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Key Points:
- We present a new location and geochemical evidence for ancient buried ice in the Southern Transantarctic Mountains
- This ice has the potential to be used for climate records from the Pleistocene and is within 1 m or Earth's surface
- Our research highlights the surface processes in hyperarid polar deserts that preserve ancient ice

Supporting Information:
- Supporting Information S1
- Tables S1–S4
- Figures S1–S9

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Million year old ice found under meter thick debris layer in Antarctica

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Abstract Cosmogenic nuclide measurements associated with buried glacier ice in Ong Valley, in the Transantarctic Mountains, suggest the preservation of ancient ice. There are three glacial tills on the valley floor which have formed from the concentration of regolith contained within sublimating glacier ice. Two tills are less than 1 m thick and underlain by ice. Measurements of cosmogenic ^{10}Be, ^{26}Al, and ^{21}Ne show that (i) the youngest buried ice unit and corresponding till are at least 11–13 ka, (ii) another ice unit and corresponding intermediate-age till are at least 1.1 Ma old under any circumstances and most likely older than 1.78 Ma, and (iii) the oldest till is at least 1.57 Ma and most likely greater than 2.63 Ma. These observations highlight the longevity of ice under thin debris layers and the potential to sample ancient ice for paleoclimate/paleoatmosphere information close to the present land surface.

1. Introduction

Ice cores from alpine glaciers and continental ice sheets provide important records of paleoclimate conditions, and significant effort in the last several decades has been devoted to obtaining the longest possible ice core records of past climate [*Dansgaard et al.*, 1969; *Jouzel et al.*, 2007; *Luthi et al.*, 2008; *Fischer et al.*, 2013]. This effort is complicated because older ice is both more likely to have been disturbed or removed by ice flow and more difficult to access since it is generally located at the base of thick ice sheets. Ice exposed near Earth's surface is easier to access but less likely to survive for long durations because it melts and/or sublimates under normal ambient conditions [*Hooke*, 2005].

The oldest continuously dated ice core is at the bottom of the Dome C, Antarctica, (3.2 km below surface) and is 0.8 Ma [*Jouzel et al.*, 2007; *Luthi et al.*, 2008]. Other measurements from ice cores in Mullins Glacier and Allan Hills, Antarctica, date ice as old as 1 Ma to 1.6 Ma at 117 m and 8 m depths, respectively [*Higgins et al.*, 2015; *Yau et al.*, 2015]. The oldest ice ever reported is from Beacon Valley and was dated from overlying volcanic ash at 8 Ma [*Sugden et al.*, 1995], though some subsequent research suggests that the ice in question may be significantly younger than the age of the ash [*Van der Wateren and Hindmarsh*, 1995; *Stone et al.*, 2000; *Ng et al.*, 2005].

It is well known that debris-covered ice can persist near the surface for long periods of time due to the suppression of sublimation processes by a relatively thin layer of debris [*Wahrhaftig and Cox*, 1959; *Hindmarsh et al.*, 1998; *Schorghofer*, 2005; *Kowalewski et al.*, 2006]. Shallowly buried ice bodies up to 20,000 years old are routinely found in mountain regions worldwide [*Konrad et al.*, 1999; *Haeberli et al.*, 2006].

We report a previously unknown buried ice body in Ong Valley, Antarctica, (Figure 1). It is unlikely for this buried ice to be replenished after its emplacement and geomorphic observations indicate that the ice and the overlying till have the same age. We use measurements of cosmogenic ^{26}Al and ^{10}Be to constrain the sublimation and erosion history of three tills on the valley floor of Ong Valley. Further, due to the age of these deposits, ^{21}Ne concentrations provide constraint for exposure ages of each till and referenced buried glacier ice.

2. Field Area and Geologic Context

Ong Valley (83°14′S, 157°37′E) is a 2.5 km wide, 7.5 km long valley in the Miller Range of the Central TAM, Antarctica (Figure 1). The head of Ong Valley contains a small unnamed alpine glacier, and the valley entrance is blocked by a ~2 km wide lobe of the Argosy Glacier. A meteorological station deployed for 1 year (2011) recorded a temperature range of −49.0° to −4.0°C and mean of −23.9°C. The valley surface rises from

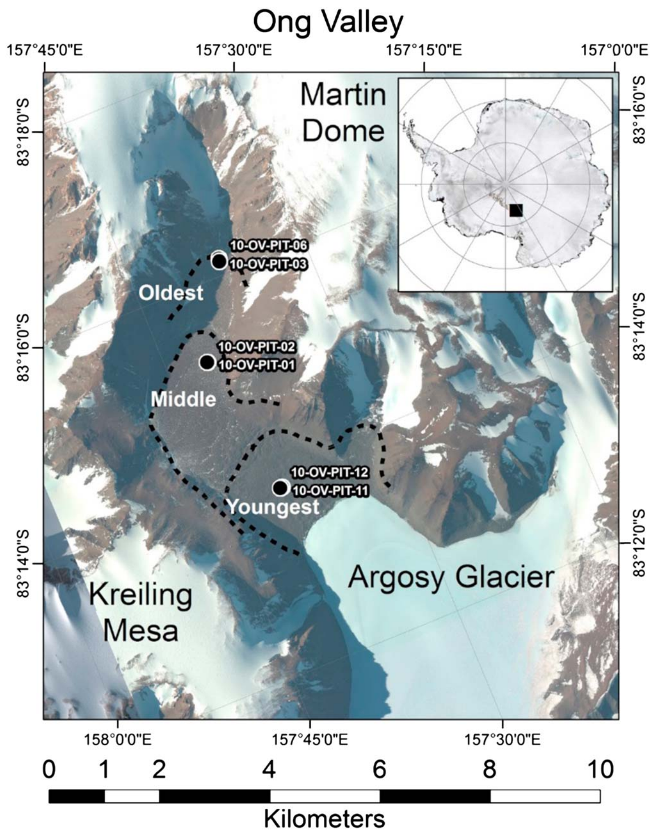

Figure 1. Ong Valley satellite image. Dashed lines are boundaries between till units, circles mark depth profile sample site locations, and inset map shows relative location of Ong Valley within the TAM. The overall valley profile slopes down toward the Argosy Glacier with the valley head (Oldest till) at the highest elevation and the valley mouth (Youngest till) at the lowest elevation. A valley floor panorama is available in the supporting information (Figure S1a).

1500 m above sea level (m asl) at the margin of the Argosy Glacier to 1700 m asl at the head of the valley. Most of the valley floor is covered by three lobate sedimentary deposits concentric to the present margin of Argosy Glacier (herein referred to as Youngest, Middle, and Oldest; (Figure 1)). These deposits were first described in 1975 from air photo analysis and were subsequently investigated as soil chronosequences [*Mayewski*, 1975; *Scarrow et al.*, 2014].

In the following paragraphs we will describe the geomorphic and geologic evidence that suggest that these tills are of sublimation origin. The lobate form of these drift sheets, presence of nonlocal lithologies, and shared provenance between englacial debris and till [*Edwards et al.*, 2014] indicate that they were emplaced by past advances of the Argosy Glacier into the valley. In contrast, the valley floor and walls outside the margin of the three drifts are covered with talus and colluvium derived from bedrock outcrops high on the valley walls. A small alpine glacier at the head of Ong Valley displays moraines distal to its present terminus, but all moraines are well above the margin of valley floor drift sheets. This suggests that alpine glaciers were not confluent with the Argosy Glacier during past advances that deposited the three drifts. The surface of the middle drift slopes toward the Argosy Glacier (down valley), (Figure S1a in the supporting information); thus, no recharge of ice from the present glacier to the middle drift ice body is expected.

The concentric relationship of the three drifts, the morphostratigraphic relationship of the moraines that form the drift boundaries, and the absence of crosscutting features all indicate that the ages of the drifts increase with distance from the present Argosy Glacier margin. The surface morphology of the drifts is consistent with this age-distance relationship. The Youngest drift has no desert varnish or desert pavement, and the surface is dominated by fine-grained silt-sized regolith. The Middle and Oldest drifts have desert pavement containing boulders and cobbles with desert varnish, suggesting that these drifts have been weathering much longer than the Youngest. Additionally, the maturity of patterned ground polygons increases from the Youngest to the Oldest drift [*Sletten*, 2003].

The Youngest and Middle drifts overlie buried glacier ice at depths of 0.46–0.48 m (Youngest) and 0.68–0.80 m (Middle). The englacial debris concentrations of the buried ice range between 3% and 10% by volume and appear banded (Figures S1b–S1d). Debris is mostly silt to sand sized with sparse pebbles and cobbles and has a similar lithology to the overlying till. We did not observe air bubbles in the uppermost 10–20 cm of ice that we were able to sample, and many small fractures throughout the ice lattice have a white/cloudy appearance. We interpret the ice to be of glacial origin because it occurs only beneath sediment of demonstrated glacial origin and has a convex cross-valley profile as expected for a lobe of the Argosy Glacier extending into the valley. No ice was found beneath the Oldest drift in hand-dug pits down to 0.67–0.78 m depth. Channels, rills, or fans are not present on drift surfaces, suggesting that liquid water has not modified these surfaces in the recent past.

To summarize, stratigraphic and geomorphic information indicates that all three drifts are sublimation tills composed of formerly englacial debris. In the case of the Youngest and Middle drifts, the original glacial ice still remains below the tills. In the following sections we will show that cosmogenic nuclide concentrations in all drifts are consistent with this interpretation.

3. Methods

3.1. Cosmogenic Nuclides

Terrestrial cosmogenic nuclides form when galactic cosmic rays interact with elements on Earth's surface [*Dunai*, 2010]. The concentration of observed in situ cosmogenic nuclides typically increases with time, decreases with depth, and includes a suite of other considerations for proper method application [*Gosse and Phillips*, 2001]. The production rate of each nuclide at each sample site was calculated and scaled for latitude, elevation, and topographic shielding following standard methods (see supporting information). We collected samples for cosmogenic nuclide analysis from the centers of large patterned ground polygons with relatively flat tops lacking large rocks or boulders. Sites were chosen in the middle of each drift to limit the possibility of rock fall contributions from valley walls. Bulk sediment was sampled at approximately 10 cm depth intervals, and in addition, samples of englacial debris were collected where buried ice was found. To evaluate the reproducibility of our results, samples are from two pits located within 10 m of each other in each drift. For each drift, we measured ^{10}Be and ^{26}Al in quartz in samples from one pit and ^{21}Ne in quartz in samples from both pits.

Quartz from each bulk sample was cleaned and prepared for ^{26}Al and ^{10}Be Accelerator Mass Spectrometry (AMS) measurement at the PRIME Lab of Purdue following standard methods [*Gosse and Phillips*, 2001; *Nishiizumi et al*., 2007; *Dunai*, 2010]. Additional clean quartz was prepared and measured for ^{21}Ne at the Berkeley Geochronology Center following methods outlined by *Balco and Shuster* [2009]. Prime Lab ^{27}Al/^{26}Al and ^{10}Be/^{9}Be isotope ratios were referenced to the standards of *Nishiizumi* [2004], *Nishiizumi et al.* [2007], and BGC ^{21}Ne concentrations were referenced to CREU-1 and CRONUS-A quartz standards.

Our field observations and the geologic context of the sample sites show that the geologic history of each drift is as follows: (i) the Argosy Glacier advanced into Ong Valley; (ii) ice flow ceased and sublimation of ice produced a sublimation till formed by concentration of the exhumed englacial debris; and (iii) once formed, the surface of the till was subject to erosion by rock and mineral weathering and/or aeolian sediment transport. This sequence of events implies several basic relationships fundamental to our subsequent discussion. (i) The present-day thickness of the resulting lag deposit is a function of the age of ice emplacement, the rate of ice sublimation, the englacial debris concentration, and the rate of till erosion. (ii) The surface erosion rate of the till must be slower than its aggradation rate; else, no lag deposit would exist atop buried ice. (iii) The sublimation rate of the ice must decrease after initial emplacement as the ice becomes insulated by a thickening till layer. (iv) The concentrations of cosmic ray produced nuclides that we observe depend on the inherited nuclide concentrations of englacial debris, the age of the glacier advance associated with each drift, the sublimation rate of glacier ice after emplacement, and the surface erosion rate of the drift.

Overall, these relationships allow quantitative prediction of observable cosmogenic nuclide concentrations and till thickness which is a function of four parameters of geological interest: the age of ice emplacement, ice sublimation/till erosion rates, and the inherited nuclide concentrations in englacial debris. In the subsequent discussion we will show that the results from cosmogenic nuclide analysis support the geologic scenario described above, in particular the age of ice emplacement.

3.2. Models

In the previous section, we have demonstrated the geologic and geomorphic evidence that suggest that the three tills on the floor of Ong Valley are of sublimation origin. It is expected that the concentration of cosmogenic nuclides at depth should also support this scenario. We apply a model that considers a steady sublimation rate, steady erosion rate, previous nuclide inheritance, evenly distributed englacial debris, and exposure time on the observed concentrations of ^{26}Al and ^{10}Be nuclides in the till. The model is based on the work of *Morgan et al*. [2010b], *Ng et al*. [2005], *Putkonen et al*. [2008], and *Schaefer et al*. [2000]. Our data set includes additional improvements by using samples from the ice till boundary and within the ice.

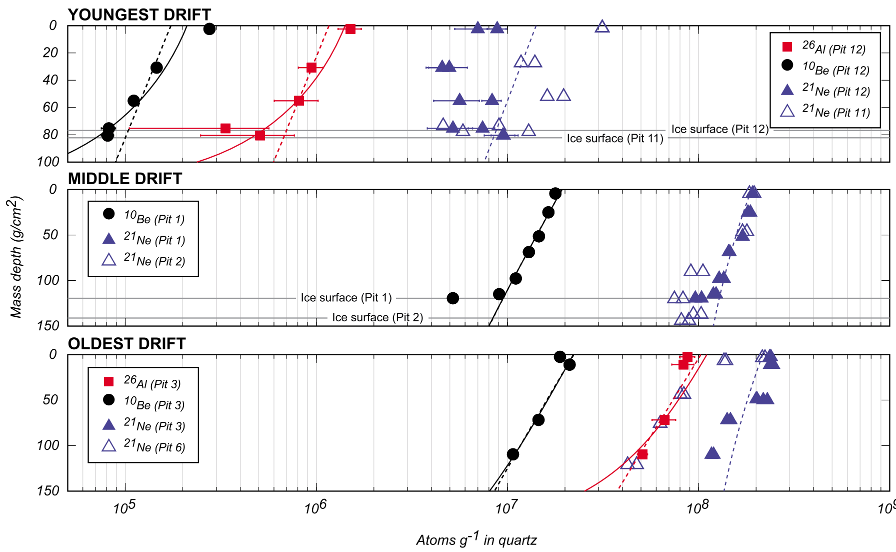

Figure 2. Subsurface cosmogenic nuclide concentrations and model results for three drifts in Ong Valley. Symbols show measured nuclide concentrations; error bars are one standard error and, where not visible, are smaller than the size of the symbol at this scale. Solid lines are model results for a model including both ice sublimation and till surface erosion fit to ^{26}Al (red) and ^{10}Be (black) data. Dashed lines are model results for a model that assumes instantaneous emplacement of the till, steady surface erosion, and no vertical mixing; these are fit to each set of nuclide concentration measurements individually. Blue dashed lines are fit to ^{21}Ne concentrations in both pits for the Youngest drift but only to data from pits 2 and 3 for the Middle and Oldest drifts, respectively, for clarity in plotting all data on the same figure.

Our rate and age calculations for this site require a two-step approach. After a few effective half-lives have passed, radiogenic ^{26}Al and ^{10}Be are better suited for resolving sublimation and erosion rates rather than resolving exposure time. To further constrain exposure ages of the three tills, we utilize concentrations of stable nuclide ^{21}Ne in each drift. We apply the modeled erosion and sublimation rates to minimum ages derived from ^{21}Ne concentrations to better constrain the true age of each till.

The sublimation/erosion model uses radiogenic ^{26}Al and ^{10}Be and assumes that the till layer is formed from the sublimation of ice with englacial debris and that after sublimation the lag deposit is subject to erosion. We assume an evenly distributed 10% concentration of englacial debris in the ice following field-based measurements. Free parameters of this model are (i) the age the ice was emplaced (e.g., the age that till began to form), (ii) the constant sublimation rate of the ice, (iii) the constant erosion rate at the till surface, and (iv) the inherited ^{26}Al and ^{10}Be concentrations in the englacial debris at the time the ice was emplaced. Varying sublimation rates, erosion rates, and englacial debris concentrations throughout time are not reflected with our single model solutions. Thus, we also compute limiting boundary conditions following methods outlined by *Ng et al*. [2005] to show that our results are within tolerance of similar clast separation models for sublimating till (see supporting information Table S4). The error associated with our model is calculated with a 10,000 run Monte Carlo simulation and reported with 1 sigma (68%) error bars.

4. Results

Nuclide concentrations from stratigraphically older drifts (Middle and Oldest) are 2 orders of magnitude greater than concentrations in the Youngest drift (Figure 2 and Table S1). We calculate the apparent age of each drift using the top sample from two adjacent pits and averaged the resulting age. An apparent age is the exposure age calculated for a single period of exposure at the present location without inheritance or erosion. Below, we will show that ^{21}Ne is best suited to resolve the minimum age of the oldest two deposits and that our reported ages match the stratigraphic relationship of each drift. The Middle and Oldest drifts have ^{21}Ne apparent ages of 1.96 ± 0.05 Ma and 2.44 ± 0.05 Ma, respectively. The Youngest drift has an apparent ^{21}Ne age of 0.23 ± 0.02 Ma. Thus, nuclide concentrations are consistent with the stratigraphic relationship of the drifts. A complete table of age calculations from all three nuclides (^{21}Ne, ^{26}Al, and ^{10}Be) is available in the supporting information (Table S3) and omitted here for brevity.

4.1. Youngest Drift

^{26}Al and ^{10}Be cosmogenic nuclide concentrations observed in 10-OV-Pit-12 are consistent with till formation from sublimation of ice with englacial debris that has uniform inherited nuclide concentrations throughout the till and no subsequent vertical mixing (Figure 2). ^{26}Al and ^{10}Be concentrations decrease with depth, and surface concentrations suggest that the ice was emplaced 11–13 ka (Table S3). The concentrations of ^{26}Al and ^{10}Be in depth profiles are too low to have reached steady state and therefore do not provide strong constraints on erosion and sublimation rates. We still provide the sublimation and erosion model results in the supporting information (Figures S4 and S5).

^{21}Ne concentrations, on the other hand, are an order of magnitude higher than ^{26}Al and ^{10}Be concentrations and do not systematically decrease with depth. ^{21}Ne concentrations are scattered around a mean of 11.4×10^6 atoms/g (Figure 2). This implies that in contrast to the ^{26}Al and ^{10}Be inventory, the majority of the present ^{21}Ne concentration is either (i) inherited from prior exposure or (ii) nucleogenic rather than cosmogenic [*Middleton et al*., 2012]. Due to the young age of the deposit and the likelihood that the majority of measured ^{21}Ne is inherited from previous exposure, concentrations of ^{21}Ne in this till are not adequate for age constraint. Thus, in this instance ^{26}Al and ^{10}Be serve as reliable age indicators for the drift. Note that the distinction between nucleogenic and inherited cosmogenic ^{21}Ne is not relevant in our analysis, as we include both equivalently as ^{21}Ne present in sediment prior to ice emplacement.

4.2. Middle Drift

^{10}Be concentrations in Middle drift samples from 10-OV-Pit-01 are also consistent with a sublimation model in which the till has not been vertically mixed. We resolve a sublimation rate of 22.7 ± 11 m/Ma, with an erosion rate of 0.89 ± 0.07 m/Ma (Figure S6). Given observed englacial debris concentrations, one can compute the till accumulation rate from these results (equation (S4)). The englacial debris concentration of the Argosy Glacier (10% by volume) implies a till accumulation rate of 1.38 m/Ma.

Fitting the sublimation model to the ^{10}Be data provides only a weak constraint on the age of ice emplacement (6.6 ± 3 Ma; see Figure S6). This is due to the tendency of nuclide concentrations to asymptotically approach a steady state value after significant erosion of the original surface has taken place. Thus, we use limiting arguments to fix unambiguous minimum limits on the age of ice emplacement. Assuming zero surface erosion and ^{10}Be inheritance equal to the ^{10}Be concentration in the lowest sample, the ^{10}Be concentration in the uppermost sample provides an unconditional minimum age of 0.61 ± 0.02 Ma. A less restrictive minimum age, which takes into account the fact that the surface erosion rate of the till must be greater than zero but still does not depend on the assumption of a constant sublimation rate, can be obtained by making the limiting assumption that all the tills that previously existed above the present surface were formed instantaneously at the time of ice emplacement and that the subsequent surface erosion rate was 0.89 m/Ma as inferred from the model-fitting exercise. This set of assumptions yields an age of 0.81 ± 0.02 Ma for the ice and drift (Table S3).

We can also obtain a second independent limiting age for the drift by performing the same exercise with the ^{21}Ne data. If we take the deepest sample (10-OV-Pit-02-80-83Ia) as the maximum possible concentration of inherited ^{21}Ne, and assume no surface erosion, the resulting unconditional minimum exposure age of the upper sample is 1.1 ± 0.04 Ma. A more realistic minimum age constraint for this drift can be computed using the assumption that the inherited ^{21}Ne concentration in this drift was equal to the average ^{21}Ne concentration measured in the Youngest drift (11.4×10^6 atoms/g quartz); this assumption yields a minimum age of 1.83 Ma for the Middle drift and underlying ice. Alternatively, assuming a maximum possible inheritance of 8.13×10^7 atoms/g quartz (10-OV-Pit-02-80-83Ia) and 0.89 m/Ma surface erosion yields an age of 1.78 Ma.

4.2.1. Concentrations in the Ice

The concentration of ^{10}Be from englacial debris (10-OV-Pit-01-68-72Ia) is less than the expected concentration implied by model fitting to the samples in the till (Figure 2). Our model approach assumes that the sublimation rate, erosion rate, and englacial debris concentrations are constant through time. Englacial debris concentrations of ^{21}Ne are also less than the expected concentration implied by model fitting (Figure 2). One possible explanation for this deviation is that small variations in the surface erosion/sublimation rate or changes in ice bound debris concentrations could lower the concentration of englacial debris nuclides, but this remains unresolved.

4.3. Oldest Drift

Concentrations of ^{26}Al, ^{10}Be, and ^{21}Ne in the Oldest drift are also consistent with a sublimation origin for the till and no subsequent vertical mixing (Figure 2). A sublimation model fit to concentrations of ^{26}Al and ^{10}Be constrains an ice sublimation rate of 19.03 ± 11 m/Ma and erosion rate of 0.74 ± 0.06 m/Ma (Figure S8). As with the Middle drift, the sublimation model provides a relatively weak constraint on the till age of 8.9 Ma, because the profile is near steady state. In contrast to the Middle drift, no ice surface was reached in pits within this drift down to 67–78 cm, so the till thickness does not provide any constraint on the age. Following the limiting age calculations described above, concentrations of ^{26}Al and ^{10}Be constrain the apparent exposure age at 0.80 ± 0.11 Ma and 1.04 ± 0.03 Ma, respectively, assuming zero surface erosion and zero prior inheritance and 1.07 ± 0.11 Ma to 1.49 ± 0.03 Ma with 0.74 m/Ma erosion (Table S3).

We obtain a second, independent measure of the age of the drift from the observed ^{21}Ne concentrations. To determine the minimum possible exposure age for the Oldest drift, we designate the deepest sample (10-OV-Pit-03-63-67 and 10-OV-Pit-06-66-78) as representative of the maximum possible concentration of inherited ^{21}Ne. The resulting average minimum exposure age of the upper sample is 1.57 Ma with zero erosion acting on the surface (Table S3). Assuming the model-derived erosion rate of 0.74 m/Ma and inheritance as stated above, the exposure age of the oldest drift is more likely at least 2.63 Ma (Table S3).

4.4. Discussion

Our reported erosion and sublimation results in Ong Valley broadly agree with comparative rates from cosmogenic nuclides observed within the McMurdo Dry Valleys. Sublimation rates of buried ice in the McMurdo Dry Valleys (MDV) range from 0.7 to 23 m/Ma [*Schäfer et al*., 1999; *Ng et al*., 2005; *Morgan et al*., 2010a], and cosmogenic nuclide-based erosion rates of regolith range from 0.19 to 2.1 m/Ma for the past 4 Ma [*Putkonen et al*., 2008; *Morgan et al*., 2010b]. The Youngest drift (8 ka) appears to correlate with the Last Glacial Maximum to early Holocene age deposits in the Transantarctic Mountains dated from 7 to 17 ka [*Ackert and Kurz*, 2004; *Di Nicola et al*., 2009; *Todd et al*., 2010].

The cosmogenic nuclide concentrations from the drifts of Ong Valley support the preservation of ancient ice beneath an insulating debris layer formed from sublimating glacial ice. It is unclear why no ice was found beneath the Oldest drift in Ong Valley, though conditions seem probable for its survival. It is evident that ice existed in the Oldest drift from the well-developed polygons, but their current morphology suggest that they have been inactive and lowering from erosion. The older age of this drift could suggest an upper bound for the preservation of ancient ice below a lag deposit, but there are many local variables that could affect ice survival. The englacial debris concentration of this drift could have been lower than that of the Middle drift; thus, the rate of accumulation would be slower, allowing for greater sublimation and more rapid ice loss. Nuclide concentrations suggest similar sublimation rates between the two drifts, 22 m/Ma and 19 m/Ma, respectively, and suggest that there may be an upper time limit for the preservation of buried ice in the Central Transantarctic Mountains based on the original ice thickness.

5. Conclusions

Geomorphic observations and cosmogenic nuclide measurements reveal that Ong Valley contains one buried ice body emplaced relatively recently (8 ka) during the Last Glacial Maximum or early Holocene as well as a second, much older, buried ice body in the Middle drift that was emplaced at least 1.1 Ma and most likely prior to 1.8 Ma. The Oldest drift is at least 1.6 Ma and more likely greater than 2.6 Ma. Our model shows the long-term mean ice sublimation rate for debris-covered ice to be 19–22 m/Ma and rate of regolith erosion of 0.8 m/Ma. These records add to the current knowledge of the East Antarctic landscape evolution and ice sheet retreat since the Pleistocene. The ice below the Middle till may provide a record of Pleistocene paleoatmosphere previously unavailable. This work continues to highlight the unique conditions in Antarctica that allow for long-term preservation of ancient ice through a dynamic balance between sublimation and concurrent erosion of an overlying lag deposit till.

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References

Ackert, R. P., and M. D. Kurz (2004), Age and uplift rates of Sirius Group sediments in the Dominion Range, Antarctica, from surface exposure dating and geomorphology, *Global Planet. Change*, *42*(1-4), 207–225, doi:10.1016/j.gloplacha.2004.02.001.

Balco, G., and D. L. Shuster (2009), Production rate of cosmogenic 21Ne in quartz estimated from 10Be, 26Al, and 21Ne concentrations in slowly eroding Antarctic bedrock surfaces, *Earth Planet. Sci. Lett.*, *281*(1-2), 48–58, doi:10.1016/j.epsl.2009.02.006.

Dansgaard, W., S. J. Johnsen, J. Møller, and C. C. Langway (1969), One thousand centuries of climatic record from camp century on the Greenland Ice Sheet, *Science*, *166*(3903), 377–80, doi:10.1126/science.166.3903.377.

Di Nicola, L., S. Strasky, C. Schlüchter, M. C. Salvatore, N. Akçar, P. W. Kubik, M. Christl, H. U. Kasper, R. Wieler, and C. Baroni (2009), Multiple cosmogenic nuclides document complex Pleistocene exposure history of glacial drifts in Terra Nova Bay (northern Victoria Land, Antarctica), *Quat. Res.*, *71*(1), 83–92, doi:10.1016/j.yqres.2008.07.004.

Dunai, T. J. (2010), *Cosmogenic Nuclides: Principles, Concepts and Applications in the Earth Surface Sciences*, 1st ed., Cambridge Univ. Press, New York.

Edwards, K. L., A. J. Padilla, A. Evans, D. J. Morgan, G. Balco, J. K. Putkonen, and T. C. Bibby (2014), Provenance of glacial tills in Ong Valley, Antarctica, inferred from quartz cathodoluminescence imaging, zircon U/Pb dating, and trace element geochemistry, 2014 Fall Meeting, AGU, San Francisco, Calif.

Fischer, H., et al. (2013), Where to find 1.5 million yr old ice for the IPICS "Oldest-Ice" ice core, *Clim. Past*, *9*(6), 2489–2505, doi:10.5194/cp-9-2489-2013.

Gosse, J. C., and F. M. Phillips (2001), Terrestrial in situ cosmogenic nuclides: Theory and application, *Quat. Sci. Rev.*, *20*(14), 1475–1560, doi:10.1016/S0277-3791(00)00171-2.

Haeberli, W., et al. (2006), Permafrost creep and rock glacier dynamics, *Permafr. Periglac. Process.*, *17*(3), 189–214, doi:10.1002/ppp.561.

Higgins, J. A., A. V. Kurbatov, N. E. Spaulding, E. Brook, D. S. Introne, L. M. Chimiak, Y. Yan, P. A. Mayewski, and M. L. Bender (2015), Atmospheric composition 1 million years ago from blue ice in the Allan Hills, Antarctica, *Proc. Natl. Acad. Sci. U.S.A.*, *112*(22), 6887–6891, doi:10.1073/pnas.1420232112.

Hindmarsh, R. C., F. M. Van der Wateren, and A. L. L. M. Verbers (1998), Sublimation of ice through sediment in Beacon Valley, Antarctica, *Geogr. Ann.*, *80*(3/4), 209–219.

Hooke, R. L. B. (2005), *Principles of Glacier Mechanics*, 2nd ed., Cambridge Univ. Press, Cambridge.

Jouzel, J., et al. (2007), Orbital and millennial Antarctic climate variability over the past 800,000 years, *Science*, *317*(5839), 793–6, doi:10.1126/science.1141038.

Konrad, S. K., N. F. Humphrey, E. J. Steig, D. H. Clark, N. Potter Jr., and W. T. Pfeffer (1999), Rock glacier dynamics and paleoclimatic implications, *Geology*, *27*(12), 1131–1134, doi:10.1130/0091-7613(1999)027.

Kowalewski, D. E., D. R. Marchant, J. S. Levy, and J. W. Head (2006), Quantifying low rates of summertime sublimation for buried glacier ice in Beacon Valley, Antarctica, *Antarct. Sci.*, *18*(3), 421–428, doi:10.1017/S0954102006000460.

Luthi, D., et al. (2008), High-resolution carbon dioxide concentration record 650,000–800,000 years before present, *Nature*, *453*(7193), 379–382.

Mayewski, P. A. (1975), Glacial geology and late Cenozoic history of the Transantarctic Mountains, Antarctica, *Inst. Polar Stud. Ohio State Univ.*, *Report 56*, 168.

Middleton, J., R. P. Ackert, and S. Mukhopadhyay (2012), Pothole and channel system formation in the McMurdo dry valleys of Antarctica: New insights from cosmogenic nuclides, *Earth Planet. Sci. Lett.*, *355-356*, 341–350.

Morgan, D. J., J. K. Putkonen, G. Balco, and J. O. Stone (2010a), Degradation of glacial deposits quantified with cosmogenic nuclides, Quartermain Mountains, Antarctica, *Earth Surf. Process. Landforms*, *36*(2), 217–228, doi:10.1002/esp.2039.

Morgan, D. J., J. K. Putkonen, G. Balco, and J. O. Stone (2010b), Quantifying regolith erosion rates with cosmogenic nuclides ^{10}Be and ^{26}Al in the McMurdo Dry Valleys, Antarctica, *J. Geophys. Res.*, *115*, F03037, doi:10.1029/2009JF001443.

Ng, F., B. Hallet, R. S. Sletten, and J. O. Stone (2005), Fast-growing till over ancient ice in Beacon Valley, Antarctica, *Geology*, *33*(2), 121, doi:10.1130/G21064.1.

Nishiizumi, K. (2004), Preparation of 26Al AMS standards, *Nucl. Instrum. Meth. Phys. Res. Sect. B Beam Interact. Mater. Atoms*, *223-224*, 388–392, doi:10.1016/j.nimb.2004.04.075.

Nishiizumi, K., M. Imamura, M. W. Caffee, J. R. Southon, R. C. Finkel, and J. McAninch (2007), Absolute calibration of 10Be AMS standards, *Nucl. Instrum. Meth. Phys. Res. Sect. B Beam Interact. Mater. Atoms*, *258*(2), 403–413, doi:10.1016/j.nimb.2007.01.297.

Putkonen, J. K., G. Balco, and D. J. Morgan (2008), Slow regolith degradation without creep determined by cosmogenic nuclide measurements in Arena Valley, Antarctica, *Quat. Res.*, *69*(2), 242–249, doi:10.1016/j.yqres.2007.12.004.

Scarrow, J. W., M. R. Balks, and P. C. Almond (2014), Three soil chronosequences in recessional glacial deposits near the polar plateau, in the Central Transantarctic Mountains, Antarctica, *Antarct. Sci.*, 1–11, doi:10.1017/S0954102014000078.

Schaefer, J. M., H. Baur, G. H. Denton, S. Ivy-ochs, D. R. Marchant, C. Schlu, and R. Wieler (2000), The oldest ice on Earth in Beacon Valley, Antarctica: New evidence from surface exposure dating, *Earth Planet. Sci. Lett.*, *179*, 91–99.

Schäfer, J. M., S. Ivy-Ochs, R. Wieler, I. Leya, H. Baur, G. H. Denton, and C. Schlüchter (1999), Cosmogenic noble gas studies in the oldest landscape on earth: Surface exposure ages of the Dry Valleys, Antarctica, *Earth Planet. Sci. Lett.*, *167*(3-4), 215–226, doi:10.1016/S0012-821X(99)00029-1.

Schorghofer, N. (2005), A physical mechanism for long-term survival of ground ice in Beacon Valley, Antarctica, *Geophys. Res. Lett.*, *32*, L19503, doi:10.1029/2005GL023881.

Sletten, R. S. (2003), Resurfacing time of terrestrial surfaces by the formation and maturation of polygonal patterned ground, *J. Geophys. Res.*, *108*(E4), 8044, doi:10.1029/2002JE001914.

Stone, J. O., R. S. Sletten, and B. Hallet (2000), Old ice, going fast: Cosmogenic isotope measurements on ice beneath the floor of Beacon Valley, Antarctica, *Eos Trans. Am. Geophys. Union 81(48) Fall Meet. Suppl., Abstr. H52C-21*.

Sugden, D. E., D. R. Marchant, N. Potter, R. A. Souchez, G. H. Denton, C. C. Swisher III, and J.-L. Tison (1995), Preservation of Miocene glacier ice in East Antarctica, *Nature*, *376*(6539), 412–414, doi:10.1038/376412a0.

Todd, C. E., J. O. Stone, H. Conway, B. L. Hall, and G. Bromley (2010), Late Quaternary evolution of Reedy Glacier, Antarctica, *Quat. Sci. Rev.*, *29*(11-12), 1328–1341, doi:10.1016/j.quascirev.2010.02.001.

Van der Wateren, D., and R. C. Hindmarsh (1995), Stabilists strike again, *Nature*, *376*(6539), 389–391, doi:10.1038/376389a0.

Wahrhaftig, C., and A. Cox (1959), Rock glaciers in the Alaska Range, *Bull. Geol. Soc. Am.*, *70*(4), 383–436, doi:10.1130/0016-7606(1959)70[383:RGITAR]2.0.CO;2.

Yau, A. M., M. L. Bender, D. R. Marchant, and S. L. Mackay (2015), Geochemical analyses of air from an ancient debris-covered glacier, Antarctica, *Quat. Geochronol.*, *28*, 29–39, doi:10.1016/j.quageo.2015.03.008.