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Middle to Late Pleistocene stability of the central East Antarctic Ice Sheet at the head of Law Glacier

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ABSTRACT

Past behavior of outlet glaciers draining the East Antarctic Ice Sheet (EAIS) remains unresolved prior to Marine Isotope Stage 2 (MIS2). Study of blue ice moraines provides a relatively untapped approach to understand former EAIS activity. We focus on a blue ice moraine near Mount Achernar in the central Transantarctic Mountains, at the edge of the polar plateau. The well-preserved moraine consists of quasi-continuous or hummocky sediment ridges that form on top of upward-flowing, sublimating ice along the margin of Law Glacier. ^{10}Be, ^{26}Al, and ^{3}He cosmogenic nuclide ages on boulders from the ridges are coherent and in general are progressively older with distance from the relatively clean ice of the Law Glacier margin. Moraines closest to the Law Glacier margin postdate MIS2; farther away, they date to the last glacial cycle, and with more distance they are hundreds of thousands of years old. We conclude that cosmogenic dating of some blue ice moraines can provide age limits for changes at the heads of outlet glaciers that drain the central East Antarctic Ice Sheet, including prior to MIS2. Furthermore, the geomorphological, cosmogenic nuclide, and sedimentological evidence imply that the East Antarctic polar plateau adjacent to the central Transantarctic Mountains has been relatively stable for at least 200 k.y.

BACKGROUND

Knowledge of East Antarctic Ice Sheet (EAIS) behavior prior to Marine Isotope Stage 2 (MIS2) is commonly obtained from ice cores or indirectly from marine records or modeling (e.g., Petit et al., 1999; DeConto and Pollard, 2016) because of the scarcity of well-dated terrestrial deposits. Exceptions include dating of lateral moraines and drift sheets in the Dry Valleys (e.g., Sugden et al., 1993; Staiger et al., 2006) and elsewhere in the Transarctic Mountains, where more widely spaced studies have tended to focus on a million-year time scale, or the history of glacier thinning since MIS2 (e.g., Mercer, 1983; Ackert and Kurz, 2004; Bromley et al., 2010; Ackert et al., 2013; Joy et al., 2014). Observations from blue ice areas in the central Transantarctic Mountains, adjacent to the polar plateau, can be used to understand past changes in the central part of the EAIS. Blue ice ablation zones are common throughout the continental interior (Bintanja, 1999), yet moraines that form in these areas have received less attention than other geologic deposits around East Antarctica (Sinisalo and Moore, 2010). Recent studies in West Antarctica show that blue ice regions offer a dateable archive of former ice sheet behavior, especially prior to MIS2 (Fogwill et al., 2011; Hein et al., 2016).

Blue ice moraines form differently than temperate ice-marginal moraines where melting dominates. Prior studies have documented the processes that lead to sediment accumulations associated with blue ice areas (e.g., Whillans and Cassidy, 1983; Chinn, 1991, 1994; Cassidy et al., 1992; Sinisalo and Moore, 2010; Fogwill et al., 2011; Campbell et al., 2013; Hein et al., 2016; Bader et al., 2017). As the EAIS encounters the Transantarctic Mountains (Fig. 1), the barrier to flow causes ice convergence into outlet glaciers. Such settings are favorable for blue ice regions, where enhanced wind scouring and sublimation along glacier margins enables upward flow, which carries sediment to the surface (see the GSA Data Repository[1]). Until recently, around the continent, it has

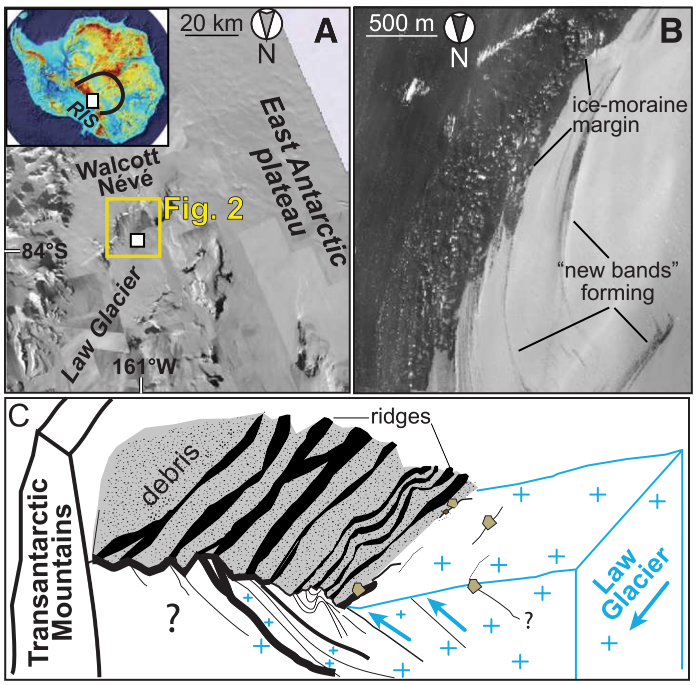

Figure 1. A: Location of Mount Achernar moraine at the head of the Law Glacier (East Antarctica). Panel B is within the small white box. In inset, color gradient shows bedrock elevation (red = high), and black line marks sector that drains through central Transantarctic Mountains (Fretwell et al., 2012). RIS—Ross Ice Shelf. B: Moraine-ice marginal zone, on DigitalGlobe (www.digitalglobe.com) image. C: Schematic cartoon, which is provided to help visualize how sediments may accumulate at Mount Achernar (Bader et al., 2017) (see Data Repository [see footnote 1]). Variable size of upward-flowing debris pathways reflects differential thickness. Question marks refer to lack of knowledge of subsurface.

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[1]GSA Data Repository item 2017324, supplemental text, figures, and tables, is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.

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remained poorly known for how long sediment accumulations have persisted on top of blue ice.

An important concept is that even after their initial formation, blue ice moraines still overlie glacier ice, and upward-flowing debris can cause continued accumulation near the surface (Fig. 1; Fig. DR1 in the Data Repository). Substantial removal of the underlying glacier ice would result in a reversal or change in gradient and flow, which should deform or even "drain" these surface sediments (e.g., Chinn, 1991, 1994; Fogwill et al., 2011; Hein et al., 2016). Conversely, a substantial increase in glacier thickness could eventually deform or displace the moraines, as perhaps observed in some areas (Chinn, 1991, 1994).

To assess past stability of the East Antarctic interior, we studied a well-preserved extensive blue ice moraine linked with Law Glacier, near Mount Achernar at the edge of the polar plateau, between the Queen Alexandra and Queen Elizabeth Ranges (Figs. 1 and 2). In this region, East Antarctic ice is sourced mainly from the Dome A sector, and it encounters the Transantarctic Mountains on the south and southwest sides of Mount Achernar (Fig. 1), where it splits into Law Glacier and Walcott Névé. Walcott Névé is slow-moving ice, a small part of which flows into the Lewis Cliff Ice Tongue (Fig. 2). Approximately 20 km down flow of Walcott Névé, the slower-moving ice converges back into Law Glacier (Fig. 1).

The Mount Achernar moraine consists of a series of troughs and ridges 1–12 m high that roughly parallel the form of the relatively clean Law Glacier margin, over an inland expanse of ~5 km (Figs. 2 and 3). The moraine overlies sediment-laden ice, and changes in surface elevation are overall on the order of tens of meters (Fig. 3) (Scarrow et al., 2014; Bader et al., 2017). Till thickness increases from <5 cm to >1 m with distance from the relatively clean surface of Law Glacier (Scarrow et al., 2014). Bader et al. (2017) used till provenance to understand better the nature of sediment accumulation at this site. They showed that distinct lithological bands can be observed quasi-continuously along ridges, for >5 km in places, and changes over time can be related to the location of subglacial erosion (Fig. DR1; Fig. 2A). The length of time the sediments have been exposed at the Mount Achernar moraine has remained largely unconstrained (Scarrow et al., 2014; Sun et al., 2015; Bader et al., 2017), except for a preliminary study by Hagen (1995) that indicated at least some exposure ages were >100 ka (Fig. 2).

RESULTS

To obtain an age framework for the moraine at Mount Achernar, we measured ^{10}Be and ^{26}Al in sandstone and ^{3}He in dolerite boulders (see the Data Repository). Our sampling strategy was to follow closely a topographic profile that is along a well-preserved part of the moraine, roughly perpendicular to ridge crests (Fig. 2; see the Data Repository). We sampled far (several kilometers) from the headwalls to avoid materials with a significant amount of pre-exposure. Within ~2 km of the clean surface of the Law Glacier margin, apparent exposure ages are ca. 5–20 ka (≤MIS2). Approximately 2 km to ~2.5 km from Law Glacier, apparent boulder ages are ca. 35 ka to ca. 100 ka (i.e., the last glacial cycle). Beyond ~2.5 km, all three nuclides yield ages ≥100 ka. Approximately 2.5–3.5 km away from the Law Glacier margin, boulders date from ca. 100 ka to ca. 200 ka. Also, on the southern end of the area, we dated two samples (MAR-11-48, MAR-11-52) left by northward-flowing local ice, which are also >100 ka (Fig. 2A). All three nuclides, ^{10}Be-^{26}Al-^{3}He, are in agreement that there is a net increase in age well into the hundred-thousand-year time scale, at least until ca. 200 ka (Fig. 3B), regardless of minor age reversals that are discussed further below.

In addition, we show an unpublished ^{10}Be-^{26}Al data set from Hagen (1995) (see the Data Repository). The recalculated ages, using present method systematics, are consistent with our findings, with the exception of one young outlier of 15 ka that is ~4 km from the Law Glacier (Fig. 2A). Hagen (1995) assumed this ca. 15 ka outlier could be explained by persistent snow in the depressed area where he collected the sample, and we do not discuss it further. It is not possible to line up precisely Hagen's (1995) sample positions along our profile, given inexact locations (Figs. 2 and 3).

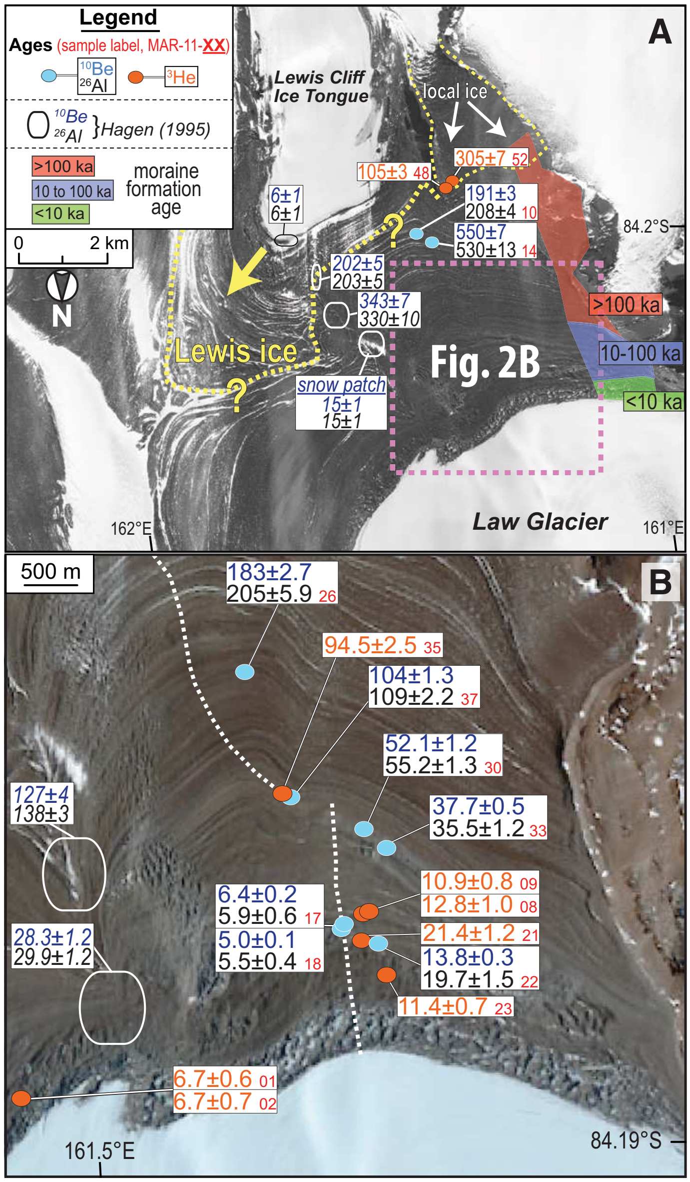

Figure 2. Blue ice moraine dating at Mount Achernar, East Antarctic Ice Sheet. A: DigitalGlobe (www.digitalglobe.com) image with locations of ^{10}Be-^{26}Al (measured on same sample) and ^{3}He ages (in ka), with analytical errors (±1σ).The 105 ka and 305 ka ages are on samples from northward-flowing local ice. Boundary between Law Glacier and Lewis Cliff Ice Tongue ice is marked in yellow, which is uncertain in places (question mark). B: Focus on north side of moraine. Dashed white line represents topographic profile in Figure 3 (from Bader et al., 2017); its orientation changes at ~2.4 km from glacier margin to follow center of well-preserved part of moraine.

DISCUSSION AND CONCLUSIONS

The Mount Achernar blue ice moraine and its setting contain a valuable record of regional ice sheet history (Fig. 1). The ^{10}Be-^{26}Al-^{3}He ages progressively increase with distance away from the relatively clean Law Glacier margin (Fig. 3B). General ^{26}Al and ^{10}Be age accordance (Fig. DR5) implies that the samples did not experience prolonged periods of burial (e.g., >100,000 yr) and re-exposure. Significant pre-exposure of ^{10}Be may exist, for example, if the samples were originally rockfall from headwalls. However, for headwall material to exist where we sampled,

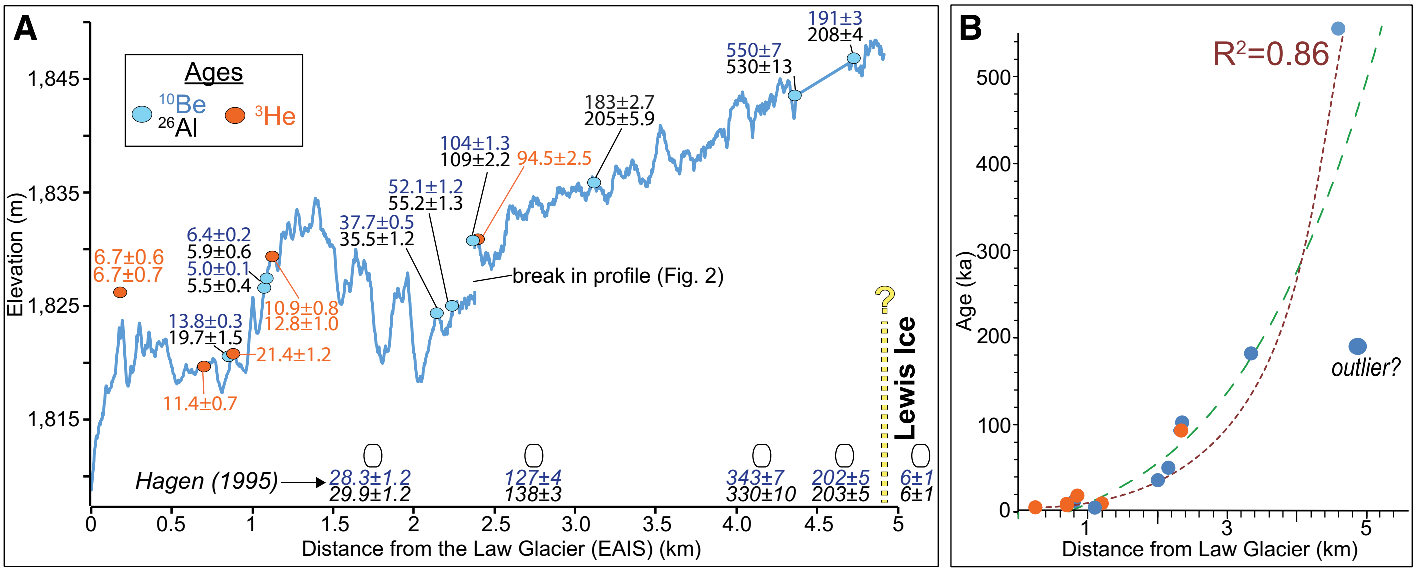

Figure 3. Net age increases away from modern Law Glacier, East Antarctic Ice Sheet (EAIS). A: Ages (in ka) plotted along topographic profile (see Fig. 2B) between Law Glacier and Lewis Cliff Ice Tongue ice (yellow line). For comparison, at estimated positions, we show the 6.7 ± 0.7 ka ^{3}He age and ^{10}Be-^{26}Al ages from Hagen (1995), except for 15 ka age (see text), which date samples to the east of the topographic profile (Fig. 2B). B: Exponential (green, long dashed) and second-order polynomial (brown, short dashed) fits are merely to show net age increase to at least ~3.5 km from Law Glacier (ca. 200 ka), and >5 km if we assume farthest dated sample, 191 ka (~5.6 km), is an outlier (see text). Errors are within symbol size.

debris would have had to have been transported against both the direction of ice flow and lateral accretion of moraine (Fig. 2A). Also, Mount Achernar is adjacent to the polar plateau, and hence there are limited upflow nunatak sources to provide rocks with pre-exposure.

The strong exposure age–distance trend shown in Figure 3B leads us to speculate that after boulders reach the surface along upward-flowing ice, they must remain somewhat stable above the thickening till (Scarrow et al., 2014; Bader et al., 2017). The age-distance progression also indicates that debris accretes laterally over time, and underlying sublimation decreases, which is consistent with the provenance-based interpretation of Bader et al. (2017) and conceptual model shown in Figure 1. Our findings are also consistent with quantitative measurements of salt accumulation (Graly et al., 2016). Specifically, the cosmogenic ages show a remarkably strong relationship ($R^2 = 0.99$) with the steady buildup of salt concentration (e.g., boron) by atmospheric deposition on the moraine surface (Graly et al., 2016).

Concerning the minor age reversals, these are discussed further because they may provide additional insight into formation of blue ice moraines. First, two samples have been exposed for less time, ~6–5 k.y. (at ~1.1 km), than boulders closer to Law Glacier (Fig. 2). We offer two possible scenarios that could cause the 6–5 ka exposure ages. Any explanation must adhere to the observation that these boulders have pristine tops with glacial striations, indicating negligible surface erosion (Fig. DR2). Periglacial processes may have been more active in this particular spot, which rotated both sampled boulders, exposing former underlying sides, by a similar amount. Alternatively, perhaps the younger 5–6 ka ages at ~1.1 km reflect the general age of the moraine surface and can be explained by the local emergence of younger sediment, possibly due to a contorted underlying ice structure (cf. as described in Chinn, 1991, 1994). Bader et al. (2017) presented findings (Fig. DR1) that are consistent with debris still being brought to the surface after initial formation of a debris layer (cf. Mackay and Marchant, 2016). Regardless of the cause, this minor age reversal does not negate the fact that the surface sediment generally increases in age away from the Law Glacier margin (Fig. 3B).

An age reversal also occurs in the older part of the sequence (Fig. 2). The 191 ka ^{10}Be (208 ka ^{26}Al) age could be too young due to periglacial processes or emergence of a younger boulder, or the 550 ka ^{10}Be (530 ka ^{26}Al) age could be too old due to recycling of a boulder with prior exposure. However, the 550 ka boulder is surrounded by more weathered sediments compared with the younger part of the sequence (Fig. DR2D), documenting qualitatively that this area of the moraine is indeed older. In agreement with this interpretation, the highest boron salt concentration measured in the Mount Achernar moraine is near the 550 (530) ka boulder, supporting that this is the oldest part of the sequence (Graly et al., 2016). We also speculate that the ca. 200 ka age from Hagen (1995) could be originally from the northward-flowing Lewis Cliff Ice Tongue (dashed yellow line in Fig. 2) and was later reworked into Law-derived moraine. However, we emphasize, again, that any of these scenarios are consistent with our conclusions: beyond ~2.5 km from Law Glacier, the deposits are at least 100 ka, and beyond 3 km they are ca. 200 ka or older (Figs. 2 and 3).

In summary, a dateable, well-preserved, laterally extensive and quasi-continuous blue ice moraine sequence exists at Mount Achernar. The geomorphology of the sequence and coherent age progression (Figs. 2 and 3B) of three isotopes, ^{10}Be-^{26}Al-^{3}He, lead us to agree with prior studies that blue ice moraines represent quasi-equilibrium forms (Fogwill et al., 2011). Specifically, at the head of Law Glacier, well-preserved and extensive ridges have persisted for well into the hundred-thousand-year time scale. The age progression also provides a temporal foundation for understanding the process by which these and other blue ice moraines form.

Our findings are not compatible with this section of the interior EAIS undergoing marked lowering over the time represented (Fig. 1). The largest elevation changes in the moraine morphology (Fig. 1) are only on the order of tens of meters (Fig. 3A). If a non-equilibrium situation occurred at Mount Achernar, such as the loss of underlying ice or the buttressing effect of Law Glacier, we infer that this disruptive event should have distorted or even gutted the blue ice moraine (Fig. 3; Fig. DR1). Other recent sediment provenance and geochemical studies at this site are also consistent with relative stability of the EAIS near the head of Law Glacier over the time represented (Bader et al., 2017; Graly et al., 2016).

More broadly, we demonstrate that at least some blue ice moraines in the central Transantarctic Mountains can be dated into the hundred-thousand-year time scale. Because these moraine sequences are fed by outlet glaciers connected to the nearby unconstrained EAIS plateau, they can be used to place limits on former ice flow, surface elevations, and thus model results for time periods such as MIS2 and prior (Sinisalo and Moore, 2010; Fogwill et al., 2011). For example, numerical models do not simulate much change where ice encounters the central Transantarctic Mountains, including during MIS2 when >500 m of surface change occurred where Law Glacier entered the Ross Sea embayment (e.g., Mercer, 1983; Bromley et al., 2010). We conclude that the EAIS in the area of the central Transantarctic Mountains has changed little through the last one or two glacial-interglacial cycles, even if major changes occurred elsewhere over the time period represented (DeConto and Pollard, 2016).

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