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# Climate archives from 90 to 250 ka in horizontal and vertical ice cores from the Allan Hills Blue Ice Area, Antarctica

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ABSTRACT

Terrestrial meteorite ages indicate that some ice at the Allan Hills blue ice area (AH BIA) may be as old as 2.2 Ma. As such, ice from the AH BIA could potentially be used to extend the ice core record of paleoclimate beyond 800 ka. We collected samples from 5 to 10 cm depth along a 5 km transect through the main icefield and drilled a 225 m ice core (S27) at the midpoint of the transect to develop the climate archive of the AH BIA. Stable water isotope measurements (δD) of the surface chips and of ice core S27 yield comparable signals, indicating that the climate record has not been significantly altered in the surface ice. Measurements of $^{40}Ar_{atm}$ and $\delta^{18}O_{atm}$ taken from ice core S27 and eight additional shallow ice cores constrain the age of the ice to approximately 90–250 ka. Our findings provide a framework around which future investigations of potentially older ice in the AH BIA could be based.



## Introduction

A global array of climate proxies, including ice cores, marine sediment cores (e.g. Shackelton and Opdyke, 1976; Lisiecki and Raymo, 2005), and speleothems (e.g. Winograd et al., 1992) have provided major breakthroughs in our understanding of the driving mechanisms of past climate change. Unlike other materials, ice cores contain trapped gases, which can be used to reconstruct paleoatmospheric composition. As a result of this advantage, ice cores have enabled some of the most fundamental discoveries in climate science. For example, the identification of abrupt high-magnitude changes in climate (Dansgaard et al., 1993; Grootes et al., 1993; Mayewski et al., 1994) and the close association between atmospheric greenhouse gases and Antarctic temperature (EPICA, 2004) can be attributed to the study of ice cores. Additionally, within ice cores, it is possible to sub-annually resolve some proxies including concentrations of soluble compounds and insoluble particle chemistry. However, traditional ice coring activities are limited by the deepest practical drilling depth and the availability of old ice. Blue ice areas offer a complementary approach that removes these limitations. In this paper we investigate the age of blue ice in the Allan Hills area of East Antarctica and show that it may contain climatic information relevant to the behavior of the Ross Ice Shelf and perhaps the West Antarctic Ice Sheet under warmer climate scenarios (Raymo and Mitrovica, 2012).

While ice cores form an essential climate archive, their use is not without challenges. Their primary restriction is latitudinal, with most long ice cores being collected in the polar regions. Even within Antarctica the number of places an undisturbed long record of climate containing well-preserved ice chemistry and atmospheric gas signals can be collected is limited (Severinghaus et al., 2010). This is problematic, as it has been demonstrated that significant regional variability exists in the ice-core record of changes in temperature, atmospheric circulation, wind intensity, and sea-ice coverage among other climate parameters (e.g. Dixon et al., 2011) and we must obtain old ice from multiple locations to confirm significant findings. There are at present, six high-resolution ice-core temperature records (Vostok, EPICA Dome C, EPICA Dronning Maud Land, Dome Fuji, Taylor Dome, and TALDICE) that fully encompass the present to the penultimate glacial maximum (Petit et al., 1999; Steig et al., 2000; Grootes et al., 2001; EPICA Community Members, 2006; Jouzel et al., 2007; Kawamura et al., 2007; Masson-Delmotte et al., 2011; Stenni et al., 2011). Of those six records only four extend beyond the penultimate glacial maximum. Additionally, the locations from

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which long ice cores can be collected are generally sites of very low accumulation. The low initial annual layer thickness can result in irresolvable or missing layers at depth. As a result of these limitations, exploring potentially complementary ice archives in unconventional locations, such as blue-ice areas (BIAs), is a goal to be pursued.

Paleoclimate records from several Antarctic BIAs have been developed over the last decade. Each of these records was collected in coastal or mountainous regions where traditional deep ice cores could not be drilled and at significantly lower resource investment. Each BIA record was also able to provide higher temporal resolution than usual in deep ice cores. The records from Scharffenbergbotnen (Sinisalo et al., 2007), South Yamato (Nakawo et al., 1988; Machida et al., 1996; Moore et al., 2006) and Mt. Moulton (Custer, 2006; Popp, 2008; Korotkikh et al., 2011) demonstrate that paleoclimate reconstructions from BIAs can be used to augment the already detailed ice-core record of past climate change, if robust age determination techniques are employed.

The primary objectives of this paper are to determine the age of ice within the main icefield (MIF) of the Allan Hills blue-ice area (AH BIA) and evaluate its surface-ice climate record. We use measurements of $^{40}Ar_{atm}$, $\delta^{18}O_{atm}$ and $\delta D$ from a series of ice cores to constrain the age and paired $\delta D$ records to assess the quality of the climate record at the ice surface.

## Glaciological and regional setting

The AH BIA is located near the northwest corner of the McMurdo Dry Valleys in South Victoria Land, East Antarctica (Fig. 1). Ice flowing into the AH BIA at the present time has an accumulation area located only ~20 km upstream (Faure et al., 1992), as such it is ideally located to capture climatic changes within the Ross Embayment and the Transantarctic Mountains. This is particularly true of paleotemperature signals because the majority of precipitation reaching the accumulation area of the AH BIA must first cross the Ross Ice Sheet (King and Turner, 1997; Sinclair et al., 2010).

As in most BIAs, ice flow through and within the MIF of the AH BIA is controlled by complex sub-ice topography and the presence of outcropping nunataks. Bedrock conditions within the AH BIA are detailed in Fudali (1982, 1989), Faure and Buchanan (1987), and Delisle and Sievers (1991); ice flow measurements are discussed in Schultz et al. (1990) and Spaulding et al. (2012). Briefly, ice enters the MIF from the south/southwest with a horizontal velocity of 50 cm a$^{-1}$ and then follows the north/northeasterly path shown as a pink swath in Figure 1. Spaulding et al. (2012) used high-precision GPS measurement to determine that path and individual velocity vectors can be seen in Figure 2 of their publication. Horizontal ice velocities decrease to a nearly stagnant 1.5 cm a$^{-1}$ near the base of the Allan Hills nunatak. Between these points, where satellite imagery indicates bare ice, positive vertical velocities of 1–3 cm a$^{-1}$ and ablation rates (~2 cm a$^{-1}$) in excess of the accumulation rates in the surrounding snow plains are reported (Spaulding et al., 2012). The low horizontal velocities, emergent vertical velocities and net ice loss through ablation combine to bring older ice to the surface and maintain its exposure over long periods of time. For a more in-depth discussion of ice dynamics in blue-ice areas, please refer to Nagata (1978), Whillans and Cassidy (1983), or Bintanja (1999). As ice flows through the MIF, small-scale compression and extension forces reshape the appearance of the present-day surface, creating the cracking, ridging, and sharp changes in surface slope (Fig. 2) observed in many locations during our first field season. The continuity of ash layers crossing transect A–B (Fig. 1) suggests that these forces have not caused significant reordering or offsetting of the original stratrigraphy (Dunbar et al., 1995).

Determining the age of ice exposed within BIAs is particularly challenging. Traditionally, ice-flow models are used to provide a first approximation of the age of ice at the surface and at depth. The required input for such models includes accumulation rates, high-resolution bedrock topography, and horizontal velocities. At the AH BIA, high-

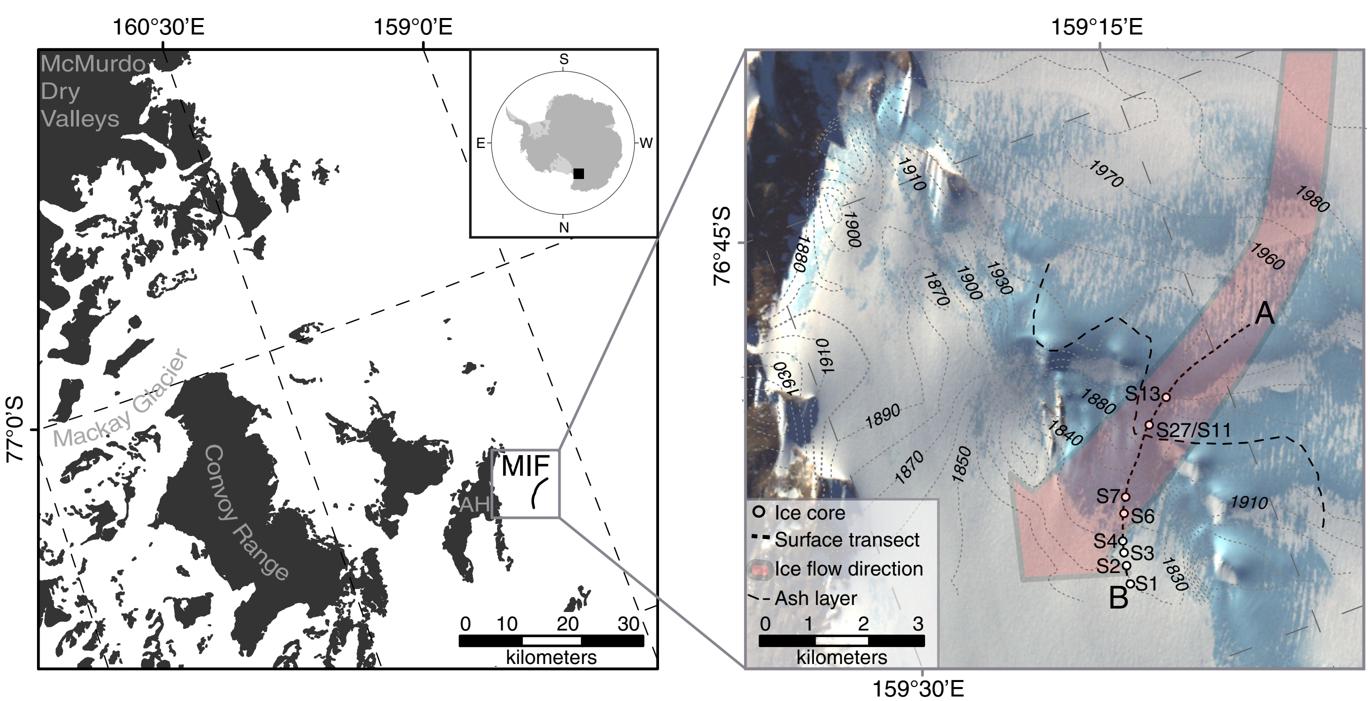


**Figure 1.** Eight shallow ice cores, one 225 m core (S27) and 536 surface samples were collected from the main icefield (MIF) of Allan Hills blue ice area during field seasons in 2010 and 2011. The surface samples were collected at 10 m intervals along transect A–B for stable water isotope analysis. Transect A–B is largely within the flow zone described in Spaulding et al., 2012. Only one of the many ash layers (Dunbar et al., 1995) crossing transect A–B was used as a stratigraphic control point.