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Reduced oxygenation at intermediate depths of the southwest Pacific during the last glacial maximum

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ABSTRACT

To investigate changes in oxygenation at intermediate depths in the southwest Pacific between the Last Glacial Maximum (LGM) and the Holocene, redox sensitive elements uranium and rhenium were measured in 12 sediment cores located on the Campbell and Challenger plateaux offshore from New Zealand. The core sites are currently bathed by Subantarctic Mode Water (SAMW), Antarctic Intermediate Water (AAIW) and Upper Circumpolar Deep Water (UCDW). The sedimentary distributions of authigenic uranium and rhenium reveal reduced oxygen content at intermediate depths (800–1500 m) during the LGM compared to the Holocene. In contrast, data from deeper waters (≥1500 m) indicate higher oxygen content during the LGM compared to the Holocene. These data, together with variations in benthic foraminiferal δ^{13}C, are consistent with a shallower AAIW–UCDW boundary over the Campbell Plateau during the LGM. Whilst AAIW continued to bathe the intermediate depths (≤1500 m) of the Challenger Plateau during the LGM, the data suggest that the AAIW at these core sites contained less oxygen compared to the Holocene. These results are at odds with the general notion that AAIW was better oxygenated and expanded deeper during the LGM due to stronger westerlies and colder temperatures. These findings may be explained by an important change in AAIW formation and circulation.

1. Introduction

The oxygen content in the ocean interior is determined by the balance between the supply of oxygen by ventilation (the process whereby surface mixed layer water is transported into the ocean interior) on one hand and its removal by bacterial respiration of labile organic matter, associated with remineralisation, on the other. Observations have shown that the oceans have lost 2% of their total oxygen content since 1960 (Schmidtko et al., 2017) and that the rate of deoxygenation has been increasing (Helm et al., 2011). Potential collapse of fisheries and enhancement of global warming in response to this worldwide increasing marine deoxygenation pushed the scientific community to focus on understanding the marine oxygen cycle (Helm et al., 2011; Diaz and Rosenberg, 2008; Keeling et al., 2010; Matear et al., 2000; Bograd et al., 2008; Nevison et al., 1995). Despite this greater attention over the last decade, the complex consequences of climatic forcing on oceanic oxygenation prevent future oxygenation projections from being made accurately (Emerson and Bushinsky, 2014).

This study focuses on the southwest Pacific sector of the Southern Ocean. Today, oceanic productivity in this region is relatively low (Murphy et al., 2001), thus ventilation and 'upstream' oxygen removal related to organic matter remineralisation constitute the primary factors controlling dissolved oxygen levels. Ventilation in this region occurs mainly through the formation of Subantarctic Mode Waters (SAMW) and Antarctic Intermediate Waters (AAIW), two oxygen rich water masses present at intermediate depths in the Southern Ocean (600–1200 m and 500–600 m, respectively; Figs. 1, 2). They are formed by subduction of Antarctic surface

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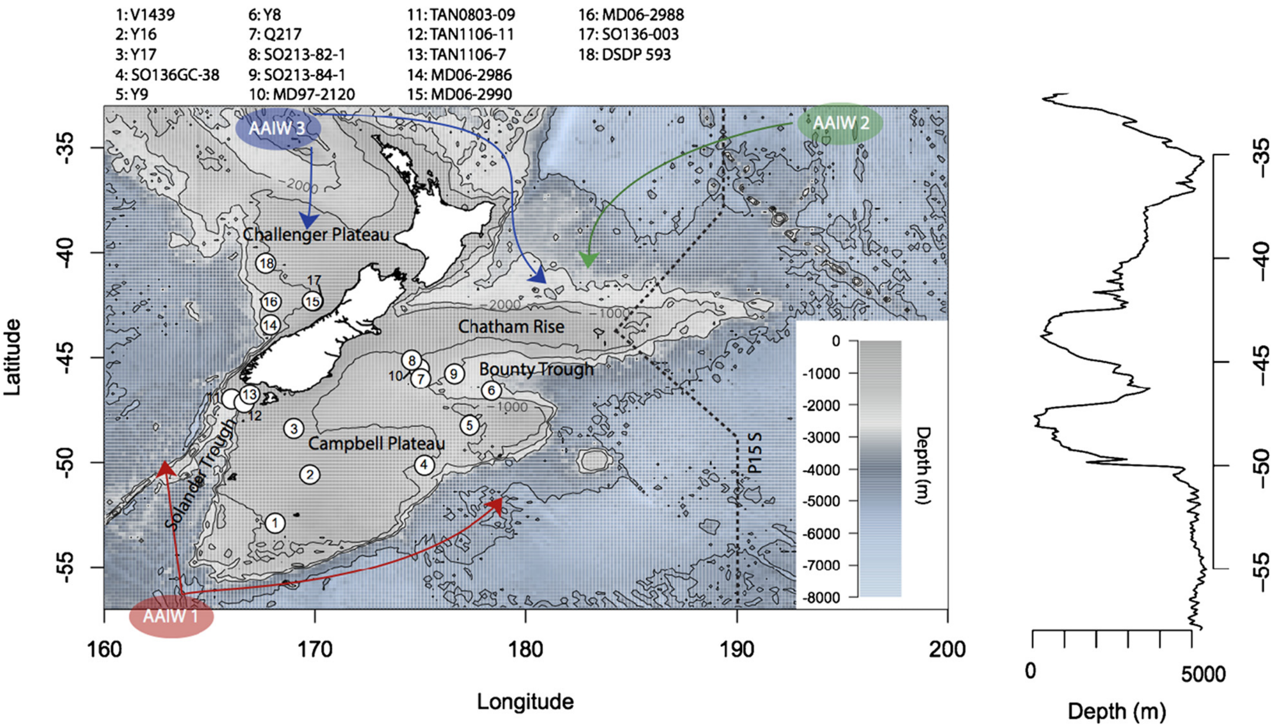

Fig. 1. Map of the bathymetry of the New Zealand region as well as the sediment core locations on the left side. The present AAIW circulation is also shown (Chiswell et al., 2015). Three different AAIW types are present in the New Zealand region: AAIW 1 is a southern source AAIW, formed locally in the southwest Pacific sector of the Southern Ocean. AAIW 2 comes from the southeast Pacific via the South Pacific gyre. AAIW 3 is a mixture between the AAIW from the southeast Pacific source and surface waters from the Tasman Sea. The position of the P15S section used in Fig. 2 is also represented. On the right side is shown the bathymetric transect from 180°W. (For interpretation of the colours in the figure(s), the reader is referred to the web version of this article.)

waters below buoyant subtropical waters (Talley, 2013). Prior to their subduction, their pre-formation is controlled by the Ekman driven upwelling of oxygen-depleted Upper Circumpolar Deep Water (UCDW, 1500–2500 m) and Lower Circumpolar Deep Water (LCDW, 2500–3000 m) under the influence of westerly winds (Fig. 2) (Sloyan and Rintoul, 2001). Upper Circumpolar Deep Water and LCDW become oxygenated through atmospheric exchanges when they reach the surface. Then, they are advected and subducted northward, feeding the AAIW and SAMW (Talley, 2013). Of the two water masses, AAIW is volumetrically the largest and dominates the oxygen supply to the ocean interior at low latitudes (Piola and Georgi, 1982). Bostock et al. (2013) showed that there are three types of AAIW present around New Zealand (Fig. 1). There is a southern source AAIW, formed locally in the southwest Pacific sector of the Southern Ocean as well as an AAIW coming from the southeast Pacific via the South Pacific gyre. Finally, the third type, which is present in the Tasman Sea, is a mixture between the AAIW from the southeast Pacific source and surface waters from the Tasman Sea. Because AAIW has an essential role in ventilating the ocean interior, modelling studies have focused on AAIW to predict future oxygen variations (Sallee et al., 2010; Rintoul and Bullister, 1999; Downes et al., 2009). However, large uncertainties remain about the mechanisms driving AAIW formation in the modern ocean (Bostock et al., 2013). Therefore, more work needs to be done in order to understand how our changing climate will influence AAIW formation and its oxygenation role.

A precise historical knowledge of how AAIW responded to past climatic forcing is essential to help understand how AAIW formation will change in the future. Hence, the reconstruction of past variations in oxygenation may be useful to better predict future oxygen changes in the Southern Ocean. Previous studies provided conflicting results regarding the AAIW geometry in the Pacific sector of the Southern Ocean between glacial and interglacial periods. Using sponge δ^{30}Si (Rousseau et al., 2016) or a combination of benthic foraminiferal δ^{18}O and δ^{13}C (Elmore et al., 2015; Pahnke and Zahn, 2005; Ronge et al., 2015), several authors reported AAIW contraction during glacial periods in the southwest Pacific sector of the Southern Ocean. They proposed that this AAIW contraction decreased the ventilation at intermediate depths. However, other authors reported increased ventilation at intermediate depths in the southeast Pacific sector of the Southern Ocean (along the Chilean margin) during the last ice age (Muratli et al., 2009). They attributed this increased ventilation to greater AAIW formation. Based on a large scale data compilation, Jaccard and Galbraith (2012) and Jaccard et al. (2014) showed that intermediate depths of the Pacific Ocean were generally better oxygenated during the Last Glacial Maximum (LGM) compared to the Holocene, while abyssal waters remained poorly ventilated. In the rest of the Southern Ocean, several studies also showed a poorer ventilation during the LGM compared to the Holocene (Wagner and Hendy, 2017; Lu et al., 2016; Frank et al., 2000; Jaccard et al., 2016); however, a general lack of data limits interpretations for this region. Consequently, uncertainties remain about past oxygen variations in the Pacific sector of the Southern Ocean. In particular, redox-sensitive metal proxies of bottom water oxygen have not been applied yet in the southwest Pacific.

In this study we aim to reconstruct the variations in the oxygen content of the intermediate waters of the southwest Pacific sector of the Southern Ocean, between the LGM and the Holocene. This region is of particular interest because parts of the shallow plateaux surrounding New Zealand are bathed by AAIW and are therefore ideal to investigate AAIW changes (Figs. 1 and 2) (Bostock et al., 2013; Forcén-Vázquez et al., 2017; Chiswell et al., 2015).

To this end, the authigenic uranium (aU) and rhenium (aRe) contents of 12 sediment cores from the New Zealand region were analysed (Campbell Plateau, Challenger Plateau, Bounty Trough) (Figs. 1, 2, Table 1). The solubility of U and Re in seawater is dependent on the seawater oxygen concentration. When the dis-