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New Constraints on the Glacial Extent of the Pacific Carbon Pool and its Deglacial Outgassing

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With 2 Figures

The analysis of air, trapped in Antarctic ice core records, documents an increase of atmospheric CO_2 by ~90 ppmv during the last deglacial transition, from 18.5–11 ka. Parallel to this, the record of atmospheric radiocarbon activities ($\Delta^{14}C$) reveals a significant decrease that was most pronounced during Heinrich stadial 1 (HS 1; ~ 17.5–14.7 ka; Parrenin et al. 2013, Reimer et al. 2013). The contemporaneous pattern of both records implies an associated underlying mechanism combining the rise of atmospheric CO_2 to the release of a radiocarbon-depleted reservoir. Because the ocean contains up to 60-times more carbon than the entire atmosphere (Broecker 1982) it has the potential to drive the atmospheric CO_2-pattern. Therefore, the release of ^{14}C-depleted CO_2 from an old deep water carbon pool is thought to explain a substantial part of the atmospheric CO_2 variabilities (Skinner et al. 2010). Indeed, several studies show the presence of old ^{14}C-depleted deep waters during the last glacial in the North and South Pacific as well as in the South Atlantic (Burke and Robinson 2012, Sarnthein et al. 2013, Sikes et al. 2000, Skinner et al. 2010) and propose the storage of CO_2 in the deep glacial ocean.

The upwelling systems in the Southern Ocean are considered to represent the pathway of this old CO_2 from the deep water toward the atmosphere (Marchitto et al. 2007). Around Antarctica, carbon rich Circumpolar Deep Waters are upwelled and hence make contact with the atmosphere. After the process of air-sea gas-exchange, the upwelled waters are mixed and provide a major source for newly formed Antarctic Intermediate Water (AAIW; Talley 2013). Due to this circulation pattern, AAIW can spread the information of upwelling of old water masses (high CO_2 and low ^{14}C) into the Atlantic, Pacific and Indian Oceans. In order to localize and time the export of upwelled deep waters from the Southern Ocean, several (in

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parts contradicting) studies have analyzed the ^{14}C-history of intermediate-water records (De Pol-Holz et al. 2010, Marchitto et al. 2007). However, the dimension of the glacial carbon pool as well as its evolution over time and its pathways towards the surface and ultimately towards the atmosphere still remain a matter of an ongoing debate.

The aim of our study is to present a new perspective on this topic by using a water mass transect of several sediment cores instead of only one record as most of the proceeding studies have done. We analysed six sediment cores from the Bounty Trough east of New Zealand that cover the water masses from the AAIW down to the Lower Circumpolar Deep Water (LCDW; 835–4339 m water depth; Fig. 1). These records were supplemented by another record that was retrieved from 3613 m water depth more than 4000 km away from New Zealand at the East Pacific Rise (Fig. 1, *top*). Our sediment core transect enables the reconstruction of ^{14}C over the last 30,000 years for multiple levels of the Southern Ocean's water column. As it is shown in Figure 1 (*bottom*), we can record ^{14}C-depleted deep-waters moving towards the south, as well as newly formed intermediate and bottom waters moving towards the north, which carry the information of deep water upwelling and air-sea gas exchange. To facilitate the direct comparison of the atmospheric $\Delta^{14}C$ record to the water mass ventilation, we reconstructed the $\Delta^{14}C$ history of all sediment cores. Depicted as a $\Delta\Delta^{14}C$ notation (direct offset of the water mass to the atmospheric record), low values indicate old, weakly ventilated waters, while higher values indicate better-ventilated younger waters (Fig. 2, top).

During the last glacial our $\Delta\Delta^{14}C$ reconstructions indicate a significant radiocarbon depletion in the Circumpolar Deep Waters between ~2000 and ~4300 m water depth (Fig. 2). Contemporaneous, the intermediate-waters were significantly better ventilated (Fig. 2) indicating a strong glacial stratification separating the intermediate-waters from the underlying deep waters. Furthermore, it is noteworthy that we didn't find the lowest ventilation towards the bottom but at ~ 2500 m water depth with better ventilated waters above and below, indicating mixing processes with better ventilated water masses. In a similar way, the $\delta^{13}C$ reconstructions of McCave et al. (2008) north of our research area, also locate weakly ventilated waters between 2000 and 3500 m water depth. The extreme mid-water ^{14}C depletion yielding $\Delta\Delta^{14}C$ values as low as –1000 ‰ is corroborated by the previous findings of Sikes et al. (2000), who reported glacial values of –870 ‰ in the Bounty Trough at ~2700 m water depth. Our open ocean record from the East Pacific Rise (Fig. 1, top) traces the radiocarbon depleted waters more than 4000 km away from the Bounty Trough, showing that these values do not only represent a local phenomenon off New Zealand but that a widespread expansion of old (^{14}C-depleted) waters prevailed in the glacial South Pacific between ~2500 and ~3600 m water depth. Furthermore, ^{14}C-depleted water masses can be traced through the Drake Passage (Burke and Robinson 2012) and into the South Atlantic (Skinner et al. 2010).

The glacial $\Delta\Delta^{14}C$ pattern shown in Figure 2 (*top*) resembles in a striking way the modern distribution of $\Delta^{14}C$ in the Pacific Ocean (Fig. 1, *bottom*), with good ventilated intermediate-waters, increasing ^{14}C depletion below in UCDW, the highest depletion (oldest an CO_2-richest waters) between 2500 and 3600 m and better ventilated waters below, towards the bottom. For this reason and because previous studies have also found radiocarbon depleted waters in the glacial North Pacific (Sarnthein et al. 2013), our data may represent the glacial return flow of old Pacific Deep Water in analogy to the modern deep water circulation as it is shown in Figure 1 (*bottom*).

To facilitate a pronounced deep water ^{14}C depletion, the deep South Pacific must have had limited access to the surface and the atmosphere in consequence of enhanced ocean stratifi-

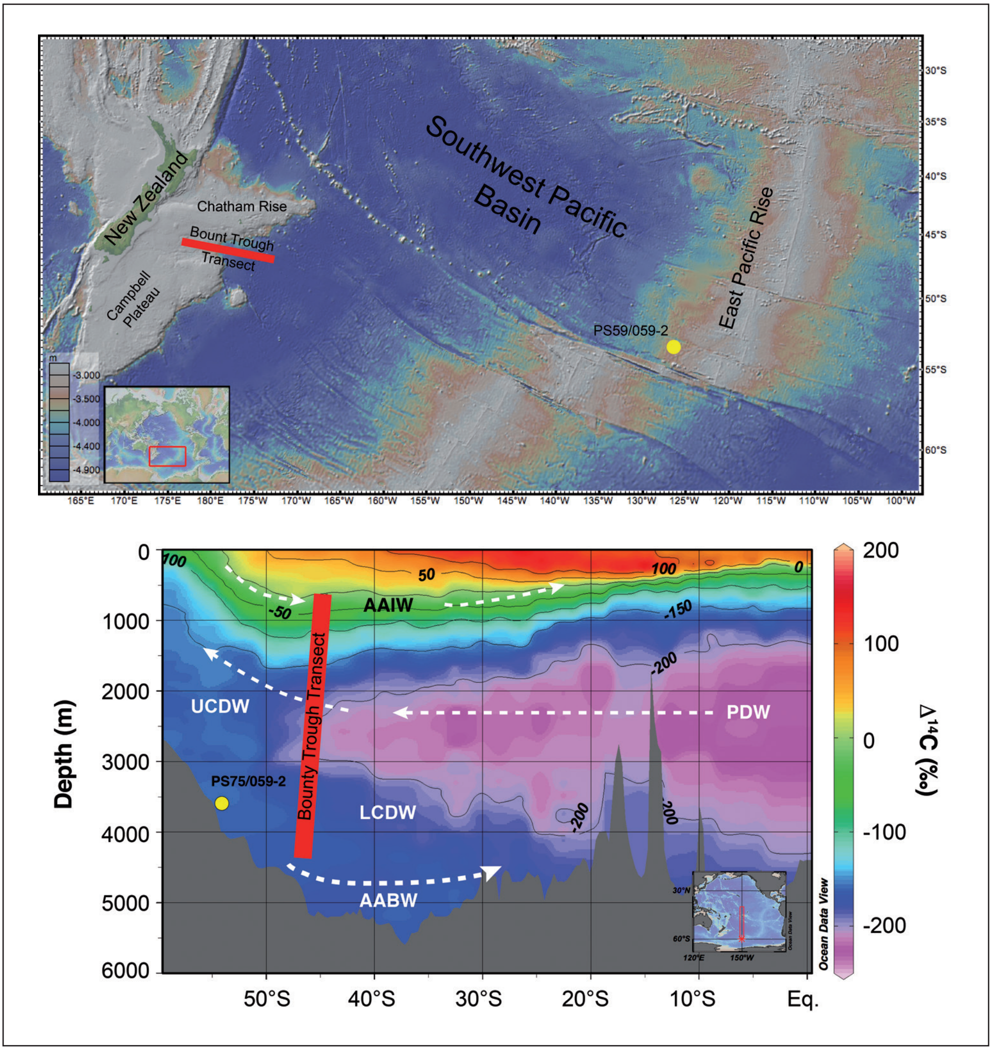

Fig. 1 (*Top*) Overview map of the southwest Pacific, indicating our research area in the Bounty Trough (red bar) and at the East Pacific Rise (yellow dot). (*Bottom*) Modern $\Delta^{14}C$ concentrations of the South Pacific. The area covered by the Bounty Trough sediment core transect is marked by the red bar. The sediment core from the East Pacific rise is indicated by a yellow circle (~ 152°W; Key et al. 2004). Antarctic Intermediate Water (AAIW); Upper and Lower Circumpolar Deep Water (UCDW and LCDW); Antarctic Bottom Water (AABW); Pacific Deep Water (PDW).

cation. Throughout the glacial expanded Antarctic sea-ice conditions (Gersonde et al. 2005) and changes in the Southern westerly wind belt (Kohfeld et al. 2013) may have hampered the upwelling of old deep waters around the Antarctic continent. Also, enhanced buoyancy-differences by increased deep water salinity (Adkins 2013) and freshening of intermediate-waters (Saenko et al. 2001) increased the stratification and inhibited the communication between the deep ocean and the surface.

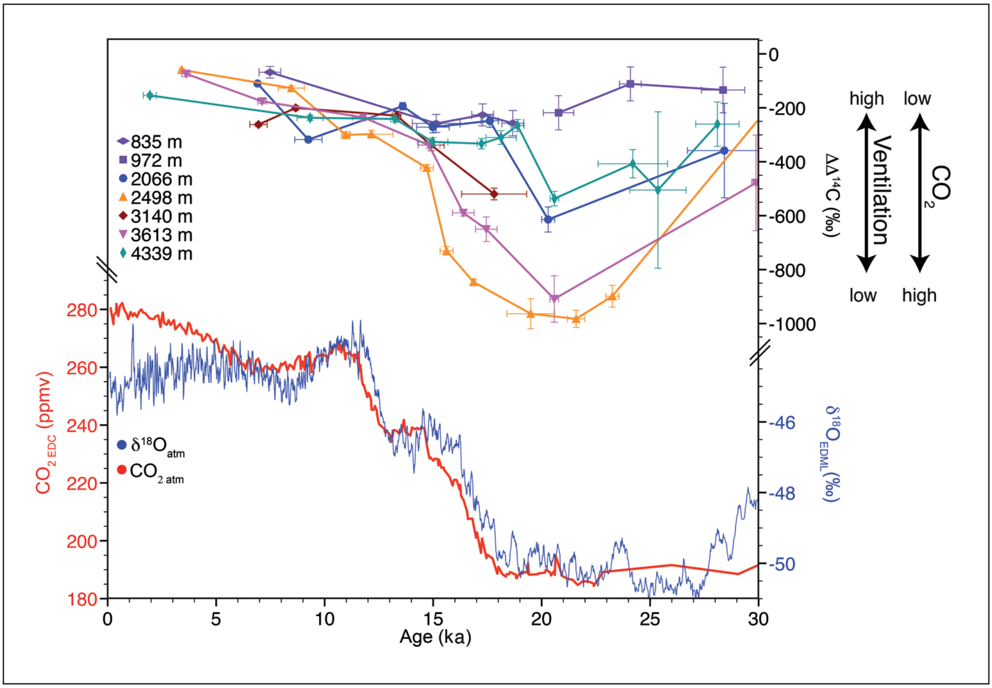

Fig. 2 (*Top*) $\Delta\Delta^{14}C$ values (offset of measured $\Delta^{14}C$ to the contemporaneous atmosphere) of the SW-Pacific. (*Bottom*) Antarctic $\delta^{18}O$ record EDML (blue; *EPICA Community Members* 2006) and atmospheric CO_2 EDC (red; Parrenin et al. 2013).

Parallel to the observed rise in atmospheric CO_2 and Antarctic temperatures, the ventilation of the deep Pacific at 2500 m significantly increases during termination 1 (Fig. 2) and point towards a transfer of old CO_2 from the depth towards the surface. This CO_2 release reduced the deep water to atmosphere offset from glacial values of about –1000 ‰ $\Delta\Delta^{14}C$ to ~ –200‰ during the Holocene. During this period of pronounced upwelling, AAIW $\Delta\Delta^{14}C$ decreases only slightly (this study; Rose et al. 2010). Therefore, we propose that the excess of upwelled ^{14}C-depleted CO_2 was not substantially incorporated in newly formed AAIW, but that it was directly transported towards the atmosphere, contributing to the observed rise of atmospheric CO_2. At the end of termination 1 (~11.5 ka), uniform $\Delta\Delta^{14}C$ values throughout the water column mark the end of the Pacific outgassing period.

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