greenland are coeval (for ex-
variations with the Greenland Ice core. Although it is plausible that
BP (Fig. 7). In calibrated-planktonic Age Model 1, sediment ac-
web version of this article.)
warm/fresh regional surface ocean conditions at
both the tuned and calibrated age models as the transition to
the CT-scan image, show a clear transition from glacier-proximal
of changing lithology.
tion of constant sediment accumulation rate through this interval
by Age Model 2 for both benthic and planktic foraminifera in
ing glacial retreat. The large projection age anomalies produced
fine-grained sediment delivery and/or winnowing at the site dur-
1-
σ
14C data in the Age Model 2 panel are su-
14C at an equivalent density horizon to
2 illustrates the sensitivity of projection age calculations to
age-model determination should be undertaken cautiously and
with support from corroborating evidence.

Age Model 1 implies that sediment accumulation rates in the
glacial–marine diamict were >500 cm/ky, an order of magni-
tude greater than average Holocene sedimentation, but fell to
~50 cm/ky by 17,010 ± 150 cal years BP, prior to the end of
glacial–marine sedimentation (Fig. 7). This apparent decrease in
sedimentation rate within the diamict is associated with changes
in P-wave velocity, sediment density, and magnetic suscepti-
that evidence a reduction of fine-grained particles in this
interval (Fig. 7). Glacial–marine sediment accumulation rates to-
day are observed to fall exponentially with distance from ice
terminus (Cowen and Powell, 1991). Such a decrease in sedi-
mentation rate within the interval of glacial–marine sedimenta-
core EW04-08-85J) implies sequential retreat of the
marine margin of the Bering Glacier between ~17,000 and
~15,000 cal years BP, consistent with regional land-based dates
(Briner et al., 2005; Shennan, 2009), and pullback onto land by
14,820 ± 110 cal years BP. This suggests that initial retreat of
ice here was essentially synchronous with that of the southern
Cordilleran Ice Sheet (Porter and Swanson, 1998; Cosma and
Hendy, 2008), as well as with glaciers in Europe, South America,
and New Zealand during the so-called “Mystery Interval” (Denton
et al., 1999; Broecker and Barker, 2007), and likely associated with
the initial rapid deglacial rise of atmospheric CO2 and the warming
that followed (Shakun et al., 2012).

Age Model 1 thus suggests an increase in the apparent
14C age of subsurface watermasses during the deglaciation (between
~14,600 and 11,900 cal years BP). We find no evidence for venti-
lation events greater than today, as has been inferred in the western
Pacific (Okazaki et al., 2010, 2012, 2014; Max et al., 2014).
The likely implication is a reduction of ventilation or an incur-
sion of older water masses during the deglacial transition. This
assumes a relatively constant preformed 14C value in interme-
tate sources waters. An alternate interpretation could be an in-
crease in the preformed age of the source waters around Antarc-
tica or elsewhere (Marchitto et al., 2007; Skinner et al., 2010;
Lund et al., 2011), although Lund (2013) discounts this hypothesis.

The comparison of projection ages based on Age Models 1
and 2 illustrates the sensitivity of projection age calculations to
age model assumptions. We present these age models not as spe-
cific alternatives, but as commonly-employed simplistic approaches
among the range of options that must be considered when in-
terpreting regional radiocarbon anomalies. An alternate way to
evaluate oceanic radiocarbon information is based on benthic-
planktonic 14C differences. Between ~795 and ~780 cmbsf in the
core the uncalibrated benthic–planktonic 14C age differences
increase to over 1000 years, reaching a maximum of 1420 ± 40 years
at 790 cmbsf (dated at 12,290 ± 105 cal years BP on calibrated
Age Model 1, or 12,450 ± 230 cal years BP on tuned Age Model 2;
Fig. 6). This event is coincident with anomalously high projection
ages on both age models, and with the younger of two projec-
tion age anomalies inferred off Baja California (Marchitto et al.,
2007). The existence of this event is independent of the details
of chronology or the projection calculations and it is sufficiently
brief (<1500 yr) that it is unlikely to be an artifact of variations
in radiocarbon production rates; it likely documents the incur-
sion of a relatively 14C-deficient “old” watermass into the shallow
subsurface North Pacific during the second half of Termina-
tion I.

The incursion of an older watermass into the shallow sub-
surface North Pacific between ~12,500 and ~12,000 cal years
BP corresponds to the younger of two deglacial episodes of
rapid rise in atmospheric CO2 (Monnin et al., 2001, timescale of
Lemieux-Dudon et al., 2010; Fig. 8). At this time, the benthic-
planktonic age difference at core EW0408-85JC converges to nearly the same value as deeper Northeast Pacific sites (Lund et al., 2011). In contrast, we find no equivalent evidence for similar homogenization of subsurface radiocarbon between intermediate and deep waters associated with the older event of rapid CO2 rise beginning at ∼18,500 cal years BP. Independent of calculations of projection age, the homogenization of benthic–planktonic age differences across a broad range of depths during the younger CO2 rise implies that the North Pacific could be part of the pathway transferring “aged” carbon from the deep ocean to the atmosphere (in turn contributing to a relatively rapid reduction in the Δ14C signature of atmospheric carbon) during the late stages of the deglacial transition. This does not imply that venting of an aged watermass at the sea surface actually occurred near the site of core EW0408-85JC. If the 14C-deficient subsurface watermass was also present at the sea surface, then benthic–planktonic age differences would be diminished; strong haline stratification and convergent downwelling along the continental margin likely precludes net release of marine CO2 to the atmosphere here. If the older watermass observed in core EW0408-85JC vented CO2 to the atmosphere in the North Pacific, a more likely place for that to occur would be in the western Pacific or Bering Sea, where winter overturn of the watermass occurs today. Unlike the highly stratified Gulf of Alaska, the venting region would likely record low benthic–planktonic age differences because of anomalously high surface–ocean reservoir ages. Such low age differences have been observed in the Okhotsk and Bering Sea during deglaciation (Max et al., 2014) although they have been interpreted as evidence of more vigorous intermediate water circulation (accompanied by high benthic δ13C) rather than as anomalously old surface–ocean reservoir ages.

Our finding of modestly reduced ventilation during late glacial time relative to modern is supported by evidence for greater watercolumn stratification during times of low sea level when the Bering Strait was closed (Zahn et al., 1991; Sigman et al., 2004). The well documented events of regional deglacial hypoxia from 14,800–13,000 cal years BP and 11,200–10,800 cal years BP are not related to abrupt stagnation events, but more likely are associated with high production and export of organic matter from near-surface waters (Davies et al., 2011; Cook et al., 2005). It is plausible, however, that the general reduction in ventilation during the deglacial interval may have pre-conditioned the system to be more sensitive to hypoxia caused by peaks in productivity.
On Age Model 1, benthic projection ages decreased (implying more effective or faster ventilation) starting at 11,510 ± 115 cal years BP (Fig. 6); Holocene (0–11,700 years BP) benthic projection ages average 1880 ± 180 years (standard error of mean, \( n = 18 \)). The apparent increase in ventilation occurs at about the same time as the flooding of the Beringian continental shelf and the opening of a connection to the Arctic Oceans via the Bering Strait. Radiocarbon dates of ~11,500 \(^{14}\text{C}\) years (with a reservoir age correction of 750 years) associated with the appearance of a Pacific bivalve in the Arctic Ocean, suggest that Bering Strait opened near ~11,800 cal years BP (Cook et al., 2005; Keigwin et al., 2006). Radiocarbon dates of 11,000 ± 60 \(^{14}\text{C}\) years on now-submerged terrestrial peats indicate Bering Strait opening prior to ~12,900 cal years BP (Elias et al., 1996). A marine foraminiferal record of transition from estuarine to fully marine conditions north of Bering Strait is dated at ~10,900 ± 140 \(^{14}\text{C}\) years (with a reservoir age correction of 300 years) suggests Bering Strait opening near ~11,800 cal years BP (Talley, 1991; Watanabe and Wakatsuchi, 1998). Although flooding of the Bering shelves may have been a gradual process, multiple lines of evidence suggest that the marine connection between the Arctic and Pacific oceans likely occurred at some point between ~13,200–11,800 cal years BP.

Today, ventilation of North Pacific Intermediate Water depends on the formation of Dense Shelf Water in the Sea of Okhotsk (Talley, 1991; Watanabe and Wakatsuchi, 1998). Northward export of buoyant low salinity surface waters via the Bering Strait helps this process by weakening haline stratification in the North Pacific (Emile-Geay et al., 2003; de Boer and Nof, 2004). The rise of
sea level that flooded the Beringian shelf and opened the Bering Strait for northward export of low-salinity surface waters may have conditioned the North Pacific for more effective ventilation of intermediate water during Holocene time.

4. Conclusions

Evaluated on a plausible chronology provided by the calibrated planktonic radiocarbon dates (Age Model 1), projected ventilation ages for intermediate waters of the Northeast Pacific were on average equivalent or greater during glacial and deglacial time (2000 ± 340 years between ~17,400 and 11,900 cal years BP, standard error of mean, n = 20), than during Holocene time (1830 ± 170 years, standard error of mean, n = 18). The apparent decrease in subsurface ventilation ages to Holocene values follows inundation of the Bering shelves and opening of Bering Strait, underscoring the importance of flooded continental shelves and Arctic export of low-salinity surface water to the North Pacific formation of intermediate waters.

Prior to ~14,500 cal years BP we find no evidence for an aged intermediate watermass in the Northeast Pacific. However, independent of the choice of age model, high benthic–planktonic radiocarbon age differences indicate near-homogenization of abyssal radiocarbon between intermediate and deep waters (Lund et al., 2011), coincident with the younger of two deglacial episodes of rapid rise in atmospheric CO₂ (Monnin et al., 2001). This finding likely implicates the high latitude North Pacific (although not the Gulf of Alaska) as a source of venting of aged carbon from the deep ocean to the atmosphere during the younger event of deglacial CO₂ rise around 12,500–12,000 cal years BP.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.epsl.2014.04.004.


