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Increased ventilation age of the deep northeast Pacific Ocean during the last deglaciation

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The rise in atmospheric carbon dioxide during the last deglaciation may have been driven by the release of carbon from the abyssal ocean[1,2]. This mechanism would require a poorly ventilated deep Pacific Ocean during the Last Glacial Maximum and enhanced exchange with the atmosphere during deglaciation. Here we use radiocarbon measurements of planktonic and benthic foraminiferal shells from a core collected at 2.7 km water depth in the northeast Pacific to estimate the ventilation age of deep waters using the projection age method. In contrast to the above scenario, we show that ventilation ages during the Last Glacial Maximum were similar to today. This suggests that this part of the Pacific was not an important reservoir of carbon during glacial times. During deglaciation, ventilation ages increased by ∼1,000 years, indicating a decrease in the ventilation rate, an increase in the surface water reservoir age in the Southern Ocean, or an influx of old carbon from another source. Despite the increased ventilation age during deglaciation, the deep northeast Pacific still had a higher ^{14}C/C ratio than intermediate waters near Baja California[3]. We therefore conclude that the deep northeast Pacific was apparently not old enough to be the source of deglacial radiocarbon anomalies found shallower in the water column.

During the Last Glacial Maximum (LGM; ∼20,000 years ago), atmospheric carbon dioxide levels were 80–90 ppm lower than pre-industrial values[4]. Because more than 90% of oceanic, atmospheric and terrestrial carbon resides in the deep ocean, this reservoir is believed to play a primary role in regulating atmospheric CO_2 on glacial–interglacial timescales[5,6]. Given that the Pacific dominates the global ocean from a volumetric standpoint, constraining its ventilation rate is critical for evaluating the ocean's role in glacial–interglacial CO_2 changes.

We reconstruct the ventilation history for the deep NE Pacific using planktonic (surface dwelling) and benthic (seafloor dwelling) foraminifera from sediment core W8709A-13PC (42.1° N, 125.8° W, 2,710 m water depth), located approximately 120 km off the coast of southwestern Oregon[7]. This site monitors North Pacific Deep Water, the oldest watermass in the modern ocean (Supplementary Fig. S2). Our reconstruction is based on 89 radiocarbon measurements spanning from approximately 22,000 to 8,000 ^{14}C yr BP (Fig. 1). The average sedimentation rate during the LGM and deglaciation is 27 cm kyr^{-1}. Five isolated planktonic ^{14}C ages from 70 to 350 cm out of stratigraphic order by more than their one-sigma analytical uncertainty. Because these samples were probably affected by bioturbation, they are not included in our estimates of ventilation age. One benthic ^{14}C age is excluded as a result of its large analytical error (>1 kyr; see Supplementary Information).

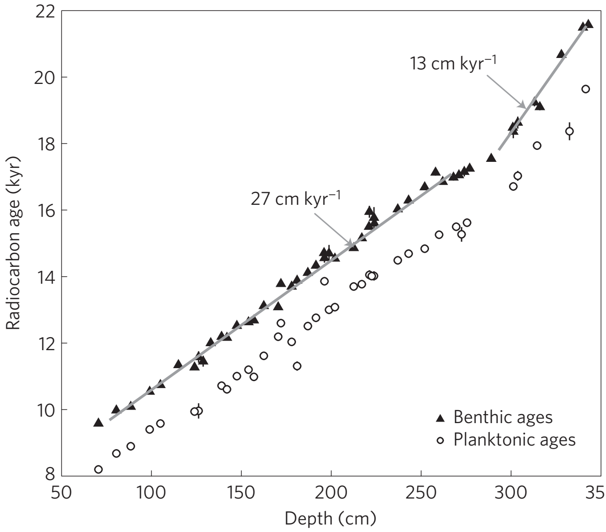

Figure 1 | Age model for W8709A-13PC showing planktonic (circles) and benthic (triangles) radiocarbon ages plotted versus depth in the core. The average sedimentation rate for the LGM and deglaciation is 27 cm kyr^{-1}. The planktonic ages at 170.5, 172, 181, 196, and 272.5 cm represent age reversals and they are not used in subsequent figures.

We estimate the mean benthic–planktonic age difference (B–P age) for W8709A-13PC was 1,580 ± 210 years (1σ) during the LGM (18–23 kyr BP, based on calendar-corrected planktonic dates; $n = 6$ pairs). This value is indistinguishable from the mean B–P age for the deglaciation of 1,530 ± 230 years (10–18 kyr BP; $n = 24$ pairs) and the modern pre-bomb difference between surface and deep water ^{14}C ages (1,420 ± 60 years; see Supplementary Information). The only clear change in B–P ages occurs during the early Holocene from 8 to 10 kyr BP (1,230 ± 100 years; $n = 5$), which postdates the deglacial increase in atmospheric CO_2 (ref. 4; Fig. 2b). Estimates of ^{14}C ventilation age (that is, benthic reservoir age) show a similar pattern (Fig. 2c; see Methods). The LGM and deglacial B–P ages from W8709A-13PC are consistent with results from 2.8 km water depth in the western equatorial Pacific[8]. Thus, it seems the LGM ventilation rate at 2.7–2.8 km in the Pacific was similar to today. A recent compilation of B–P ages from the western North Pacific suggests that ventilation rate of intermediate waters increased early in the deglaciation, but data at water depths greater than 1,500 m are inconclusive[9].

Although straightforward to calculate, B–P and ^{14}C ventilation ages are problematic when atmospheric Δ^{14}C varies through time because deep waters retain a memory of Δ^{14}C from when

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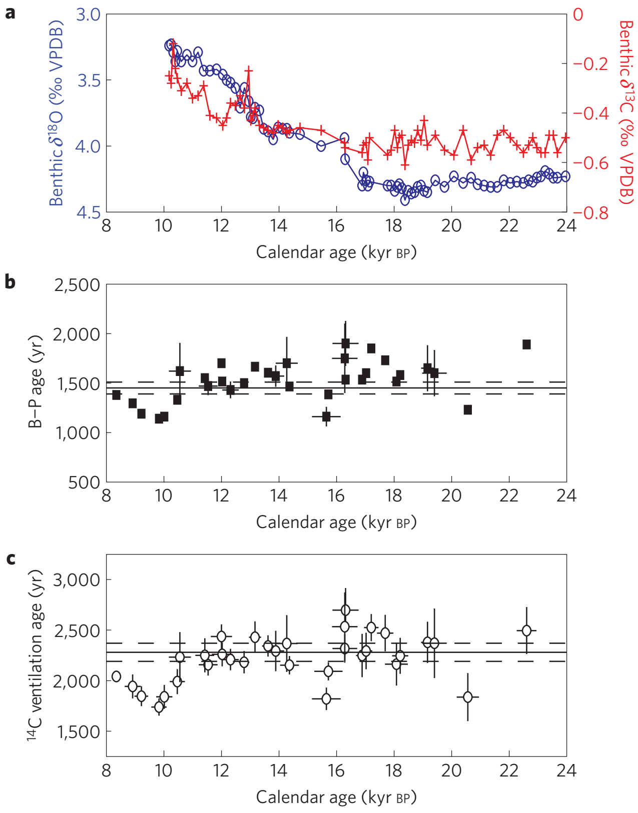

Figure 2 | Stable isotope data, benthic–planktonic ages, and ^{14}C ventilation ages for W8709A-13PC. a, Benthic foraminiferal $\delta^{18}O$ (blue circles) and $\delta^{13}C$ (red crosses) for W8709A-13PC (ref. 7) plotted using the calendar ages presented in this paper. **b**, Benthic–planktonic ^{14}C ages spanning the LGM and deglaciation, with one-sigma error bars. Solid black line is the difference in ^{14}C age between water at 2,710 m and surface water near the core site today (see Supplementary Information). Dashed lines are the $\pm 1\sigma$ uncertainty. Overall there is little change in B–P age from the LGM through deglaciation, with the exception of younger B–P ages in the early Holocene. **c**, Estimates of ^{14}C ventilation age (that is, benthic ^{14}C ages minus contemporaneous atmospheric ^{14}C ages). Solid black line is the difference in ^{14}C age between water at 2,710 m and the modern atmospheric ^{14}C age (see Supplementary Information). Dashed lines are the $\pm 1\sigma$ uncertainty.

they were last in contact with the atmosphere. To account for variable atmospheric $\Delta^{14}C$ during the last deglaciation, we use the projection age method[10] (see Methods). This approach is based on two assumptions. First, the ^{14}C content of a watermass must be subject to closed system decay; that is, it is not influenced significantly by mixing with watermasses with different radiocarbon values. Second, the preformed ^{14}C for the deep watermass must not change significantly through time. If these assumptions are approximately correct, the projection age method will yield ventilation ages that more accurately reflect the amount of time elapsed since water in the ocean interior was last at the sea surface.

To estimate $\Delta^{14}C$ at 2.7 km water depth, we use a local surface water reservoir age of 730 ± 200 years (1σ), which we propagate through the calendar calibration to estimate uncertainty in our calendar ages (see Methods). We also create an alternative calendar chronology for W8709A-13PC by matching changes in planktonic foraminiferal faunal abundance to the well-dated Bølling–Allerød and Younger Dryas events in the North Greenland Ice Core Project (NGRIP) $\delta^{18}O$ record (Supplementary Fig. S1). Both approaches yield similar calendar ages, indicating that surface water reservoir ages varied by less than ±200 years during the deglaciation.

Estimates of benthic $\Delta^{14}C$ for W8709A-13PC are shown in Fig. 3a. Also included are the decay trajectories for each benthic $\Delta^{14}C$ result. The difference in calendar age for each benthic $\Delta^{14}C$ value and its intersection point with the INTCAL09 atmospheric $\Delta^{14}C$ curve is the projection age relative to the atmosphere[10]. We subtract the surface water reservoir age for the Southern Ocean to obtain projection ages for the deep NE Pacific (see Methods). The projection ages from 17 to 21 kyr BP (1,360 ± 270 years) are within the error of the modern value (1,220 ± 200 years; Fig. 3b). From 17 to 14 kyr BP, projection ages increased by ~1,000 years, followed by a gradual return to LGM-like values by 12 kyr BP. Note that the timing of the deglacial projection age anomaly depends on the calendar calibration. If instead we use INTCAL04, which differs from INTCAL09 during the early deglaciation (Supplementary Fig. S4), the increase in projection age for W8709A-13PC begins at ~18 kyr BP (Supplementary Fig. S7).

The deep subpolar NE Pacific had a similar overall history of projection ages from 20 to 10 kyr BP. At 3,650 m water depth, projection ages were stable or decreased from 20 to 17 kyr BP and then increased by 1–2 kyr between 17 and 14 kyr BP (Fig. 3c)[11–13]. After 14 kyr BP, projection ages at 3,650 m approached modern values, consistent with the pattern at 2,710 m. The time history of projection ages at 2,800 m in the western equatorial Pacific matches the NE Pacific pattern[8] (Fig. 3c), suggesting that multiple water depths and locations in the Pacific experienced a similar ventilation history.

Higher projection ages during the deglaciation may have been due to: (1) decreased ventilation of the deep Pacific, (2) lower preformed $\Delta^{14}C$ values in the source region for deep Pacific waters, or (3) input of old carbon from another source. The first option seems unlikely given inferred higher rates of upwelling and deep overturning in the Southern Ocean during the deglaciation[14]. A decrease in the ventilation rate of the deep Pacific from ~17 to 12 kyr BP would have also increased the residence time of water in the abyss. Such a change would promote the sequestration of respired carbon, inconsistent with the idea that release of CO_2 from the abyssal ocean drove the deglacial increase in atmospheric CO_2 (ref. 1).

Alternatively, the increase in Pacific projection ages may have been driven by lower preformed $\Delta^{14}C$ values (that is older surface water reservoir ages) in the Southern Ocean. Such a change seems plausible if this region was the pathway by which ^{14}C-depleted carbon was released from the deep ocean[3]. Surface water reservoir ages at 44° S in the Atlantic sector of the Southern Ocean apparently increased by ~1 kyr during the deglaciation[2], but the timing of this anomaly (~16–21 kyr BP) is different from the projection age anomaly in W8709A-13PC (~12–17 kyr BP). The core site in ref. 2 is also located north of the modern Antarctic Polar Front and therefore not an optimal location for monitoring the preformed ^{14}C value of Pacific deep waters. Enhanced upwelling south of the Antarctic Polar Front from 10 to 16 kyr BP (ref. 14) may have yielded older surface water reservoir ages, but the resulting signal would have arrived in the deep NE Pacific after 15 kyr BP, inconsistent with the projection age history. An increase in reservoir age would also make the calendar age model for the upwelling time series in ref. 14 younger, creating an even larger time offset between the Southern Ocean and deep Pacific records. Reduced flux of ^{14}C-enriched deep water from the North Atlantic into the Southern Ocean during Heinrich Stadial 1 (ref. 15) may have lowered the preformed $\Delta^{14}C$ value for Pacific deep waters, but the vertical profile of $\Delta^{14}C$ in the deep North Atlantic was similar during both the LGM and Heinrich Stadial 1 (ref. 16). In summary, there is little evidence to support an increase in preformed $\Delta^{14}C$ for Pacific deep waters during the deglaciation.

One other possible explanation of the high projection ages during the deglaciation is input of ^{14}C-depleted carbon from an abyssal reservoir. Accounting for the projection age anomaly at 2,710 m

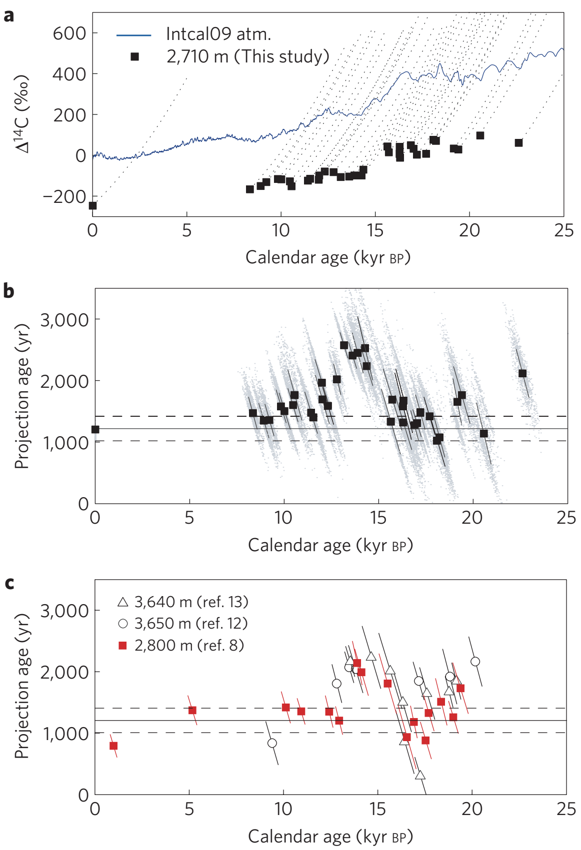

Figure 3 | Summary of projection age estimates for the deep Pacific. **a**, Time series of benthic Δ^{14}C for W8709A-13PC (black squares) plotted with radiocarbon decay trajectories (dashed lines) and INTCAL09 atmospheric Δ^{14}C (blue line)[24]. **b**, Projection ages for W8709A-13PC (black squares) assuming a 1,100 year surface water reservoir age in the deep water formation region (see Methods). The full range of projection ages (grey dots) and the ±1σ range (sloping black lines) are shown for each point. Solid horizontal line is the projection age for the modern NE Pacific at 2.7 km water depth (1,220 years) and dashed lines are the 1σ uncertainty (±200 years). The deglacial anomaly in projection ages begins at ~18 kyr BP when the INTCAL04 calibration is used (Supplementary Fig. S7). **c**, Projection ages for 3,650 m in the NE Pacific (ODP 887; circles)[11], 3,640 m in the NE Pacific (MD02-2489; triangles)[12], and 2,800 m in the western equatorial Pacific (MD01-2386; red squares)[8]. The age model for ODP 887 was taken directly from ref. 11 whereas the age model for MD02-2489 was based on planktonic radiocarbon ages in ref. 12 (see Supplementary Information).

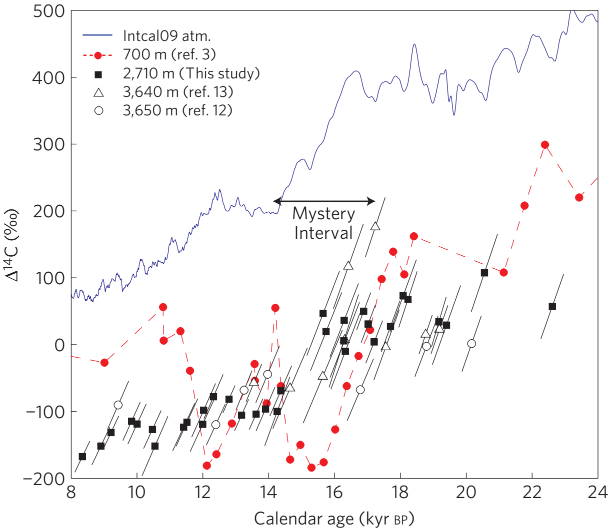

Figure 4 | Time series of northeast Pacific Δ^{14}C. Δ^{14}C for 2,710 m water depth (W8709A-13PC; black squares), 3,650 m (ODP 887; circles)[11], 3,640 m (MD02-2489; triangles)[12], and 700 m (MV99-MC19-GC31-PC08; red circles)[3]. Atmospheric Δ^{14}C is shown in blue (INTCAL09; ref. 24). Error bars for the oceanic Δ^{14}C values represent the compounded uncertainty from the benthic ^{14}C age and its paired planktonic calendar age (see Methods). The Δ^{14}C uncertainty for W8709A-13PC is dominated by the calendar age uncertainty, which is in turn primarily a function of the assigned reservoir age error (±200 years; 1σ). During the Mystery Interval and Younger Dryas, deep Pacific Δ^{14}C was more positive than at 700 m water depth. The age model for ODP 887 was taken directly from ref. 11 whereas the age model for MD02-2489 was based on planktonic radiocarbon ages in ref. 12 (see Supplementary Information).

water depth would require water 1,000 years older, with no dilution by mixing. There is at present no evidence for such an old watermass in the NE Pacific. The Δ^{14}C of water at 3.6 km was approximately 0‰ during the LGM (refs 11,12), similar to that at 2.7 km (Fig. 4). Evidence for an old abyssal reservoir is also lacking at 4,400 m in the tropical Pacific[17]. Although we cannot completely reject this scenario, it seems to be implausible based on the available data.

Our results are relevant for understanding the large Δ^{14}C anomalies documented near Baja California[3] and the Galapagos[18] during the last deglaciation. In W8907A-13PC, benthic Δ^{14}C values of ~50‰ during the LGM decreased to −150‰ during the early Holocene, with an overall trend similar to atmospheric Δ^{14}C (Fig. 4). Before 18 kyr BP and after 12 kyr BP, Δ^{14}C in the deep Pacific was lower than at intermediate depths, which is to be expected given the longer residence time for deep waters. However, the vertical Δ^{14}C gradient in the NE Pacific was reversed for much of the deglaciation. During the Mystery Interval (17.5–14.5 kyr BP; ref. 1), Δ^{14}C at 2,710 m water depth remained near 0‰, whereas Δ^{14}C at 700 m plunged to −200‰. Because Δ^{14}C of the deep North Pacific was much less depleted than −200‰, it is an unlikely source of old carbon. Water at 3,650 m may have been somewhat older than at 2,710 m, but it was still not old enough to account for anomalies at intermediate depths (Fig. 4).

Given that neither changes in circulation nor an abyssal source of old carbon can easily account for the ventilation history of the Pacific, we speculate that input of ^{14}C-depleted carbon from another source may have been involved. One possibility is carbon from the mantle ($\Delta^{14}C = -1{,}000$‰, $\delta^{13}C = -7 \pm 2$‰; ref. 19). If mantle carbon drove the ~100‰ decrease in deep Pacific Δ^{14}C during the early deglaciation, there should be a contemporaneous δ^{13}C anomaly of approximately −0.7‰. Although there is no evidence for such a change in the benthic δ^{13}C record in W8709A-13PC (Fig. 2), the magnitude of the signal would be mitigated in the deep ocean by dissolution of carbonate ($\delta^{13}C \sim 0$‰). Additional influences on benthic foraminiferal δ^{13}C, such as growth of the terrestrial biosphere[20], local changes in export production[21], and air–sea gas exchange[22,23] could further obscure any mantle δ^{13}C anomaly. Full evaluation of the mantle CO_2 possibility will require careful scrutiny of high-resolution δ^{13}C time series from multiple locations and water depths in the Pacific, Indian, and Atlantic oceans.

Methods

Core W8709A-13PC comes from the eastern flank of the Gorda Ridge and is composed of primarily hemipelagic clay with low carbonate and opal content[7]. Thin sand layers (inferred turbidites) at 206–208, 230–232, 252–256, 322–325, and 355–358 cm were avoided during sampling. The one exception at 252 cm yields a planktonic ^{14}C age consistent with the age model (Fig. 1). Samples were freeze-dried and washed with distilled water over a 150 μm sieve. Planktonic

(*Neogloboquadrina pachyderma* and *Globigerinoides ruber*) and mixed benthic foraminifera (avoiding infaunal genera such as *Globobulimina*) were picked from the $>150\,\mu$m size fraction, sonicated in distilled water to remove debris, and dried at low heat. Foraminiferal samples were analysed for ^{14}C at the Keck Carbon Cycle Accelerator Mass Spectrometry (AMS) Laboratory at the University of California, Irvine. Each sample was leached in 0.1 N HCl to remove contaminants, and the remaining calcite was hydrolized in 85% phosphoric acid and then reduced to graphite for analysis by AMS. Radiocarbon results are provided in Supplementary Tables S1 and S2. Note that the sample at 272.5 cm in Supplementary Table S2 was erroneously labelled 227.5 cm in the original published data[21].

We developed the age model for W8709A-13PC by converting planktonic ^{14}C ages to calendar ages using CALIB 6.0 (http://calib.qub.ac.uk/calib/), which is based on the INTCAL09 calibration curve[24]. We used a surface water reservoir age of 730 years, based on the three nearest Oregon coast locations in the CALIB marine reservoir database[25]. We assign a one-sigma reservoir age uncertainty of ±200 years, which yields calendar ages with a typical one-sigma error of ±300 years. An alternative chronology based on correlation of % *N. pachyderma* in W8709A-13PC to the Bølling–Allerød and Younger Dryas events in the NGRIP $\delta^{18}\mathrm{O}_{\mathrm{ice}}$ record gives similar results (Supplementary Fig. S1), implying that surface water reservoir ages varied by less than ±200 years during the deglaciation.

Estimates of deep Pacific Δ^{14}C are based on the following equation:

$$\Delta^{14}\mathrm{C} = (Fe^{\lambda(\text{calendar age})} - 1) \times 1{,}000‰$$

where F is the fraction modern for benthic foraminifera, $\lambda = 1/8{,}267$ is the decay constant for ^{14}C with a 5,730 year half-life[26] and calendar age is the calibrated age based on planktonic foraminifera. Uncertainty estimates reflect the compounded analytical uncertainty of F and calendar age, determined using a Monte Carlo approach. For clarity, we plot only the major axis of each error ellipse in Fig. 4.

We estimate ventilation age using three separate techniques, including benthic–planktonic (B–P) age differences, ^{14}C ventilation ages, and projection ages. B–P age differences were calculated by subtracting the planktonic ^{14}C age from the benthic ^{14}C age at the same stratigraphic level. Radiocarbon ventilation ages were calculated by subtracting INTCAL09 atmospheric ^{14}C ages from contemporaneous benthic ^{14}C ages[2]. (Radiocarbon ventilation ages are the same as benthic reservoir ages.) Uncertainty for the ^{14}C ventilation ages was determined using the range of atmospheric ^{14}C ages that correspond to the $\pm 1\sigma$ range in calendar age for each benthic data point.

We also estimated ventilation age using the projection age method[10]. This method takes into account atmospheric Δ^{14}C ($\Delta^{14}\mathrm{C}_{\mathrm{atm}}$) at the time of watermass formation and therefore compensates for changes in the slope of the $\Delta^{14}\mathrm{C}_{\mathrm{atm}}$ curve that may produce spurious ventilation ages. We calculate the projection age relative to the atmosphere by determining the difference in calendar age of a benthic Δ^{14}C value and the point at which this value intersects the atmospheric Δ^{14}C curve when it is projected backwards in time according to the radiocarbon decay trajectory. To determine the projection age, we then subtracted the surface water reservoir age in the deep water formation region. We used a mean value of $1{,}100 \pm 200$ years (1σ), which is based on all points south of 60° S in the CALIB Marine Reservoir Correction Database ($n = 16$; http://calib.qub.ac.uk/marine/). The projection age method assumes that the surface water reservoir age in the zone of watermass formation remains approximately constant, and that subsurface watermasses undergo closed system ^{14}C decay (that is, limited mixing with other watermasses). Higher projection ages may reflect either slower circulation, an increase in the preformed reservoir age, or mixing with an older carbon source.

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Author contributions

D.C.L. and A.C.M. initiated the project. D.C.L. processed the sediment samples for foraminifera and D.C.L. and A.C.M. prepared the foraminifera for ^{14}C dating. J.S. performed the radiocarbon analyses and initial data quality assessment. D.C.L. performed the ventilation age calculations and wrote the initial manuscript. Both A.C.M. and J.S. provided key editorial input during the writing process.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://www.nature.com/reprints. Correspondence and requests for materials should be addressed to D.C.L.