**Reduced deep ocean ventilation in the Southern Pacific Ocean during the last glaciation
persisted into the deglaciation**

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28 **ABSTRACT**

29 Marine radiocarbon (^{14}C) is widely used to trace ocean circulation and the ^{14}C levels of interior
30 ocean water masses can provide insight into atmosphere-ocean exchange of CO_2 the since the
31 last glaciation. Using tephras as stratigraphic tie points with which to estimate past atmospheric
32 $\Delta^{14}\text{C}$, we reconstructed a series of deep radiocarbon ages for several time slices from the last
33 glaciation through the deglaciation and Holocene in the Southwestern Pacific. Glacial ventilation
34 ages were much greater in magnitude than modern and had a strong mid-depth $\Delta^{14}\text{C}$ minimum
35 centered on ~2500 m. Glacial radiocarbon ages of intermediate depth waters (600-1200 m) were
36 ~800 to 1600 ^{14}C years, about twice modern and persisted through the early deglaciation.
37 Notably, in the glaciation shallower depths were significantly more enriched in ^{14}C than waters
38 between 1600-3800m, which were ~4000 to 6200 ^{14}C years, or about 3-5 times older than
39 modern. Abyssal waters deeper than 4000m were also more ^{14}C rich than the overlying deep
40 water. With radiocarbon ages of 1800-2300 ^{14}C years, this was similar to modern values. In the
41 early deglaciation, $\Delta^{14}\text{C}$ depleted waters were flushed from shallower depths first and replaced
42 with progressively younger waters such that by ~18 ka, the deep to intermediate age difference
43 was reduced by half, and by ~14 ka a modern-type $\Delta^{14}\text{C}$ profile for deep ocean water masses was
44 in place. Our results 1) confirm a deep ^{14}C depleted water mass during the LGM and early
45 deglaciation, and 2) constrain the extent of this “old” water in the Southern Pacific as between
46 1600m and 3800m. The availability of atmospheric ages from tephras reveals that the presence
47 of older surface reservoir ages in the glaciation caused the estimation of ventilation ages from
48 simple benthic-planktonic offsets to significantly underestimate the depletion of $\Delta^{14}\text{C}$ in deep
49 waters. This may have had a role in masking the large change in reservoir ages since the
50 glaciation when using benthic-planktonic reservoir age estimates.

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53 **1. INTRODUCTION**

54 The ocean is the dominant reservoir of exchangeable carbon on the Earth's surface, containing
55 about 60 times the CO₂ of the atmosphere. The radiocarbon (¹⁴C) content of the atmosphere and
56 ocean CO₂ reservoirs is dynamic, reflecting the balance between ¹⁴C production in the
57 atmosphere, equilibration with surface waters, aging of isolated interior water, and the
58 subsequent cycling of those waters back to the mixed layer of the ocean. These influences make
59 marine radiocarbon a viable tracer of deep-water circulation in the modern and past ocean. On
60 millennial time scales, the capacity for sequestration of CO₂ in the deep ocean is influenced
61 strongly by the pace of global thermohaline circulation (e.g., Sigman et al., 2010). During the
62 last glacial period, atmospheric CO₂ levels were ~90 ppm lower than Holocene values (Monnin
63 et al., 2001) and most mechanisms proposed for this reduction invoke circulation changes that
64 sequester CO₂ in the ocean (Broecker and Peng, 1993; Francois et al., 1997; Knox and McElroy,
65 1984; Sarmiento and Toggweiler, 1984; Siegenthaler and Wenk, 1984; Sigman and Boyle, 2000;
66 Stephens and Keeling, 2000; Toggweiler, 1999).

67 Air-sea gas exchange in the Southern Ocean plays an important role in regulating the distribution
68 of CO₂ between the ocean and atmosphere (e.g. Sigman and Boyle, 2000; Takahashi et al.,
69 2009). Today, Circumpolar Deep Water (CPDW; ~1600-3000 m), rich in respired CO₂ upwells
70 around Antarctica. Part of this upwelled CPDW is transported northward as surface water, which
71 warms and freshens while losing CO₂ to the atmosphere before sinking to form Antarctic
72 Intermediate Water (AAIW; 800-1600 m) (Orsi et al., 1995). Warmer, saltier and less dense
73 Subantarctic Mode Water (SAMW; 400-800 m) forms farther north (Belkin and Gordon, 1996).
74 Both AAIW and SAMW flow northward beneath the subtropical surface waters of the Pacific
75 Ocean. These shallow interior water masses retain the signal of atmospheric gas exchange in the
76 Southern Ocean in their enriched $\Delta^{14}\text{C}$ signatures (Key and al., 2004).

77 Changes in shallow circulation can control the radiocarbon content of surface water ($\Delta^{14}\text{C}$) on
78 decadal time scales (Druffel and Griffin, 1993; Druffel et al., 2014) ($\Delta^{14}\text{C}$ is defined as the ¹⁴C
79 activity corrected for mass-dependent fraction and corrected for decay using the Godwin half-life
80 for known-age samples (Stuiver and Polach, 1977)). Changes in thermohaline circulation that
81 alters the true ventilation rate (or age since formation) will affect the $\Delta^{14}\text{C}$ of deep water. This in

turn can alter the $\Delta^{14}\text{C}$ of the surface water at formation sites. Inhibited air-sea exchange in the Southern Ocean during the last glaciation has been suggested to have reduced the outgassing of CO_2 and to have lowered the initial $\Delta^{14}\text{C}$ content of waters formed there (e. g. Francois et al., 1997; Sigman and Boyle, 2000; Toggweiler, 1999; Toggweiler et al., 2006). Evidence of higher $\Delta^{14}\text{C}$ levels in the atmosphere (Muscheler et al., 2004) are consistent with this mechanism.

The behavior of the ocean-atmosphere system on glacial timescales is known to have been strongly influenced by fundamental changes in thermohaline circulation. Globally, evidence from the last glaciation for low $\Delta^{14}\text{C}$ in deep ocean waters does indicate more poorly ventilated deep waters, but the magnitude of this radiocarbon evidence is highly variable spatially. The North Atlantic and North Pacific appear to have been significantly depleted in ^{14}C relative to today below around 2.5 km (Galbraith et al., 2007; Keigwin, 2004; Keigwin and Schlegel, 2002; Robinson et al., 2005; Shackleton et al., 1988). Data from high latitude southern hemisphere locations suggests that both deep and intermediate waters were ^{14}C -depleted (Barker et al., 2010; Burke and Robinson, 2012; Goldstein et al., 2001; Sikes et al., 2000; Skinner et al., 2015; Skinner et al., 2010). Overall, $\Delta^{14}\text{C}$ estimates for the LGM deep ocean based on ^{14}C -independent chronologies (coral based U/Th) have by and large, older ages (Adkins et al., 1998; Burke and Robinson, 2012; Robinson et al., 2005) than those based on benthic-planktonic foraminiferal difference estimates (Broecker et al., 2008; Broecker et al., 2004)

Numerous other geochemical evidence point to higher levels of respired dissolved inorganic carbon in the glacial deep ocean (e.g. Curry and Oppo, 2005; Galbraith et al., 2007; Lund et al., 2011). The ^{14}C -depletion below 2.5 km observed in the Atlantic (Keigwin, 2004; Keigwin and Schlegel, 2002; Robinson et al., 2005) is also reflected in $\delta^{13}\text{C}$ records from that ocean (Lund et al., 2011). In the Pacific, depleted $\delta^{13}\text{C}$ (Sikes et al submitted, (Charles et al., 2010; McCave et al., 2008) also supports the available ^{14}C data (Shackleton et al., 1988; Sikes et al., 2000) indicating the sequestration of respired CO_2 in a poorly ventilated glacial ocean. The rapid response of the ocean-atmosphere system to changes in circulation is borne out by the evidence that ocean circulation changes associated with climate fluctuations even as brief as the Younger-Dryas are known to alter atmospheric ^{14}C and surface ocean ^{14}C levels (Bard et al., 1994; Edwards et al., 1993; Hughen et al., 2004; Hughen et al., 1996; Hughen et al., 2000; Siani et al., 2013; Stocker and Wright, 1996). Nonetheless, detailed records of the deep-ocean $\Delta^{14}\text{C}$ history

have proved elusive, without which a full accounting of the volume and $\Delta^{14}\text{C}$ of this reservoir continues to prove intractable (Broecker and Barker, 2007).

Volcanic tephra provide regional stratigraphic markers that can be used to correlate marine and terrestrial records. These linked marine-terrestrial time horizons enable the calculation of absolute offsets between atmosphere and deep ocean $\Delta^{14}\text{C}$ levels. Within the marine record, this allows the interpretation of foraminiferal data without assuming a surface-ocean reservoir age, which is a necessary step in conventional benthic-planktonic calculations. Such assumptions cannot fully account for any transient changes in the reservoir age of surface water (e.g. Bard et al., 1994; Siani et al., 2013; Sikes and Guilderson, 2015 submitted; Sikes et al., 2000) and these assumptions introduce uncertainty into the estimation of water mass ages. In New Zealand, numerous studies correlating radiocarbon-dated plant material associated with macroscopic ash fall layers resulting from volcanic eruptions on the North Island of New Zealand has created a robust tephra stratigraphy (Alloway et al., 2007; Lowe et al., 2013; Lowe et al., 2008; Vandergoes et al., 2013). These terrestrial studies have provided atmospheric ^{14}C ages for the time of the tephra eruptions (e.g. Lowe et al., 2013). Studies using ash layers provide stratigraphic control and a direct reference to past atmospheric $\Delta^{14}\text{C}$. Both indicate significant age changes in both surface and deep waters during the last glaciation and deglacial transition (Bard et al., 1994; Rose et al., 2010; Siani et al., 2013; Sikes and Guilderson, 2015 submitted; Sikes et al., 2000; Skinner et al., 2015).

Here, we present both new and previously published foraminiferal ^{14}C ages from a depth transect of cores from the New Zealand region of the South Pacific. Updated tephra ages are used to estimate deep ventilation ages of ocean water masses in the Southwest Pacific and Southern Ocean.

2 METHODS

2.1 Stratigraphy and calendar age determination

New benthic foraminiferal radiocarbon ages were generated for late glacial and deglacial intervals from 9 cores to the north and east of New Zealand. Of these, eight were raised from subtropical waters of the Bay of Plenty (5 cores) and Hikurangi Trough (3 cores), and one from sub-Antarctic waters on the South Chatham Rise of New Zealand (1 core). Combined with

previously published results (Sikes et al., 2000), these cores provide a regional depth transect from 665 to 4389 meters water depth (**Figure 1 and Table S1**). New cores described here and obtained on cruise RR0503 on the Roger Revelle were supplemented with samples from cores archived at NIWA in Wellington, New Zealand (S794, S931, and S938). Ash identification of macro-tephra layers for all cores has been previously published (Carter et al., 1995; Kohn and Glasby, 1978; Rose et al., 2010; Shane et al., 2006; Sikes et al., 2000). All new cores in this study have the Kawakawa tephra (Kkt) present as a macroscopic ash bed, and cores from north of the Chatham Rise contain one or more of five major deglacial tephras (Whakatane, Rotoma, Mamaku, Waiohau, Rerewhakaaitu; **Table 1**) depending on the extent of the eruption (Shane et al., 2006).

Radiocarbon calibration to determine calendar ages in the early deglaciation is the subject of active research and refinement (Reimer et al., 2009; Reimer et al., 2013). These calibration changes impact the conversion of radiocarbon dates to calendar ages for the deglacial tephras in this study (Lowe et al., 2013). The most recent calculations of calendar ages for the terrestrial New Zealand ashes (Lowe et al., 2013; Vandergoes et al., 2013) used a ^{14}C -calendar calibration (Reimer et al., 2009) that is now outdated (Reimer et al., 2013). Consequently, we reassessed and updated the calendar ages of the relevant ashes (**Table 1**; (Sikes and Guilderson, 2015 submitted). Our calculations followed published methods (Lowe et al., 2013) and utilized the same data base and identical Bayesian modeling program, Bacon, (Blaauw and Christen, 2011) that was applied to the Kaipo bog tephra-peat sequence (Hajdas et al., 2006) and the P_Sequence function in OxCal4.1.7 (Bronk Ramsey, 2009) for discrete ash composites. The only difference was to employ the IntCal13 calibration (Reimer et al., 2013) to produce updated calendar ages for the tephra (Sikes and Guilderson, 2015 submitted); **Table 1**, also see supplemental material). In addition, we have reassessed previously published data for named tephras and time series in the region (Rose et al., 2010; Sikes et al., 2000) that are presented here in light of the revised radiocarbon calibrations (Reimer et al., 2013).

2.2 Sample processing and calculations

Radiocarbon ages for deep water masses were determined from foraminifera sampled from directly above and below documented ashes. Bulk sediment samples were oven-dried at 35°C, weighed prior to disaggregating with deionized water, and wet sieving through a 63 μm sieve.

171 The benthic species *Planulina wuellerstorfi* was removed for benthic stable isotopic analyses and
 172 the remaining mixed benthic species were selected from the >150 μ m fraction for
 173 radiocarbon analyses. The tests were cleaned by brief sonication in methanol before being
 174 chemically leached in dilute HCl, converted to CO₂ and graphitized prior to AMS-¹⁴C analysis at
 175 Lawrence Livermore Center for Accelerator Mass Spectrometry (CAMS). When samples were
 176 large enough, foraminifera were physically cracked and sonicated in methanol prior to leaching.
 177 $\delta^{13}\text{C}$ corrections were derived from stable isotope analyses on the same samples and
 178 backgrounds were subtracted based on similarly and simultaneously prepared ¹⁴C-free calcite.
 179 ¹⁴C age calculations were based on international convention (Stuiver and Polach, 1977).

180 Benthic $\Delta^{14}\text{C}$ values (¹⁴C ages) for foraminifera picked from above tephra were consistently
 181 higher (younger) than those for sediment levels below the ashes, as expected with typical
 182 sedimentation and modern water structure (Rose et al., 2010; Sikes et al., 2000). Exceptions
 183 were the specimens associated with the Rerewhakaaitu in core TC83 and the Kawakawa ash in
 184 JPC06 (**Table S2 and S3**). These results suggest sedimentation disruption in those cores. In
 185 some cores, dates from above the Kawakawa were much younger than the accepted age
 186 terrestrial age of the tephra (as much as 10kyr) suggesting a significant lag after the emplacement
 187 of the tephra and the subsequent accumulation of sufficient foraminifera in the sediment to
 188 provide usable results for reservoir determination. We do not include these data in our
 189 calculations, but report them here for completeness.

190 The estimation of past radiocarbon activities of deep water masses were determined by two
 191 methods: subtracting the ¹⁴C ages of coexisting benthic foraminifera from the accepted ¹⁴C ages
 192 of the tephra (Bard et al., 1994; Sikes et al., 2000) and by differencing from atmospheric levels
 193 of ¹⁴C determined by IntCal13 (Reimer et al., 2013). The most recent estimate of radiocarbon
 194 ages of the of the tephra (Lowe et al., 2013) were used for the first method and the calendar ages
 195 used for the ashes in the second method were those recalculated, as described above using the
 196 IntCal13 curve (Reimer et al., 2013) and the ¹⁴C ages in Lowe et al. (2013). Reconstruction of
 197 past surface-to-deep water mass radiocarbon differences were determined by subtracting the ¹⁴C
 198 ages of coexisting planktonic and benthic foraminifera found in the same sediment and plotted
 199 using the ¹⁴C ages of the tephra (Bard et al., 1994; Sikes et al., 2000). Planktonic ¹⁴C reservoir
 200 ages are reported and discussed in a companion manuscript (Sikes and Guilderson, 2015)

submitted) and values from that study employed here are reported in **Tables S4 and S5**.

Throughout this manuscript, we present results in both ^{14}C year offsets between marine and terrestrial material as well as $\Delta^{14}\text{C}$ as previously defined (Stuiver and Polach). All ^{14}C year values discussed in the text are rounded to the nearest 10 years.

Ventilation age averages (aka reservoir ages) for the same tephra sampled from several cores were generated by first averaging AMS results from the different cores. For ash averages, samples from above or below the tephra in a given core were averaged first, before averages across the ash were calculated; this was to prevent any bias from sediment horizons for which more data were available. Single core averages were then used in calculating multi-core-ash average reservoir ages to ensure that results were not weighted more heavily to cores that had more analyses. With a large suite of cores for the same ash (the Kawakawa) we were able also assess the effect of bioturbation as a control on differences in the radiocarbon ages between cores by examining bias owing to sedimentation rate. If bioturbation were the main effect, one would expect a negative correlation between the sediment accumulation rate and the offset between the foraminiferal radiocarbon ages and the ash age. This is not evident in our cores (**Figure S1**). Similarly, there was no correlation of sedimentation rate with depths in this suite of cores (**Figure S2**).

To provide a time series of subsurface reservoir ages for the Bay of Plenty and Chatham Rise, we recalculated published data from the region (Rose et al., 2010) incorporating the new tephra ages into the independent age model for the Bay of Plenty and then using this age model to estimate early deglacial ventilation ages for ~600 m and ~1200 m for this region of the South Pacific. This recalculation both updates the ages of the tie points in JPC64 and uses the more widely used method of reservoir age calculation (e.g. Marchitto et al., 2007; Skinner et al., 2010) bringing this data set in line with conventional practices and the revised radiocarbon calibrations over the last decade. The conventional practice is to use the radiocarbon level in the sample as measured and the “true” half-life of radiocarbon to calculate the “true” $\Delta^{14}\text{C}$ of the sample. From this the water $\Delta^{14}\text{C}$ values are obtained, and then age-corrected for calendar age using an independent calendar age stratigraphy. We have done this for the individual ash-based time-slices, but also for the Bay of Plenty time series using a piecewise linear age-model to the ash horizons and for the South Chatham Rise using the age tie points of Rose et al. [2010] (**Table S6**). The updated

stratigraphy on which the recalculated time series in JPC64 is based is provided in **Table S6**, along with the previously published radiocarbon results from Rose et al [2010]. Neither the data nor the stratigraphy from MD2120 has been modified; the calendar age-model calculation methodology alone has been revised.

3 RESULTS AND DISCUSSION

3.1 Depth structure of ventilation ages in the Southwest Pacific since the glaciation

There are two widely used methods for obtaining deep ocean reservoir ages, one is to determine a calendar age for a carbonate sample and then directly difference the $\Delta^{14}\text{C}$ measured in the sample, such as coral or planktonic foraminifera, from the atmospheric $\Delta^{14}\text{C}$ (e.g. Edwards et al., 1993; Robinson et al., 2005). The contemporaneous atmosphere-ocean difference ($\Delta\Delta^{14}\text{C}$) can be expressed as per mil (‰), or converted to ^{14}C years. It is also common to estimate deep ventilation ages by taking the difference between benthic and planktonic ^{14}C from foraminifera in the same sediment sample (e.g. Broecker et al., 1984; Broecker et al., 1991; Shackleton et al., 1988). These benthic-planktonic ^{14}C differences (B-P) or deep ventilation estimations, are made in reference to surface ocean values without consideration of possible changes in surface reservoir ages. Implicit in this type of analysis is that the surface reservoir age varies little or less than deep ventilation ages (e.g. Broecker et al., 2008; Galbraith et al., 2007; Shackleton et al., 1988). However, it has been shown recently that surface reservoir ages can vary substantially even at lower latitudes with changes in surface and thermohaline circulation (e.g. Druffel et al., 2014; Komugabe et al., 2014; Ortlieb et al., 2011; Siani et al., 2013; Sikes and Guilderson, 2015 submitted; Sikes et al., 2000). Models suggest that surface reservoir ages are also sensitive to atmospheric CO_2 levels (Galbraith et al., 2015). In the present study we are able to use a third method and directly difference the ^{14}C ages of the tephra (representing atmosphere ^{14}C age) from the benthic foraminiferal ages to obtain a deep reservoir age relative to the atmosphere. Unlike the B-P calculation this method doesn't rely on the assumption of a constant surface reservoir age.

Holocene deep ventilation ages obtained by differencing accepted tephra ^{14}C ages from dates on benthic foraminifera (Sikes et al., 2000) at two depths (2000 and 1627 m) and for two tephras: (4830 and 7250 ^{14}C years) were ~ 1500 ^{14}C years, not appreciably different from modern values in the region. (**Figure 2a**). Deglacial deep reservoir ages at 12,420 ^{14}C years ago (~ 14 ka or

14,000 CalyrBP), of ~ 500 to 1000 ^{14}C years were also similar to the ages seen in water presently between the depths of 665 and 1627m. Likewise, in the early deglaciation at 14,700 ^{14}C years ago (~ 17.9 ka) water at 665 m had reservoir ages equivalent to modern. However, at that same time, deep reservoir ages at 1600m were about 800 years older than present (~2200 ^{14}C years) or about double modern.

Deep ventilation ages for the glaciation (Kawakawa tephra) were universally greater than modern, ranging from 1600 to 6800 ^{14}C years across water depths of 651 to 4097 m. For any given depth deep ventilation ages were between 300 and 5400 ^{14}C years older than today (**Figure 2a**). Despite scatter in the data, an overall trend can be seen with depth, with the largest increase in ventilation ages relative to modern sitting between 1300 and 3800 m and increasing with depth. Our depth transect has sufficient resolution to constrain the spatial extent of the bulge of very ^{14}C -depleted waters as between 1600-3800 m. Below 4000m, abyssal water ages were only 300 years older than present. This indicates the presence of a body of old deep water in the Southwest Pacific in the glaciation that was deeper than present by almost 1000 meters. The magnitude of the ages are roughly in agreement with a number of previous studies (Sikes et al., 2000; Skinner et al., 2010), but the work here places a better depth constraint on the locus of oldest waters. Interior waters above 1300 m were about 1000 years older than modern which was likely caused by some combination of reduced exchange with the atmosphere and the influence of the highly depleted CPDW endmember seen at the mid-depths in our profile. Below 4000m, the deep water ages of only ~300 years older than present (~2100 ^{14}C years), suggest continued formation and active ventilation of deepest, abyssal waters in the glaciation.

A strong mid-depth minimum in $\Delta^{14}\text{C}$ in the glaciation implies there was a significant gradient in $\Delta^{14}\text{C}$ between intermediate and deep waters as well as between deep and abyssal waters within the Pacific sector of the Southern Ocean. This structure has also been observed in ^{13}C results from the New Zealand region with a similar deep water mass boundary at ~3200m observed with $\delta^{13}\text{C}$ enriched water underlain by $\delta^{13}\text{C}$ depleted water (McCave et al., 2008). This structure was not seen in the glacial Southern Atlantic (Hodell et al., 2003). The difference between basins has been attributed to deep water formation in the Ross Sea that remained restricted to this region of the Southern Ocean by sill depths (McCave et al., 2008). Modeling results have suggested that extended Antarctic sea ice cover during the LGM would have caused shoaling of the boundary

between upper and lower water masses (Ferrari et al., 2014) and that changes in circulation alone would reduce the radiocarbon content primarily in the mid-depths (Burke et al., 2015). Evidence for an increase in surface radiocarbon age in the source region of deep waters during the LGM (Sikes and Guilderson, 2015 submitted) would have reduced the $\Delta^{14}\text{C}$ waters even more. Our data confirm the presence of a bulge of very poorly ventilated, low $\Delta^{14}\text{C}$ waters in the mid-depth glacial southwest Pacific.

3.2 The effect of surface reservoir ages on ventilation age estimates

Conventional deep ventilation ages determined from benthic-planktonic ^{14}C differences assume a constant surface reservoir age. In contrast to the deep reservoir ages discussed above that were calculated in reference to atmospheric ^{14}C levels using tephra ^{14}C ages for an atmospheric endmember, our B-P deep ventilation ages obtained for the same samples were not substantially different from modern (**Figure 2b**). In the data here, this is because variations in surface reservoir ages in a given core and for the same overlying water mass generally co-varied with changes in deep ventilation age. Analysis of this same data set for surface reservoir ages indicate that subtropical water surface ages were ~700 years, or about twice modern (Sikes and Guilderson, 2015 submitted). This can be attributed to several factors. Models suggest that with reduced atmospheric CO_2 in the last glaciation, air-sea redistribution of radiocarbon would have caused a negligible increase of the age differences between coeval benthic and planktonic foraminifera (Galbraith et al., 2015). Changes in the mixing between surface and underlying waters also serves to depress surface radiocarbon values, either through vertical mixing or lateral transport. In the Australia-New Zealand region of the Southwest Pacific, horizontal mixing processes appear to be the dominant control on surface ^{14}C content (Druffel and Griffin, 1993). In the last few centuries fluctuations of as much as 100 ^{14}C years in surface mixed layer ages in the Tasman Sea have been attributed to changes in the subsurface delivery of SAMW from the Southern Ocean (Komugabe et al., 2014). Subpolar surface water $\Delta^{14}\text{C}$ levels were even more depleted relative to subtropical surface water in the glaciation (Sikes and Guilderson, 2015 submitted). This suggests that in the glaciation and early deglaciation, much older sub-surface waters would have served as the source for SAMW. Planktonic foraminiferal stable isotopic evidence from the Bay of Plenty suggests that sub-thermocline waters there had a higher contribution of proximally sourced SAMW in the past (Schiraldi, 2013). The delivery of these

very old waters to the sub-thermocline in the Bay of Plenty serves as a plausible mechanism contributing to older surface reservoir ages at that time (Sikes and Guilderson, 2015 submitted).

The fact that surface reservoir ages tend to increase when deep reservoir ages are increased has the ultimate effect of concealing deep ventilation ages relative to atmosphere changes. Enhanced surface reservoir ages in subtropical areas during the glaciation and deglaciation (Siani et al., 2013; Sikes and Guilderson, 2015 submitted; Skinner et al., 2015) may partially explain why the benthic-planktonic calculations of deep ventilation ages show relatively little difference from the modern in many studies including those at low latitude (Broecker et al., 2008). The exception in our records are the core at 3225 m where the very large B-P appears to be driven by very young planktonic ages above the ash that may be an artifact of dissolution (Broecker et al., 1999; Broecker et al., 1984). The effect on B-P estimates of deep reservoir ages for cores where there is no independent estimate of surface reservoir age, is for those greater surface reservoir ages to partially or completely mask enhanced deep ventilation ages in the past as suggested by models (Galbraith et al., 2015). Thus, the potential volume of an isolated abyssal reservoir may have been relatively larger than previously assumed and the $\Delta^{14}\text{C}$ radiocarbon-depletion may have been low enough to account for the magnitude of the atmospheric $\Delta^{14}\text{C}$ drop during the deglaciation as suggested by previous work (Burke and Robinson, 2012).

3.3 Sedimentation influences on ventilation ages

The difference in ages obtained from sediments above and below ashes informs our glacial reconstructions of deep reservoir ages. Sediments from above the ash consistently have ages younger than the ash. This almost certainly reflects the time lag between deposition of tephra and repopulation of the sediment with foraminifera after the volcanic event. Bioturbation serves to mix down more recently deposited foraminifera into the sediment immediately above the undisturbed ash. In the cores used in this study, this effect is only a significant factor with the Kawakawa for which our results indicate that there was a significant time lag; the foraminifera dated above the tephra are substantially younger than reported terrestrial ages (**Table S3**) and these are probably not strictly coeval with the tephra suggesting the possibility of dissolution effects (Broecker et al., 1999; Broecker et al., 1984). These “very young” above ash dates are not ideal for determination of ventilation ages. Conversely, bioturbation below the ash should move older foraminifera closer to the ash serving to skew these ages to older (Peng and

Broecker, 1984). Ventilation ages determined using only dates from below the ashes increase deep ventilation ages by 300-3000 years (**Figure 2a**). Likewise, surface reservoir ages determined using only dates from below the ashes, showed age reconstructions increase by ~ 100-200 years for the Holocene, and by ~200- 400 years for the deglacial (Sikes and Guilderson, 2015 submitted). If bioturbation was the main control on the radiocarbon ages between cores there should be a negative correlation between the sediment accumulation rate and the offset between the foraminiferal radiocarbon ages and the ash age. However, we found no consistent offset with sedimentation rate (**Figure S1**) suggesting differential dissolution as a possible cause very young ages above the glacial tephra (Broecker et al., 1990).

3.4 Depth structure of atmosphere ocean radiocarbon offsets during the deglaciation

The deglaciation was a time of rapidly changing atmospheric $\Delta^{14}\text{C}$ levels (Reimer et al., 2013) and the fact that atmospheric radiocarbon has varied through time must be accounted for in calculations of ocean-atmosphere offsets (e.g. Broecker and Barker, 2007) (**Figure 3**). As discussed above, the radiocarbon-calendar age calibration used to obtain the atmospheric $\Delta^{14}\text{C}$ has been revised for the early deglaciation and this affects both calendar age determinations and the estimation of reservoir ages for our single time point evaluations. The accepted calendar ages of the Waiohau, Rerewhakaaitu, and Kawakawa were recently amended (Lowe et al., 2013) based on revisions to the global calibration (Reimer et al., 2009) and also by using updated mathematical analysis of the range of ages in the available radiocarbon dates which is dependent on the calibration curve chosen (Froggatt and Lowe, 1990; Lowe et al., 2013; Lowe et al., 2008). The calendar ages for the tephra in Lowe et al (2013) using IntCal09 have been superseded by IntCal13 as recommended by the radiocarbon community. Our calculations using the same Bayesian framework techniques and the IntCal13 calibration provide the most up to date estimates for the tephra calendar ages (**Table 1**) (Sikes and Guilderson, 2015 submitted). Consequently, the surface reservoir ages and $\Delta^{14}\text{C}$ calculated here vary somewhat from published values for these ashes (Rose et al., 2010; Sikes et al., 2000; Skinner et al., 2015). Using these updated calendar ages for the tephra as our chronological base, we determined the difference between atmospheric and marine levels of $\Delta^{14}\text{C}$ ($\Delta\Delta^{14}\text{C}$) for our time slices. The terrestrial ash ages were used to estimate the calibrated (absolute, or calendar age) age of the

380 contemporaneous marine sediment bracketing the ash. The atmosphere- ocean difference
381 ($\Delta\Delta^{14}\text{C}$) is expressed as “per mil” (‰), or can be converted to ^{14}C years.

382 Atmosphere-ocean offsets for our tephra time slices calculated using this method tell largely the
383 same story as the tephra-atmosphere differences based solely on ^{14}C discussed above (compare
384 **Figure 2a** with **3**). For depths ~2000 m and above, Holocene and late deglacial ventilation ages
385 were very similar to modern, and show a small spread between cores at SAMW, AAIW and
386 CPDW depths (**Figure 3**). However, in the early deglaciation and the glaciation the spread
387 across depths was greater with glacial $\Delta\Delta^{14}\text{C}$ offsets being both larger and showing a wider
388 spread overall. Two distinct patterns emerge when we bin the $\Delta^{14}\text{C}$ results by depth range for the
389 several cores that contained each tephra (represented by the depth averaged points in **Figure 3**).
390 At depths of 1200m or above, corresponding to modern SAMW and AAIW, atmosphere –ocean
391 $\Delta\Delta^{14}\text{C}$ were about twice as large in the glaciation than they are today ($\Delta\Delta^{14}\text{C}$ of about 280‰;
392 **Figure 3**). This was rapidly reduced to near modern offsets by ~18 ka, with modern-level $\Delta\Delta^{14}\text{C}$
393 (average 115‰ range, 30-160‰,) maintained throughout the rest of the deglaciation. Glacial
394 deep water at or below 1600m and above ~ 3800 m showed a depletion relative to the glacial
395 atmosphere that was 3 times as large as today ($\Delta\Delta^{14}\text{C}$ average ~ 690 ‰; range 320 to 1040 ‰
396 **Figure 3**). By ~18 ka the data from our 1600m core were similar to those at 2000 m (Skinner et
397 al., 2015) indicating that deep water ventilation ages were reduced by about half ($\Delta\Delta^{14}\text{C}$ 370 ‰).
398 Nevertheless, water at ~1600 m still had more than twice the offset seen in shallower waters
399 ($\Delta\Delta^{14}\text{C}$ 110 ‰). This indicates a substantial loss of old CO_2 from deep water between the early
400 glaciation ~25 ka and the beginning of Heinrich Stadial 1 early in the deglaciation. Nonetheless,
401 deep and intermediate water remained substantially radiocarbon depleted relative to modern.

402 By 14ka atmosphere-ocean offsets showed a substantial decrease in the deep water ^{14}C content
403 relative to the glaciation. Even so, the $\Delta\Delta^{14}\text{C}$ for AAIW-depth water remained about 110 ‰
404 depleted relative to the atmosphere and deep water $\Delta\Delta^{14}\text{C}$ was 180 ‰, or about 80‰ more
405 depleted than at intermediate depths. The overall profile was relatively similar to modern
406 indicating substantially better ventilation of subsurface water (**Figure 2**). The timing and change
407 in the relative offset between deep and intermediate depths were similar to those seen over the
408 same time frame in the South Atlantic and Drake Passage (Burke and Robinson, 2012) and in the
409 Atlantic (Chen et al., 2015). Together, these data from different ocean basins suggest that the

deep ocean had largely returned to a ventilation state similar to modern across the Atlantic and South Pacific with the timing coincident with the reinvigoration and deepening of meridional overturning circulation after Heinrich Stadial 1 and the beginning of the Antarctic Cold Reversal (ACR ~14.8 to 12.7 ka) (Gherardi et al., 2009; McManus et al., 2004).

Using tephra calendar ages as a stratigraphic base allows us to create a time series of $\Delta^{14}\text{C}$ changes. These changes in SAMW and AAIW from ~18 ka to 14 ka were previously examined (Rose et al., 2010). Here, we recalculated the ventilation ages from Rose et al. (2010) for the Bay of Plenty (600m) and the South Chatham Rise (1200m) (**Figure 3, Table S6**). $\Delta^{14}\text{C}$ at ~ 600m roughly paralleled the atmosphere $\Delta^{14}\text{C}$ signal indicating that by ~18 ka SAMW was well ventilated and it maintained a consistent and modern-level offset from the atmosphere throughout this period. In contrast, the 1200m core which sits at AAIW depths, showed a greater offset to the atmosphere early in the deglaciation with the difference between AAIW and SAMW progressively diminishing and disappearing by the ACR (**Figure 3**). This confirms the trend seen in the time slice data. This indicates that the surface waters that formed AAIW were more poorly ventilated (farther from equilibrium with the atmosphere) in the glaciation and became increasingly better ventilated through the early part of the deglaciation. The data from the Chatham Rise (1200 m) places the boundary between well ventilated and more poorly ventilated water in the early deglaciation between 600 and 1200 m. If we consider coral data from the Atlantic showing continuous ventilation in water above ~850 m (Chen et al., 2015) we can place that boundary between 850 and 1200 m before the ACR. We can then estimate a deepening of the ventilation surface by ~ 400 to 600 m between ~18 and 14 ka. This deepening fits with model projections that suggest that this deepening ventilation would have been caused by the proportional movement southward of the formation zones of these waters by around 4° to 6° latitude (Ferrari et al., 2014).

Paralleling the shallower interior waters, deep water in the Southwest Pacific became substantially better ventilated in the deglaciation. The resolution of our depth transect documents the depth range of very old water between 1600 and 3800 in the glaciation but only resolves the increasing $\Delta^{14}\text{C}$ in waters between 1600-2050 m by ~18 ka and the subsequent development of a relatively modern profile at these depths by ~14 ka. Considering our data together with published results from deep cores in the Atlantic at ~3770 m and ~4900m (Barker

et al., 2010; Skinner et al., 2010) the combined depth transect resolves the evolution of subsurface waters across a broad depth range through the deglaciation. It appears that in the glaciation there was significantly more ventilation at abyssal depths of ~3770m and below in both basins than was evident in deep (mid-depth) waters of the Pacific. The decrease in the differences between the mid-depth bulge in low $\Delta^{14}\text{C}$ and upper and lower -most water by ~14 ka implies that much of the $\Delta^{14}\text{C}$ depleted CO_2 from 800-3800 m had been released to the atmosphere by the time of the ACR when both atmospheric CO_2 and atmospheric $\Delta^{14}\text{C}$ levels plateaued (Marcott et al., 2014; Reimer et al., 2013) (**Figure 3**). Our results are largely in agreement with those observed from a more limited depth scope (Burke and Robinson, 2012; Chen et al., 2015; Skinner et al., 2015) and consistent with previously published work reporting the presence of very old water masses here and in other sectors of the Southern Ocean (Burke and Robinson, 2012; Skinner et al., 2010). These results also agree with data from the North Atlantic and North Pacific suggesting a poorly ventilated deep water mass persisted until ~15 ka at ~3000 m and below (Galbraith et al., 2007; Robinson et al., 2005).

Ocean–atmosphere CO_2 equilibration in the Southern Ocean appears to have been significantly reduced during the last glacial period. Our glacial results from the Southwest Pacific add to the growing body of evidence that a significant portion of the Pacific interior was poorly ventilated and ^{14}C poor in the last glaciation. The range of depths in our glacial profile strongly suggests that the oldest waters sat at deep, but not abyssal depths. Low levels of ^{14}C in intermediate waters during the last glaciation and earliest deglaciation reveal that the deep water upwelling in the Southern Ocean and subducting to form shallow water masses (AAIW) equilibrated even less with the atmosphere than at present. This resulted in waters at 1100-1300 m being between 50‰ and 300‰ more offset from the contemporaneous atmosphere than today. The progressive increase in intermediate water ventilation in the early deglaciation parallels the drop in atmospheric $\Delta^{14}\text{C}$ and increase in atmospheric CO_2 through the early deglaciation suggesting a connection between the ventilation of these waters and the deglacial increase in wind-driven upwelling (Anderson et al., 2009). The reinvigoration of thermohaline circulation in the second half of the deglaciation (e.g. Gherardi et al., 2009; McManus et al., 2004) accompanied the coalescing of deep water ages across our depth profile to resemble modern, suggesting this flushed and ventilated deeper waters across this timeframe.

4 CONCLUSIONS

Our tephra-bracketing technique which pairs terrestrially-dated tephras with marine carbonate samples enables the calculation of a series of ventilation ages to produce a depth transect of well constrained radiocarbon ages for several time slices from the LGM through the Holocene for subsurface waters in the Southwest Pacific Ocean. These data show much older ages in the glaciation that became progressively younger through the deglaciation with different sequence and patterns of change for different water depths. Specific conclusions are:

- 1) In the glaciation oldest waters were between 1600-3800. With ventilation ages of 1600 to 7000 ^{14}C yrs, these waters were significantly more depleted (3-5x) than modern. Water masses shallower than 1600m had ages of ~ 1600 ^{14}C years ($\sim 2\text{x}$ modern) and water deeper than 3800 m were ~ 2100 ^{14}C years, similar to modern. Our results confirm the presence of a deep, $\Delta^{14}\text{C}$ depleted, water mass in the Southern Pacific and constrain the extent as being below 1600m and extending to at least 3800m.
- 2) In the early deglaciation (~ 81 ka) ventilation ages for deep waters (1600-2000m) of ~ 2200 ^{14}C years were reduced by half from glacial levels but remained twice modern. In contrast, AAIW and SAMW ages of ~ 500 to 1000 ^{14}C years had decreased to close modern levels. By ~ 14 ka subsurface waters at 1600m had ventilation ages similar to modern. In conjunction with data from other Southern hemisphere locations this suggests that a modern $\Delta^{14}\text{C}$ profile was in place by the ARC.
- 3) A assessment with surface reservoir ages suggests that the ^{14}C content of surface subtropical waters was sufficiently lower in the glaciation and early deglaciation to mask the depletion of $\Delta^{14}\text{C}$ in deep waters when estimating ventilation ages from benthic- planktonic offsets.

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Figures list:

Figure 1. Site map and vertical cross sections of water properties in the study area. a) Pacific Ocean with study area outlined in black box, red line marks the location of WOCE transect P16. b). Inset of study area showing core locations. c) Vertical cross section of WOCE P16 with contoured ^{14}C data. Core depths and latitudes indicated by squares.

Figure 2. Ventilation ages for subsurface waters in the deglaciation and glaciation. Symbols are as listed on the figure. **a)** Atmosphere-ocean age differences calculated using benthic foraminifera ^{14}C and differencing from reported ^{14}C years for tephras. Both above and below ash ages are displayed as well as the across ash averages for the deglacial ashes. Only below ash results are displayed for the Kawakawa. The modern ^{14}C from WOCE stations 182 and 22 are shown for comparison. **b)** Benthic- planktonic (B-P) age differences. The modern ^{14}C from WOCE station 22 as well as the value “corrected” for the modern surface reservoir age of 400 years are shown for comparison. Note that although the ventilation ages in the glaciation are substantially higher than modern, the B-P values for the same samples are largely indistinguishable from modern.

Figure 3. $\Delta^{14}\text{C}$ of the atmosphere and subsurface ocean. Symbols are also indicated on the figure. Solid black line is atmospheric $\Delta^{14}\text{C}$ reconstructions based on IntCal13 (Reimer et al., 2013). Small symbols represent individual benthic $\Delta^{14}\text{C}$ results. Large symbols represent depth-binned ash averages for intermediate, 600-1200 m (large green triangles); deep, 1600-3800 m (large blue squares) and abyssal water; below 3800 m (red circle). Glacial data for all three depths illustrate that subsurface waters were significantly less ventilated than modern in the glaciation. The different trajectories (solid lines) for the intermediate and deep waters illustrate that increased ventilation of intermediate water reached modern levels by the HS1 whereas deep did not reach modern levels of $\Delta^{14}\text{C}$ until the ACR. Recalculated data from the Bay of Plenty (600m; green dashed line, and South Chatham Rise ,1200m; green dotted line; (Rose et al., 2010) show similar trajectories. Results from previously published studies in the deep South Atlantic (pink dotted line (Barker et al., 2010)), (purple dashed line (Skinner et al., 2010)) are included for comparison. Note that the South Atlantic data aligns with our abyssal data in the glaciation and with our deep cores from HS1 through the Holocene.

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531 Table 1 tephra ages ^{14}C

Ash name	Age ^{14}C yrs	Lowe et al 2013 cal yrs	This study cal yrs
Whakatane	4830 $\pm$ 20	5530 $\pm$ 145	5499 $\pm$ 60
Mamaku	7250 $\pm$ 20	7940 $\pm$ 257	8009 $\pm$ 69
Rotoma	8530 $\pm$ 10	9423 $\pm$ 120	9296 $\pm$ 220
Waiohau	12417 $\pm$ 29	14009 $\pm$ 155	13998 $\pm$ 110
Rerewhakaaitu	14,700 $\pm$ 110	17,496 $\pm$ 462	17906 $\pm$ 147
Kawakawa	21,299 $\pm$ 122	25,358 $\pm$ 162	25650 $\pm$ 40

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Figure 1

Atmosphere- ash difference

Benthic -Planktonic ages

Figure 2

Figure 3