

The oldest ice on Earth in Beacon Valley, Antarctica: new evidence from surface exposure dating

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Abstract

Beacon Valley, Antarctica, contains unique remnants of glacier ice underneath a till layer covering the valley floor. To constrain the age and evolution of this important indicator of Antarctic paleoclimate, we analyzed two dolerite erratics from the till surface and one from within the ice for cosmogenic helium and neon. A conservative minimum exposure age of the older surface sample is 2.3 Ma, but taking into account erosion, the true exposure age of this boulder is likely to be considerably higher. The buried sample contains more than 20 times less cosmogenic noble gases than the old surface sample, although its current shielding would imply only a three times lower production rate. This indicates that the ice level has slowly been lowered by sublimation at the rate of a few m/Ma. The high exposure age of the surface sample as well as the very low sublimation rate of the relict ice both support the conclusion that the remnant ice in Beacon Valley was deposited many million years ago [Sugden et al., *Nature* 376 (1995) 412–414] and has never been thinner than at present. In addition, we found that cosmogenic helium and neon are released quantitatively from pyroxene at temperatures of $< 900^{\circ}\text{C}$ and $> 1000^{\circ}\text{C}$, respectively. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Beacon Valley in the Dry Valleys region, Antarctica, preserves a unique glaciological mystery: the till layer on the valley floor rests on remnant ice bodies, which represent sensitive indicators of

Antarctic paleoclimate. Sugden et al. [1] dated volcanic ashes found in wedges on top of the till. The $^{40}\text{Ar}/^{39}\text{Ar}$ age of 8.1 Ma indicates that this till – and the underlying ice – is of Miocene age, which requires exceedingly low long-term sublimation rates. These authors argue that sublimation rates of such till-covered ice may indeed be of the order of several tens of cm/Ma only, if the till has been saturated with moisture and climate was constantly cold. On the other hand, Hindmarsh et al. [2] expect that sublimation is

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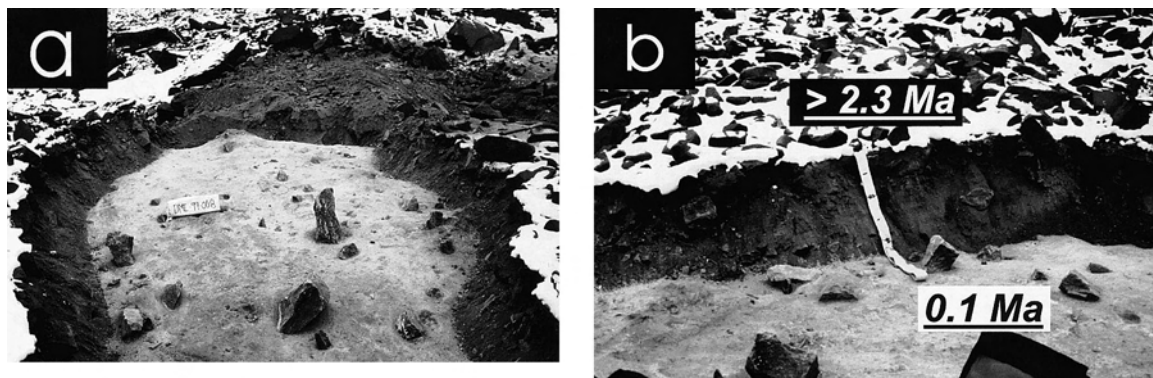


Fig. 1. (a) Sampling site showing the pit dug into the boulder field on the Beacon Valley floor, the underlying till layer and the uncovered relict ice body. The rocks partly sticking in the ice have been covered by the till and display fresh surfaces, whereas the boulders on top of the till display all different stages of weathering (see also figs. 1 and 2 of the **EPSL Online Background Dataset**¹). (b) Detailed positions of the samples. The rock to the right of the ruler on the bottom of the pit is DME*1. It is partly sticking in the ice and has been covered by 40 cm of till. We analyzed the bottom of this rock, which is additionally shielded by 30 cm of rock. Samples DME*2 and DME*3 are elements of the boulder field on top of the till. The age of 2.3 Ma for sample DME*3 is a conservative minimum age, based on the assumption of no erosion and no uplift. The ‘apparent’ age of DME*1 of 0.1 Ma is calculated ignoring the shielding situation of this sample (see text).

several orders of magnitude higher and rather independent of vapor concentration and air temperature. In the latter case, it would be highly unlikely that the relict ice is several million years old and the ashes would probably have been re-worked [3].

We present here a pilot study to constrain age, evolution and sublimation rate of a relict ice body in Beacon Valley using cosmogenic ³He and ²¹Ne. We analyze glacial erratics lying on the till surface and compare the results with those of a boulder removed from the ice. This latter rock is to our knowledge the first sample dated by cosmogenic nuclides that comes from within glacier ice beneath a veneer of till. The exposure age of the sample on the ice is a conservative lower limit for the age of the remnant ice body. The differences between the samples on and within the ice allow us to constrain how the ice thickness above the buried sample varied with time.

2. Geological setting and methods

2.1. The remnant ice in Beacon Valley

The ice body investigated here is probably a relict of Taylor glacier that filled Beacon Valley

in the past. It covers almost the entire floor of Beacon Valley and is at least 80 m deep (see also [1,2]). It is overlain by 40 cm till and a layer of dolerite erratic boulders (Fig. 1 and fig. 2 of the **EPSL Online Background Dataset**¹). Within the ice dolerite boulders were detected in the first few meters, but most likely they exist at all depths. Direct rockfall from the valley slopes to the sample position can be excluded. The erratics on the till represent all stages of weathering whereas all visible boulders within the ice are fresh. This strongly indicates that the surface boulders had been elements of the ice body before sublimation of overlying ice uncovered them, one after the other, which has left behind an armor of till and erratics on top of the remaining ice.

2.2. Sublimation

Sublimation dominates the ablation of the remnant ice underneath the till, but effective sublimation rates are poorly known. While ice and snow surfaces in Antarctica sublimate in the order of cm/yr [4–6], overlying till decreases this rate sig-

¹ <http://www.elsevier.nl/locate/epsl>; mirror site: <http://www.elsevier.com/locate/epsl>

nificantly. However, there is considerable discussion about how sublimation depends on moisture content in the till and the atmospheric temperature, e.g. [7] versus [2]. Consequently, suggested sublimation rates for the Beacon Valley ice remnant span three orders of magnitude [1,3].

2.3. Sampling and analyses

The sampling site and the positions of the three analyzed erratics are shown in Fig. 1 (see also fig. 2 of the **EPSL Online Background Dataset**¹). The appearance, especially the brownish desert varnish of the surface samples DME*2 and DME*3 (fig. 1 of the **EPSL Online Background Dataset**¹), indicates relatively low stages of weathering. Sample DME*3 shows even a pit hole erosion pattern exclusively at the exposed surface, which on the one hand indicates that this surface eroded slowly but steadily over a long period of time and on the other hand argues against turning of the sample in the past. In contrast, slabs of several centimeters thick appear to have been spalled off from DME*2. Also parts of the bottom side of DME*2 look similar to the exposed surface, hence a turn-over during exposure is probable. In addition, this sample does not show any pit hole erosion indicating less surface exposure

than DME*3. For these reasons we focus on the surface sample DME*3. The surface of DME*1 is fresh and shows neither varnish nor any weathering features or split-off fragments (Fig. 1b and fig. 1 of the **EPSL Online Background Dataset**¹). Obviously, DME*1 has been safely stored in the ice. The fact that this sample never has been in contact with the atmosphere for a significant time in combination with the evolution of the boulder condensation horizon discussed above makes a pre-exposure very unlikely. Note that all additional ‘within ice’ rocks visible in Fig. 1 (and fig. 2 of the **EPSL Online Background Dataset**¹) show these fresh surfaces as well. From DME*2 and 3 we sampled the top few centimeters from the exposed surface whereas the bottom side from DME*1 was chosen for analysis to achieve maximum shielding. We separated pyroxene grains of < 300 μm using heavy liquids and magnetic separation.

In order to determine the ideal temperature range to separate cosmogenic and non-cosmogenic helium and neon from pyroxene, a sample from Sirius Formation at Mt. Feather which had been measured before was analyzed by an appropriate stepwise heating method. This sample is uniquely suited due to its extremely high concentrations of cosmogenic noble gases combined with very low

Table 1

Cosmogenic noble gases and exposure ages for the samples on (DME*2, DME*3) and within (DME*1) the ice in Beacon Valley as well as for the ‘calibration’ sample from Mt. Feather (see text)

Sample	³ He _{cos} (10 ⁶ atoms/g)	²¹ Ne _{cos} (10 ⁶ atoms/g)	Minimum ³ He ages (Ma)	Minimum ²¹ Ne ages (Ma)
DME*3, stepwise	892 ± 28	226 ± 17	2.32 ± 0.07	2.18 ± 0.17
DME*3 TE	880 ± 76	252 ± 14	2.28 ± 0.04	2.47 ± 0.14
DME*2, stepwise	40 ± 5	14 ± 2	0.10 ± 0.01	0.15 ± 0.02
DME*2 TE	47 ± 15	18 ± 13	0.12 ± 0.04	
DME*1, stepwise	42 ± 4	11 ± 2	0.11 ± 0.01	0.12 ± 0.02
DME*1 TE	44 ± 8	17 ± 4	0.11 ± 0.02	
Mt. Feather, < 50 μm, stepwise	5293 ± 327	–		
Mt. Feather, 50–150 μm, stepwise	4725 ± 276	1445 ± 151		
Mt. Feather, > 300 μm, stepwise	5131 ± 170	1368 ± 43		
Mt. Feather, > 300 μm, TE ^a	5210 ± 77	1567 ± 68		

All concentrations are given within 95% confidence limits. Errors due to uncertainties of calibration gas amounts are not included but are < 3%. TE = total extraction (1800°C). For ³He_{cos} all steps ≤ 900°C, for ²¹Ne_{cos} all steps > 900°C are considered (see text). Corrections for nucleogenic neon according to [10]: 1% (DME*3), 27% (DME*1, DME*2) of excess Ne. Ages for the surface samples DME*3 and DME*2 are minimum, as erosion and uplift are neglected. The complete dataset is given in Table 2, for production rate calculations see Table 3.

^aData published in [8].

Table 2
Noble gases of the samples DME*1, DME*2 and DME*3 (stepwise heating and total extraction data)

Sample	Release temperature (°C)	³ He (10 ⁶ atom/g)	⁴ He (10 ¹² atom/g)	³ He/ ⁴ He (R/R _a) (%)	²⁰ Ne (10 ⁹ atom/g)	²¹ Ne/ ²⁰ Ne (10 ⁻³) (%)	²¹ Ne _{ex} (10 ⁶ atom/g)	²¹ Ne _{ex} (%)
DME*3	1800 ²¹ Ne _{at}	879.5 ± 76.4	102.71 ± 9.43	6	66.32 ± 0.42	6.76 ± 0.20	252.23 ± 13.82	2.40 (1%)

All concentrations are given with 95% confidence limits. Errors due to uncertainties of calibration gas amounts are not included but are < 3%. Note the increased ²¹Ne/²⁰Ne in the > 900°C neon steps compared to total extraction. Total ²¹Ne_{ex} of the stepwise heating steps are also given in percent of the total extraction measurement (TE = 1800°C). ²¹Ne_{ex} differs from separate to separate of the same rock. Note that the high ⁴He concentrations (and thus low ³He/⁴He ratios (< 1R_a for DME*1 and DME*2, < 8R_a for DME*3)) are due to the high contribution of radiogenic ⁴He (and not to inherited He), which is indicated by the temperature release pattern of the cosmogenic helium (Fig. 2) as well as by the consistency of cosmogenic He and Ne ages (Table 1). Helium exposure ages are based on the steps up to 900°C whereas higher steps are considered for the calculation of neon exposure ages (see Fig. 3) with the one exception of the 1800°C step of DME*1. This step is dominated by non-cosmogenic neon and is therefore excluded.

^aInterference of nucleogenic ²¹Ne estimated after [10]; corrections are given in absolute values as well as in percent of the ²¹Ne_{ex}.

concentrations of radiogenic helium and trapped neon [8]. We measured three different grain size fractions in up to seven temperature steps (300–1800°C). Further details of noble gas analyses are described in [9].

3. Results

The entire dataset of the Beacon Valley erratics, including elemental composition and deduced production rates, is listed in Tables 1–3. Additional data for the Mt. Feather sample used to calibrate the temperature degassing pattern of cosmogenic helium and neon from pyroxene are published in table 1 of the **EPSL Online Background Dataset**¹.

3.1. Temperature release pattern from pyroxene

Fig. 2 shows schematically the temperature release of helium and neon of the Mt. Feather sample. Significant release of cosmogenic helium starts at 300°C. For all grain sizes the main fraction (97% of ³He_{cos} and also > 90% of ⁴He_{rad}) is released between 400 and 900°C. For the < 50 μm samples 92% of ³He_{cos} is released even below 610°C in two steps (400 and 610°C). In contrast

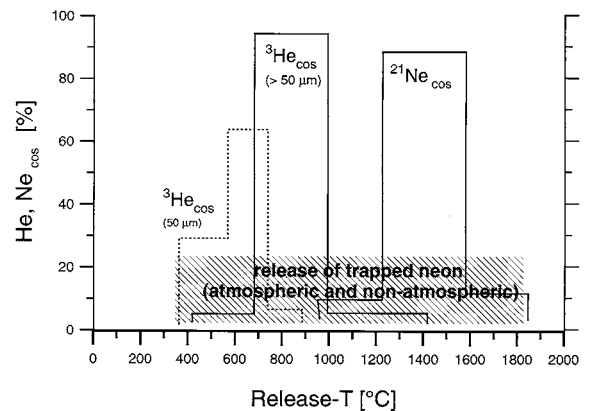


Fig. 2. Release of helium and neon from pyroxene as a function of temperature. The dotted line shows the cosmogenic helium release pattern for pyroxene grains of ~ 50 μm, the straight line the release of cosmogenic helium and neon for bigger pyroxene grains. The cross-hatched rectangle indicates the temperature range for the release of the trapped, non-cosmogenic neon.

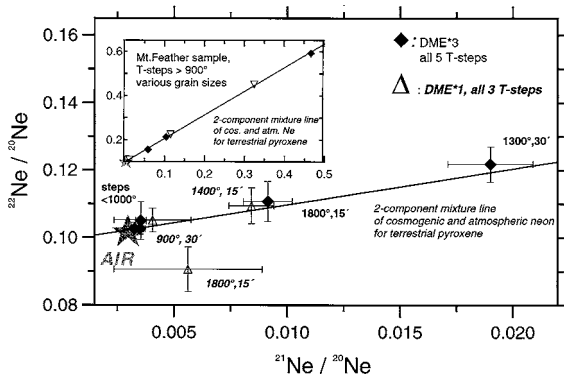


Fig. 3. Neon-3 isotope plot for the high-temperature steps of the Mt. Feather sample used here to calibrate the degassing pattern of pyroxene (inset) and for the two key samples discussed here, the ‘surface’ sample DME*3 and the ‘buried sample’ DME*1. Two-component mixture line of cosmogenic and atmospheric neon for pyroxene: $y = 1.069x + 0.099$ [8]; errors are given within 95% confidence. Except for the 1800°C step of DME*1 all data points fall on the line, indicating absence of any disturbing neon component.

to helium, for all grain sizes less than 10% of the cosmogenic neon is released at $< 900^\circ\text{C}$ (see also Fig. 3, inset, and table 1 of the **EPSL Online Background Dataset¹**) whereas 50% or more of the trapped neon is liberated below 900°C . This principally allows a reduction of trapped neon background in the high-temperature steps that contain most of the cosmogenic neon. The temperature release pattern for cosmogenic noble gases from the Mt. Feather pyroxene observed here is consistent with those of the remnant ice erratics and other pyroxene separates measured in our laboratory. Therefore we conclude that pyroxene does have a well-defined degassing pattern for cosmogenic helium and neon, and suggest

three temperature steps to optimize analysis in cosmogenic noble gas studies: a first step at 900°C to release the total cosmogenic helium and parts of the trapped neon, a second step at 1400°C that releases most of the cosmogenic and the remaining trapped neon, and a total extraction at 1800°C .

3.2. Samples from the remnant ice

As noted above, we assume that all ^3He in the 900°C step of DME*1, DME*2 and DME*3 is cosmogenic and that the total $^3\text{He}_{\text{cos}}$ is released in this step. The neon isotopic composition of the individual temperature steps of DME*1 and DME*3 is displayed in Fig. 3. Total cosmogenic ^{21}Ne is assumed to be the ^{21}Ne excess over air of the two higher temperature steps, corrected for nucleogenic neon after [10]. All corrections are lower than 30% (see also Table 2). As expected from the sample’s appearance, DME*3 contains much higher concentrations of cosmogenic noble gases than DME*2, a sample we do not consider further, for the reasons discussed in Section 2. Strikingly, the surface sample DME*3 shows more than 20 times as much cosmogenic noble gases as the buried and non-eroded sample DME*1. The nominal minimum exposure age of sample DME*3 is 2.3 Ma, whereas the ‘apparent’ exposure age of the buried sample DME*1, neglecting the shielding situation, is 0.1 Ma. Helium and neon ages are identical within errors, which demonstrates that non-cosmogenic noble gas fractions, i.e. nucleogenic neon or inherited helium, do not significantly compromise the cosmogenic signal.

Table 3
ICP–AES results and production rates

Sample	Altitude (m.a.s.l.)	Si (wt%)	Mg (wt%)	Al (wt%)	$^{21}\text{Ne}_{\text{cos}}$ production rate, sea level (at/(g yr))	$^{21}\text{Ne}_{\text{cos}}$ production rate used (at/(g yr))	$^3\text{He}_{\text{cos}}$ production rate, sea level (at/(g yr))	$^3\text{He}_{\text{cos}}$ production rate used (at/(g yr))
DME*1	1385	27.5	7.9	0.8	27	95	110	385
DME*2	1385	26.2	7.7	1.3	26	91	110	385
DME*3	1385	29.7	8.1	2.5	29	102	110	385

We used $P_{21}(\text{Si}) = 42.5$ atoms/(g yr) ([18] updated by a personal communication from S. Niedermann), $P_{21}(\text{Mg}) = 185$ atoms/(g yr), $P_{21}(\text{Al}) = 51$ atoms/(g yr) [8,19], and $P_3 = 110$ atoms/(g yr) ([8] and references therein); the scaling for altitude of samples is done after [20]. Estimated overall uncertainty of used production rate is about 15%.

4. Discussion

4.1. Minimum age of the remnant ice

The conservative minimum age for the deposition of the relict ice at Beacon Valley determined here is 2.3 Ma. To arrive at a more realistic age we need to consider erosion. Although Antarctic rocks present the lowest rates worldwide [8,11–14], long-term values lower than a few cm/Ma are unrealistic for this lithology and altitude. Very low maximum rates of 8–36 cm/Ma from dolerite surfaces of Dry Valley samples at similar altitudes and climate zone [15] as those studied here have been determined in [8]. The lowest of these values, 8 cm/Ma, shifts the age to > 3 Ma, the mean value of the given range of 22 cm/Ma shifts the age to > 8 Ma. These figures still neglect any uplift or snow cover during exposure, two effects that would further increase the age. Moreover, since the exposure age of the till samples dates their first appearances on top of the sublimating ice, they yield lower limits to the age of the ice deposition. We therefore believe that the true age of the ice is greater than 3 Ma and conclude that our data are entirely consistent with the $^{40}\text{Ar}/^{39}\text{Ar}$ age of 8.1 Ma determined from ash layers [1]. Further, neither a collapse of the ice remnant connected to climate warming (e.g. [16]) nor a reworking of the till and boulder layer by a glacial advance [3] occurred since formation of the remnant ice.

4.2. Ice level evolution in Beacon Valley

The relict ice in Beacon Valley is indeed by far the oldest ice body on earth yet discovered. It has survived for millions of years. This requires very low sublimation rates. We will now constrain the paleo-sublimation of the ice by comparing the exposure histories of surface sample DME*3 and buried sample DME*1. The latter contains only 4% as much cosmogenic ^3He and ^{21}Ne as DME*3 while its actual shielding by the 40 cm of overlying till and 30 cm of rock (Fig. 1b) corresponds to a production rate of still some 30% of that on the surface ($\rho_{\text{till}} = 2 \text{ g/cm}^3$ and $\rho_{\text{rock}} = 3 \text{ g/cm}^3$ are assumed). Evidently, DME*1 has never been clos-

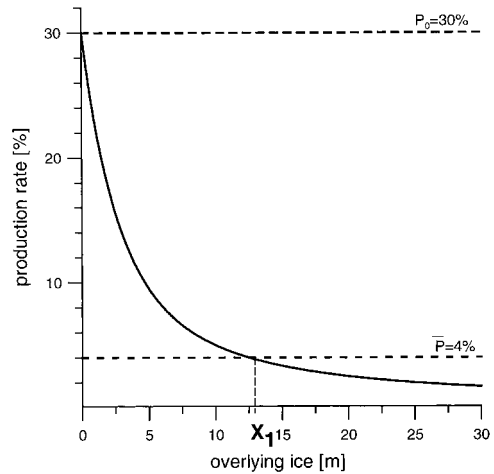


Fig. 4. Integrated production rate for the buried sample DME*1 as a function of the thickness of formerly overlying ice, assuming a constant sublimation rate. 0 m overlying ice relates to the current shielding of DME*1, corresponding to $P_0 = 30\%$ of the production rate of surface sample DME*3 (see text and Fig. 1b). Used densities: $\rho_{\text{rock}} = 3 \text{ g/cm}^3$, $\rho_{\text{till}} = 2 \text{ g/cm}^3$, and $\rho_{\text{ice}} = 0.9 \text{ g/cm}^3$; the mean cosmic ray attenuation length Λ_{ice} is assumed to be 150 g/cm^2 . Even a conservative uncertainty of some 30% for Λ_{ice} is of negligible influence for the conclusions drawn in the text. The thickness of the sublimated ice x_1 is given by the intersection of this line with the apparent production rate of DME*1 $\bar{P} = 4\%$ of the surface production.

er to the ice surface than at present for a significant period of time. Rather, the shielding by overlying ice has been permanently higher in the past. We propose that this reflects a slow lowering of the ice level in Beacon Valley by sublimation of the ice underneath the till. If we assume a constant sublimation rate, we can calculate (Eq. 1) the total thickness of formerly overlying and meanwhile sublimated ice (x_1) that leads to a reduction of the integrated nuclide production in DME*1, from currently 30% (P_0) to the observed 4% (\bar{P}):

$$\bar{P} = \frac{1}{|x_1|} \int_0^{x_1} P_0 \exp\left(-\frac{\rho}{\Lambda}x\right) dx \quad (1)$$

ρ is the density of ice: 0.9 g/cm^3 ; Λ is the mean attenuation length, assumed to be 150 g/cm^2 ; and x_1 is the thickness of the formerly overlying and sublimated ice. We plotted the integrated production rate for the buried sample DME*1 as a func-

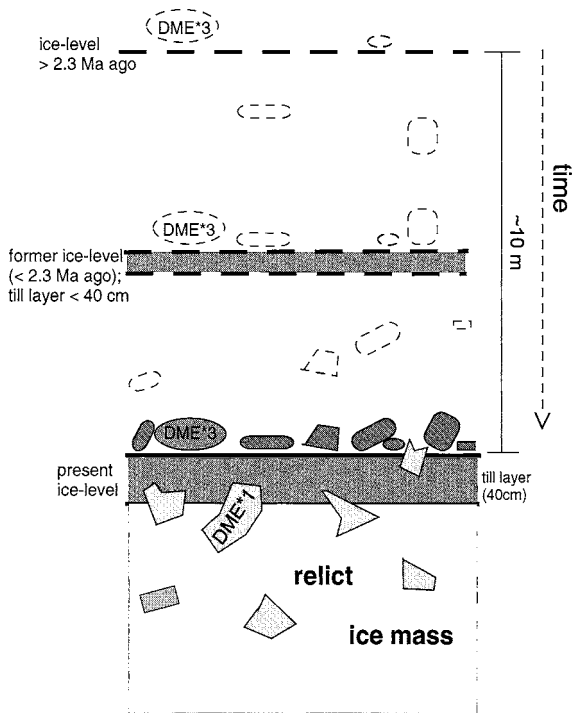


Fig. 5. Ice level evolution model for Beacon Valley. Dotted parts of the figure represent former ice levels in Beacon Valley. Note that our deduced mean sublimation rate of a few m/Ma in maximum does not exclude an interval of faster sublimation directly after deposition of the initially till-free ice surface followed by a slower sublimation period after the armor of till was built up.

tion of formerly overlying ice in Fig. 4. This figure shows that a *total* sublimation $x_1 = 13$ m of overlying ice is required to explain our data. Together with the minimum age of 2.3 Ma, the maximum value for the mean sublimation rate $S = x_1/2.3$ Ma is therefore of the order of several m/Ma only. Any increase in assumed erosion rate and consequently in age of sample DME*3 would further decrease the rate of sublimation. Our model of ice level evolution in Beacon Valley is sketched in Fig. 5. The range of sublimation deduced here is consistent with the value estimated by [1]. These low values imply that even a till layer as thin as a few tens of centimeters overlying an ice surface decreases the sublimation rate by orders of magnitude although the physical process that slows down the sublimation is unclear [2].

The presented scenario, currently based on the

comparison of two samples only, will be cross-checked in future studies. A possible pitfall is a significant pre-exposure of sample DME*1. This would not affect the derived age of the ice but would change our sublimation rates. Fig. 4 shows that essentially all the cosmogenic noble gas concentration in the buried sample DME*1 would have to be due to pre-exposure to increase the sublimation rates by several orders of magnitude. However, any pre-exposure of sample DME*1 is very unlikely due to the completely fresh appearance of this sample. If our scenario is right, it should be possible to find surface samples with minimum exposure ages even older than DME*3. In addition, the till should be rich in meteorites and possibly interplanetary dust particles. A further check would be to measure the radiogenic ^4He diffusing from the bedrock into the ice [17]. In any case, this study of the unique glacial relict underlying Beacon Valley has shown the potential of exposure dating to determine its age and long-term sublimation history when analyzing samples *on* and *within* the ice.

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