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Controls on interior West Antarctic Ice Sheet Elevations: inferences from geologic constraints and ice sheet modeling

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A B S T R A C T

Knowledge of the West Antarctic Ice Sheet (WAIS) response to past sea level and climate forcing is necessary to predict its response to warmer temperatures in the future. The timing and extent of past interior WAIS elevation changes provides insight to WAIS behavior and constraints for ice sheet models. Constraints prior to the Last Glacial Maximum (LGM) however, are rare. Surface exposure ages of glacial erratics near the WAIS divide at Mt. Waesche in Marie Byrd Land, and at the Ohio Range in the Transantarctic Mountains, range from ~10 ka to >500 ka without a dependence on elevation. The probability distribution functions (PDF) of the exposure ages at both locations, are remarkably similar. During the last glaciation, maximum interior ice elevations as recorded by moraines and erratics were reached between 10 ka and 12 ka. However, most exposure ages are older than the LGM and cluster around ~40 ka and ~80 ka. The peak in the exposure age distributions at ~40 ka includes ages of alpine moraine boulders at Mercer Ridge in the Ohio Range. Comparison of the PDF of exposures ages from the Ohio Range and Mt. Waesche with the temperature record from the Fuji Dome ice core indicates that the youngest peak in the exposure age distributions corresponds to the abrupt warming during the Last Glacial termination. A prominent peak in the Ohio Range PDF corresponds to the penultimate termination (stage 5e). During the intervening glacial period, there is not a consistent relationship between the peaks in the PDF at each location and temperature. A combined ice sheet/ice shelf model with forcing scaled to marine $\delta^{18}O$ predicts that interior WAIS elevations near the ice divide have varied ~300 m over the Last Glacial cycle. Peaks in the PDF correspond to model highstands over the last 200 ka. In the simulated elevation history, maximum ice elevations at Ohio Range (+100 m) and Mt. Waesche (+60 m) occur at ~10 ka, in agreement with observations from these sites. During collapse of the marine portion of the WAIS, ice elevations at Ohio Range and Mt. Waesche are drawn down at least 200 m below the present ice elevation. The good correspondence between the model results and observations at both the Ohio Range and Mt. Waesche supports the conclusion that interior WAIS highstands do not occur during glacial maximums. Rather, the highstands are controlled primarily by increased accumulation during temperature maximums that occur early in the interglacials. Interior down-draw events follow highstands, resulting from the arrival of a wave of thinning triggered by retreat of the WAIS grounding line coupled with decreasing accumulation rates.

1. Introduction

Over the last decade, new glacial geologic and ice core data combined with ice sheet models indicate that the WAIS did not approach equilibrium during the Last Glacial Maximum (LGM) (Ackert et al., 1999; Waddington et al., 2005; Ackert et al., 2007; Price et al., 2007). While changes at the peripheral, marine-based margins of the WAIS, have been driven primarily by ice sheet/ocean interactions, the interior of the ice sheet is thought to respond primarily to changes in accumulation rates controlled largely by temperature e.g. (Alley and Whillans, 1984; Steig et al.,

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2001). Thus, during the LGM (~20 ka), when the WAIS was at its maximum extent in the Ross and Weddell Seas (Anderson et al., 2002), interior ice-surface elevations were no higher than present, and possibly lower. Maximum surface elevations in the interior occurred during the early Holocene at ~10 ka as a result of increased accumulation (a consequence of maximum atmospheric temperatures) over cold, slowly flowing ice formed during the glacial maximum, prior to the arrival of a wave of thinning that propagated inland following grounding line retreat (Ackert et al., 1999; Steig et al., 2001; Ackert et al., 2007; Ackert et al., 2011). However, WAIS behavior prior to the LGM remains poorly constrained. In this regard, surface exposure ages of erratics and bedrock on mountains projecting through the WAIS provide opportunities to gauge past ice sheet elevations over timescales ranging from thousands to millions of years (Ackert et al., 1999; Stone et al., 2003; Ackert et al., 2007; Mackintosh et al., 2007; Ackert et al., 2011).

We focus on two sites within interior West Antarctica: Mt. Waesche and the Ohio Range. Mt. Waesche (77° 13′S; 125° 5′W) is a volcano projecting through the WAIS near the dome in Marie Byrd Land (Fig. 1). At the opposite end of the WAIS divide, the Ohio Range (85°S; 114°W) forms an east-west trending escarpment rising 500 m above the adjacent surface of the WAIS in the Horlick Mountains (Fig. 1). Features common to both Mt. Waesche and the Ohio Range are local ablation (blue ice) areas that result from interaction of prevailing winds with topography. Moraines and erratics deposited along the ice margin in long-lived local ablation areas directly record past changes in interior ice sheet elevation within the accumulation area of the Antarctic ice sheet. However, significant amounts of exposure of boulders may occur on the blue ice surface prior to deposition on the adjacent ice-free terrain, complicating the interpretation of exposure age distributions. In the Ohio Range, clasts with exposure ages >200 ka occur on the WAIS surface (Ackert et al., 2011; Fogwill et al., 2012).

At Mt. Waesche, surface exposure ages of basalt erratics indicate that ice elevations stood at least ~45 m above the present level at ~10 ka (Ackert et al., 1999). A single exposure age indicates that ice elevations were possibly as much 85 m above the present ice elevation at ~12 ka. In the Ohio Range, granite erratics extend ~125 m above the present WAIS elevation. Exposure ages of 10.5 ka and 12.5 ka were obtained from erratics along the trim line (Ackert et al., 2007). However, at both sites, most of the sampled

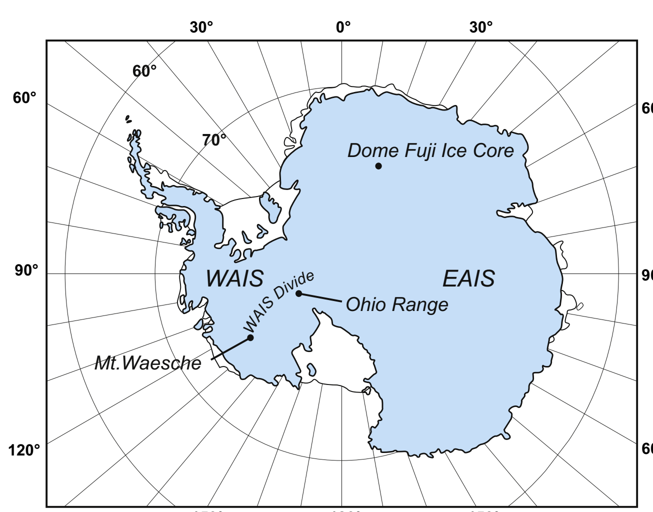

Fig. 1. Map of Antarctica showing the location of field sites and ice cores discussed in the text.

erratics have older exposure ages ranging from the LGM to >500 ka that have the potential to provide information on earlier WAIS history.

Outstanding questions regarding the pre-LGM WAIS history include: What is the timing and extent of earlier WAIS highstands and collapse events? What is the extent and duration of draw down of the land-based portions of the WAIS during collapse of the marine portions of the ice sheet? What is the response of the ice sheet in interior Antarctica to warmer temperatures? To address these questions, we report new ^{3}He and ^{36}Cl exposure ages of basalt erratics above the present WAIS surface at Mt. Waesche, and ^{3}He exposure ages of dolerite and sandstone boulders from ice-cored moraines of local alpine moraines in the Ohio Range. These data, along with ^{10}Be and ^{3}He exposure ages of granite erratics from the Ohio Range (Ackert et al., 2011) are compared to an ice core temperature record and WAIS elevation changes simulated by a continental ice sheet model. We conclude that in interior West Antarctica the peaks in exposure age distributions are linked to rising ice levels and relative highstands resulting from increased regional accumulation, as well as, locally higher ablation (sublimation) rates during periods of increased temperatures.

2. Geologic setting and methods

Descriptions of the geologic setting, sampling procedures, and analytical methods appear in earlier reports that highlighted the youngest exposure ages from the most recent WAIS highstands at Mt. Waesche and the Ohio Range Escarpment (Ackert et al., 1999; Ackert et al., 2007). In interior WAIS, extremely low subaerial erosion rates and non-erosive cold-based ice results in the pervasive occurrence of bedrock and regolith with long exposure to cosmic radiation (Mukhopadhyay et al., 2012). On the other hand, low erosion rates mean that for samples younger than ~125 ka, cosmogenic nuclide concentrations are not significantly affected by erosion. Thus, while erratics with prior exposure are expected, anomalously young exposure ages are unlikely; samples with the lowest apparent exposure ages (erosion rate = 0) provide the best estimate of the most recent highstand of the WAIS (Ackert et al., 2007; Mackintosh et al., 2007; Johnson et al., 2008; Stone et al., 2003; Bentley et al., 2010; Todd et al., 2010). However, most erratics at Mt. Waesche and the Ohio Range have apparent exposure ages older than the most recent highstand, but significantly younger than that of local bedrock outcrops (Ackert et al., 1999; Ackert et al., 2011; Mukhopadhyay et al., 2012), These samples are not readily distinguished by surface characteristics from those with the youngest exposure ages, and are not likely to have experienced significant erosion. A brief summary of the sampling locations and previous results from Mt. Waesche and the Ohio Range Escarpment appears below. In addition, we provide more detailed descriptions from the Ohio Range of the ice-cored lateral moraines of alpine glaciers bordering Mercer Ridge on Mt. Schopf.

2.1. The Ohio Range

2.1.1. Ohio Range Escarpment

The Ohio Range Escarpment exposes Permian sandstones and tillites overlying granitic basement rocks. Ablation zones (blue ice areas) occur on the western sides of Darling and Discovery Ridge in the lee of the prevailing winds as well as on the alpine glaciers (Fig. 2). Extensive areas of ice-cored moraine occur on the WAIS within the blue ice areas. We conducted transects from the WAIS ice margin to the peaks of several nunataks within the blue ice area west of Darling Ridge and on the escarpment at Darling and Discovery Ridge. In the Ohio Range, granite erratics lacking evidence of subaerial weathering are rare. Hence, we focused on clasts with