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# Fast-growing till over ancient ice in Beacon Valley, Antarctica

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**ABSTRACT**

We analyze published cosmogenic $^3$He depth profiles through the till that covers relict glacier ice in Beacon Valley, Antarctica, in order to derive rigorous constraints on the till-thickness history, and on the amount and rate of ice loss by sublimation. The till is a residue of debris-laden ice that sublimed. The $^3$He profiles show that the lower 80% of the till formed in the past 310–43 kyr under sublimation rates averaging >7 m·Myr$^{-1}$. Such rapid, recent growth of the till contradicts previous interpretations that it is older than 8.1 Ma at an adjacent site, where it encloses volcanic ash of this age. We question whether the ash provides a valid age constraint for the ice. Cosmogenic nuclide analysis of the till where the ash was collected for dating should resolve this question.

**Keywords:** Antarctica, Dry Valleys, glacial deposits, cosmogenic elements, sublimation.

## INTRODUCTION

The recent history of East Antarctica is key to understanding the response of large ice sheets to climate forcing. Field evidence has spurred a debate on two conflicting scenarios advocated for this history: stable glacial conditions since the middle Miocene (Sugden et al., 1993) and ice-sheet disintegration under warming during the Pliocene (Webb et al., 1984). The ice in Beacon Valley is important in this context. It is debris-laden, thought to be the remains of an expansion of Taylor Glacier into the valley, and lies under a till layer produced by its own sublimation. Sugden et al. (1995) argued for prolonged glacial conditions because they discovered 8.1 Ma volcanic ash in the till. Under their interpretation, the ash is a direct air-fall deposit into a former frost crack in the till, and the ice, till, and crack all predate 8.1 Ma. This interpretation implies not only the oldest glacier ice on Earth, but also a low sublimation rate for its survival—and hence, a persistent cold climate—since the Miocene, with correspondingly little extra accretion of the till. In contrast, ice sublimation rates from a physical model are high, ~$10^3$ m·Myr$^{-1}$ (Hindmarsh et al., 1998). Given a reasonable initial thickness for the ice of no more than a few hundred meters (Potter et al., 2003), its age should be less than 1 Ma (Van der Wateren and Hindmarsh, 1995).

One way to resolve this age controversy is to decipher the history of the till from cosmogenic nuclide measurements. The till is a diamict formed mainly from debris originally in the ice, although its upper part contains eolian sand and weathered rocks also. Material deep in the ice is shielded from cosmic rays, but is uncovered, becomes less shielded as the ice sublimes, and finally accretes to the base of the till, feeding its growth (Fig. 1A). In such material, the production rate of nuclides, such as $^3$He, increases as the overlying ice thins; then, after the material joins the till, its depth and the production rate remain constant. We develop a model of nuclide accumulation to reexamine published data from Beacon Valley.

Schäfer et al. (2000), Phillips et al. (2000), and Marchant et al. (2002) analyzed cosmogenic $^3$He in clasts from three vertical profiles in the till overlying the ice (Table 1). The profiles are within ~1 km of each other. $^3$He concentration $N$ decreases rapidly with depth $z$. This result is expected because the production rate attenuates with depth and because, in a sublimation till, deep clasts are exposed for a shorter time compared to shallow clasts after they accrete to the till (Fig. 1). The profiles' monotonic decrease suggests that the till did not undergo cryoturbation (Phillips et al., 2000; Marchant et al., 2002), even though the ground in Beacon Valley is patterned conspicuously by contraction-crack polygons (Berg and Black, 1966; Black, 1973; Sletten et al., 2003).

Two arguments to support antiquity of the ice have been made using cosmogenic depth profiles: (1) Some clasts at the surface have exposure ages of 2–3 Ma, so the ice beneath is at least as old (Schäfer et al., 2000; Oberholzer et al., 2000; Marchant et al., 2002). (2) Schäfer et al. (2000) devised a method of calculating the thickness of ice that sublimed using $^3$He concentrations in surficial–basal clast pairs from the till. When coupled with the till surface exposure age—a minimum age in view of weathering of the surficial clasts—their method indicates maximum (average) sublimation rates of ≤90 m·Myr$^{-1}$, which are considered to be low enough for ice survival.

Here we reach different conclusions. We argue that the $^3$He profiles constrain minimum, not maximum, sublimation rates; that the surficial clasts are unreliable indicators of age. Moreover, new constraints on the history of till thickness suggest that the ash was not emplaced in the way Sugden et al. (1995) envisaged. These results emerge when we analyze how the profiles record the sublimation and accretion processes.

## MODEL OF NUCLIDE CONCENTRATION

Consider first a model for simulating the $^3$He profiles from clast-exposure history (Fig. 1). We assume a nondeforming till of porosity $\phi$. We measure the depth $z$ relative to the lowering surface and let $\ell(T)$ be the till thickness, where $T$ denotes age. If the sublimation rate is $S(T)$ and the debris concentration of the subliming ice (by volume) is $c$ (<<1), then the till thickens at a rate

$$-\frac{d\ell}{dT} = \frac{cS}{1-\phi}. \qquad (1)$$

The debris concentration $c$ varies with $T$ if debris in the ice is not uniformly distributed; we return to the consequences of this situation later.

Cosmogenic dating models that are used widely to constrain exposure age and erosion rate of rock surfaces (Lal, 1991) do not adequately describe our system. Although the ice may be likened as being eroded as it sublimes, the till is a lag that has no analogue in such models. Here we follow the depth history of each clast, $z = h(T)$, to calculate its exposure history. Given its depth today, $z_0$, we reconstruct $h$ by backtracking (Fig. 1B)—observing that $h$ is constant after the clast accretes to the till; that the age of accretion, $T_A$, satisfies $\ell(T_A) = z_0$; and that, although $h$ differs from $z_0$ prior to accretion, the clast, contained then by the ice, approaches the surface at velocity $S + d\ell/dT$. These considerations yield

$$\begin{aligned} h(T) &= z_0 && \text{for } 0 \le T \le T_A, \\ h(T) &= \ell(T) + \int_{T_A}^{T} S(\xi)\, d\xi && \text{for } T > T_A, \end{aligned} \qquad (2)$$

in which the integral represents the overlying ice thickness ($\xi$ is the variable of integration). We distinguish three stages in the clast's exposure history: *inheritance* ($T \ge T_{AS}$), *preaccretion* ($T_{AS} > T > T_A$), and *postaccretion* ($T_A > T \ge 0$), where $T_{AS}$ is the age of the till surface ($= T_A$ for $z_0 = 0$; Fig. 1). Inheritance thus comprises nuclide contributions before the till layer develops. We separate inheritance from preaccretion, because it includes exposure contributions before the clast was incorporated into the ice, which are unknown. This uncertainty makes it difficult to determine how the stages partition the nuclide concentration $N$ measured for a given clast.

For a stable cosmogenic nuclide such as $^3$He, we model its accumulation rate in the clast (using Lal's (1991) formulation) as

$$-\frac{dN}{dT} = P_0 e^{-\frac{\rho_I}{\Lambda}[h(T) - \ell(T)]_{0+}} e^{-\frac{\rho_S}{\Lambda}(1-\phi)z_0}, \qquad (3)$$

where $P_0$ is the surface production rate, $\rho_I$ is ice density, $\rho_S$ is sediment density, $\Lambda$ is absorption mean free path, and $[x]_{0+} = \max(x,0)$. In equation 3, the first exponential factor describes shielding of the clast by ice; the second exponential factor describes shielding of the clast by overlying debris, which remains above the clast after enclosing ice sublimes away. Equation 3 ignores $^3$He production by muon-induced reactions, whose rate at the surface has not been calibrated but is estimated at ~3% of the corresponding rate by spallation (Lal, 1987). We expect muon-induced production to dominate at depths >4–5 m. Including its effect in our (spallation-only) model leads to a slight increase in the $^3$He accumulated in clasts prior to accretion that lowers the bound $T_{A,max}$, raises the bounds $S_{min}$ and $\Delta_{I,min}$ derived below, and strengthens the conclusions of this paper.

Now, the integral of equation 3 from $T = T_{AS}$ to $T = 0$ represents the $^3$He accumulated in the clast since the till layer began forming. We substitute for $h$ from equation 2 and, by replacing $z_0$ with $z$, generalize this integral for all clasts. If we include the inheritance stage, the outcome is an expression for today's depth profile:

$$\begin{aligned} N(z) &= N_{\mathrm{Inh}}(z) && \text{(inheritance, by } T_{\mathrm{AS}} \text{ years ago)} \\ &+ P_0 e^{-\frac{\rho_S}{\Lambda}(1-\phi)z} \int_{T_A(z)}^{T_{\mathrm{AS}}} \exp\left[-\frac{\rho_I}{\Lambda} \int_{T_A(z)}^{T} S(\xi)\, d\xi\right] dT && \text{(preaccretion)} \\ &+ P_0 e^{-\frac{\rho_S}{\Lambda}(1-\phi)z}\, T_A(z) && \text{(postaccretion),} \end{aligned} \qquad (4)$$

in which we identify each exposure stage and $N_{\mathrm{Inh}}$ denotes the inherited concentration in material at depth $z$ today. In a forward simulation $S(T)$ and $c(T)$ are specified, and equation 4 is evaluated with the accretion age distribution $T_A(z)$ (or $\ell(T)$, its inverse) found from equation 1.

## THE INVERSE MODEL

The challenge is the opposite: to find the sublimation and till-thickness histories $S(T)$ and $\ell(T)$, given $N(z)$. Equations 4 and 1 cannot be solved for these histories uniquely because of the extra unknowns $N_{\mathrm{Inh}}$ and $c$. In particular, the debris concentration $c(T)$ of the sublimed ice may differ from $c$ for the relict ice today. The measured profiles also are discrete. Here we seek constraints instead of solution.

We first raise a caveat on the method by Schäfer et al. (2000) that explains also our apparent reversal of their maximum bound on sublimation rate in this paper. They assumed a constant rate of sublimation $S_c$ and inheritance-free clasts ($N_{\mathrm{Inh}} = 0$). In this case, the ratio of $N$ for two clasts from the surface and base of the till can be used to find the initial ice thickness between the clasts, because the overall shielding effect of the ice as it sublimed is predictable. For the clasts, equation 4 reduces to

$$N(0) = P_0 T_{\mathrm{AS}}, \quad N(\ell_0) = P_0 e^{-\frac{\rho_S}{\Lambda}(1-\phi)\ell_0} \int_0^{T_{\mathrm{AS}}} \exp(-\rho_I S_c T / \Lambda)\, dT, \qquad (5)$$

where $\ell_0$ is the till thickness today, and the ratio of $N$ can be written in the form

$$\frac{N(\ell_0)}{N(0)e^{-\rho_S(1-\phi)\ell_0/\Lambda}} = \frac{1}{Z}\int_0^Z e^{-\rho_I \xi/\Lambda}\, d\xi = \frac{1 - e^{-\rho_I Z/\Lambda}}{\rho_I Z/\Lambda}, \qquad (6)$$

where $Z = S_c T_{\mathrm{AS}}$ is the sublimed ice thickness in the model. Schäfer et al. (2000) used equation 6 to determine $Z$ from the end data of a profile, and the sublimation rate from $S_c = Z/T_{\mathrm{AS}} = P_0 Z/N(0)$. They claimed that in the last step, surface erosion would render $T_{\mathrm{AS}}$ (denominator) a minimum age, making $S_c$ a maximum sublimation rate. The caveat is that $Z$ (numerator) is not an upper-bound estimate: the actual sublimed ice thickness could exceed $Z$ if unsteady sublimation (e.g., due to climate change) had violated the assumption that $S$ was constant. Therefore, the value $S_c$ does not constrain sublimation rates and cannot be used to dismiss the model results of Hindmarsh et al. (1998). (But, as expected, $S_c$ satisfies our constraint below where we allow for all possible sublimation histories. For profiles I, II, and III, Marchant et al. [2002] and Schäfer et al. [2000] obtained $S_c \approx 20$, 90, and 6 m·Myr$^{-1}$, respectively.)

In contrast, an approach is now developed to give robust *minimum* mean sublimation rates ($S_{min}$). The crux is to derive, for any pair of clasts in a profile, a *lower* bound on the original thickness of ice that separated them ($\Delta_{I,min}$) and an *upper* bound on the time over which this ice sublimed ($t_{max}$). The result $S_{min} = \Delta_{I,min}/t_{max}$ is rigorous.

**Constraint on Ice Thickness**

Suppose the clasts are numbered 1 (lower) and 2 (upper) and have concentrations $N_1$ and $N_2$, depths $z_1$ and $z_2$, respectively (Fig. 1A). We can constrain their original separation in the ice ($\Delta_I$) because the concentrations reflect different depth histories. The clasts' separation today is $\Delta_S = z_1 - z_2$, so the intervening sediment thickness is $(1 - \phi)\Delta_S$. Given the shielding by this sediment, we can predict what the ratio $N_2/N_1$ should be, but the data show that the ratio is always larger, which could only have resulted because of intervening ice that has disappeared. If we neglect $^3$He inheritance before the clasts were incorporated into the ice, then the minimum intervening ice thickness, $\Delta_{I,min}$, can be computed from

$$e^{[\rho_I \Delta_{I,min} + \rho_S (1 - \phi)\Delta_S]/\Lambda} = \frac{N_2}{N_1}. \qquad (7)$$

The value $\Delta_{I,min}$ is the minimum initial ice thickness, because the ice could only have thinned: for a smaller initial thickness, past $^3$He production rates in the clasts would have been too similar for us to explain the data. We calculate $\Delta_{I,min}$ from $N_1$, $N_2$, and $\Delta_S$ (Table 1). Equation 7 holds regardless of sublimation rate changes and does not depend on $P_0$. $^3$He production by muon-induced reactions, which have large attenuation lengths, effectively increases $\Lambda$ used in our model, making $\Delta_{I,min}$ an underestimate.

**Constraint on Sublimation Time**

Next, we deduce a maximum sublimation time $t_{max}$ for the ice between clasts 1 and 2. This ice began subliming after clast 2 (the upper clast) accreted to the till and none of it remains today (Fig. 1A), so the maximum accretion age of clast 2 suffices as our choice for $t_{max}$. For any clast, its maximum accretion age ($T_{A,max}$) is simply the maximum duration of its postaccretion stage, which we can calculate by attributing all of its measured $N$-value to exposure at its current depth $z$ in the till; thus,

$$T_A(z) \leq T_{A,max}(z) = \frac{N(z)}{P_0 e^{-\rho_S (1 - \phi) z/\Lambda}}. \qquad (8)$$

Accordingly we put $t_{max} = T_{A,max}(z_2)$. In Table 1, dividing $\Delta_{I,min}$ by $T_{A,max}(z_2)$ gives $S_{min}$, our minimum sublimation rate.

The bound $t_{max}$ cannot be tightened, for we cannot deduce from the profiles the most recent time at which the lower clast (clast 1) could have joined the till (i.e., a minimum $T_A$) without making assumptions. Consequently, for a given depth profile, we cannot resolve the different sublimation periods for ice that existed between successive clast pairs. For any two clasts, the time over which $S_{min}$ is defined (and constrains the sublimation rate) is fixed by the upper clast—it begins no earlier than the age $T_{A,max}(z_2)$ and ends at the present, regardless of where in the profile the lower clast is taken. Hence we pick the lower clast always from the base of the till, to ensure the largest admissible $\Delta_{I,min}$ for calculating $S_{min}$.

**DISCUSSION**

Our results (Table 1) shed new light on the evolution of the ice and overlying till in Beacon Valley. Mean sublimation rates have not necessarily been low. Profiles I, II, and III indicate minimum mean rates $S_{min}$ of ~4, 23, and 2 m·Myr$^{-1}$, respectively, within the past 1.1 Myr, 170 kyr, and 1.6 Myr, causing at least several meters of ice loss at all three sites. Erosion of the surficial clasts can invalidate these results, but not the higher $S_{min}$ values for the more recent past indicated by buried clast pairs.

Rapid sublimation (Hindmarsh et al., 1998) could be considered likely, *if* one is prepared to make assumptions about the ice that sublimed. Its maximum average debris concentration can be calculated from our results as the ratio of sediment thickness to minimum ice thickness: $c_{max} = (1 - \phi)\Delta_S/\Delta_{I,min}$ (Table 1). $c_{max}$ is several times $c_0$ (~3%) for the relict ice. In contrast, one might expect the ice that sublimed to contain less debris than the relict ice, if the latter is basal ice from Taylor Glacier, as assumed by Sugden et al. (1995). Thus our bounds may be overconservative. By assuming ice no dirtier than today's, i.e., $c(T) \le c_0$, alternative minimum bounds can be found from $\Delta_{I,min}{}^R = (1 - \phi)\Delta_S/c_0$ (for sublimed ice thickness) and $S_{min}{}^R = \Delta_{I,min}{}^R/T_{A,max}$ (for sublimation rate). These bounds indicate mean sublimation rates exceeding ~10–100 m·Myr$^{-1}$ (Table 1), consistent with an independent estimate of 50 m·Myr$^{-1}$ from $^{10}$Be analysis of the ice and of debris within the ice (Stone et al., 2000) in the part of Beacon Valley where profiles I to III were measured.

Equation 8 constitutes a powerful constraint on the till accretion history. On the depth vs. age plot of Figure 2A, the accretion history $T = T_A(z)$ is confined to the region right of the line representing the maximum accretion age $T = T_{A,max}(z)$. Consequently the line also limits the till thickness: the apparent exposure age of a clast, $T_{A,max}$ (calculated on the basis of current shielding), implies that the till was, at that age, no thicker than the till above the clast today. Prior to $T_{A,max}$ the clast must have still been in the ice and below the till. For discrete depth profiles, this constraint takes the form of a staircase (Figs. 2B, 2C) provided that the till had not thinned over time.

We stress that, according to Figures 2B and 2C, all but the topmost 20% of till at the sites measured by Phillips et al. (2000) and Marchant et al. (2002) formed within the past 310 kyr (profile I) and 43 kyr (profile II). Prior to these times the till was exceptionally thin: ≤14 cm (profile I) and ≤9 cm (profile II), and by these times there were relatively old clasts aged 800 ka (I) and 130 ka (II) at the surface. These surficial clasts have uncertain provenance; unlike subsurface clasts released by ice, they might have originated via rockfall onto Taylor Glacier. Prior exposure may account for most of their $^3$He concentration, so that they may not be used to infer a minimum age for the ice, which could be as little as several hundred thousand years. Although the old exposure age of the surficial clasts can be explained in other ways (e.g., the ice that originally separated them from the next lower clast in the profile was very thick, or sublimed very slowly), we caution against using them to support the case for ancient ice.

An outstanding conundrum is the past relationship between ash and till. The interpretation advanced by Sugden et al. (1995) is that the ice in Beacon Valley was already mantled by ~50 cm of till at 8.1 Ma, when ash filled a frost crack, and that the till has thickened little since. In contrast, our analysis shows that no more than a thin veneer of till existed prior to 310 ka, and that the bulk of the till has accreted since. The $^{3}$He profiles examined here are not located at the "ash site", and their differences reflect some spatial variability in till evolution. Nevertheless, the profiles are close enough spatially and in stratigraphic context for our interpretation of them to challenge the antiquity of the till enclosing the ash. Our results show that the ash may not be a reliable stratigraphic indicator. The case for Miocene ice is likely to remain unsettled until a profile similar to the ones already discussed is measured at a site containing old ash.

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## FIGURE CAPTIONS

Figure 1. Model of subliming ice and accreting till with no deformation. A: Processes in a reference frame fixed to the ice. B: Depth vs. age plot shows processes in a reference frame fixed to till surface $z = 0$. Heavy dashed line denotes till-thickness history $\ell$. Solid arrowed line is depth history $h$ of clast at $z = z_0$ today; sublimation uncovers clast until it accretes to the till at age $T_A$, whose value depends on (and is a function of) $z_0$. Trajectories of several other clasts are shown dotted.

Figure 2. Constraint on past till thickness using $^3$He depth profiles. A: On depth vs. age plot (right panel), the till-thickness history $z = \ell(T)$ or equivalently the accretion age distribution $T = T_A(z)$ (dashed line) must lie outside hatched region, to the right of the boundary $T = T_{A,max}(z)$. This boundary (solid line), given by data (left panel) via equation 8, indicates the maximum till thickness at a given time. B, C: Application of model in A to profiles I and II. In these cases the boundary $T_{A,max}(z)$ is step-like.

TABLE 1. COSMOGENIC $^{3}$He IN CLASTS FROM BEACON VALLEY TILL AND MODEL RESULTS

| Data | | Results | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| $z$ (cm) | $N$ ($\times 10^{6}$ atoms·g$^{-1}$) | Clast pair (cm) | $\Delta_S$ (cm) | $\Delta_{I,min}$ (m) | $T_{A,max}$ (Ma) | $S_{min}$ (m·Myr$^{-1}$) | $c_{max}$ (%) | $\Delta_{I,min}^{R}$ (m) | $S_{min}^{R}$ (m·Myr$^{-1}$) |
| <u>Profile I</u> | | | | | | | | | |
| 0 | 612 | 0–70 | 70 | 4.52 | 1.123 | 4.02 | 10.3 | 15.6 | 13.9 |
| 14 | 140 | 14–70 | 56 | 2.37 | 0.310 | 7.66 | 15.8 | 12.4 | 40.2 |
| 21 | 85 | 21–70 | 49 | 1.69 | 0.206 | 8.21 | 19.3 | 10.9 | 52.8 |
| 59 | 28 | 59–70 | 11 | 0.69 | 0.113 | 6.10 | 10.6 | 2.44 | 21.7 |
| 70 | 16 | 70–70 | — | — | 0.075 | — | — | — | — |
| <u>Profile II</u> | | | | | | | | | |
| 0 | 93 | 0–38 | 38 | 3.90 | 0.171 | 22.9 | 6.5 | 8.44 | 49.5 |
| 9 | 21 | 9–38 | 29 | 1.62 | 0.043 | 37.3 | 11.9 | 6.44 | 148.3 |
| 25 | 8.9 | 25–38 | 13 | 0.54 | 0.023 | 23.9 | 16.0 | 2.89 | 126.8 |
| 38 | 5.4 | 38–38 | — | — | 0.016 | — | — | — | — |
| <u>Profile III</u> | | | | | | | | | |
| 0 | 880 | 0–70 | 70 | 3.44 | 1.615 | 2.13 | 13.6 | 15.6 | 9.63 |
| 70 | 44 | 70–70 | — | — | 0.205 | — | — | — | — |

*Note*: Symbols: $z$ = depth of clast sample; $N$ = $^{3}$He concentration; $\Delta_S$ = clast-pair separation; $\Delta_{I,min}$ = minimum original interclast ice thickness; $T_{A,max}$ = maximum accretion age of upper clast of pair; $S_{min}$ = minimum sublimation rate of interclast ice; $c_{max} = (1 - \phi)\Delta_S/\Delta_{I,min}$ = maximum debris concentration of ice that sublimed; $\Delta_{I,min}^{R} = (1 - \phi)\Delta_S/c_0$ (see discussion); $S_{min}^{R} = \Delta_{I,min}^{R}/T_{A,max}$ (see discussion). Data sources: Phillips et al. (2000) and Marchant et al. (2002) for profiles I and II and Schäfer et al. (2000) for profile III. Deepest clast of each profile is located at the base of till. In the $\Delta_{I,min}$ column, subtracting two values gives $\Delta_{I,min}$ for the two clasts appearing on the same row as the values. Model does not correct for the (unknown) sampling position on each clast. Model constants: $\rho_I$ = 0.9 g·cm$^{-3}$, $\rho_S$ = 3.0 g·cm$^{-3}$, $\phi$ = 1/3, $\Lambda$ = 150 g·cm$^{-2}$, $c_0$ = 0.03, and (following Marchant et al., 2002) $P_0$ = 545 atoms·g$^{-1}$ per year.

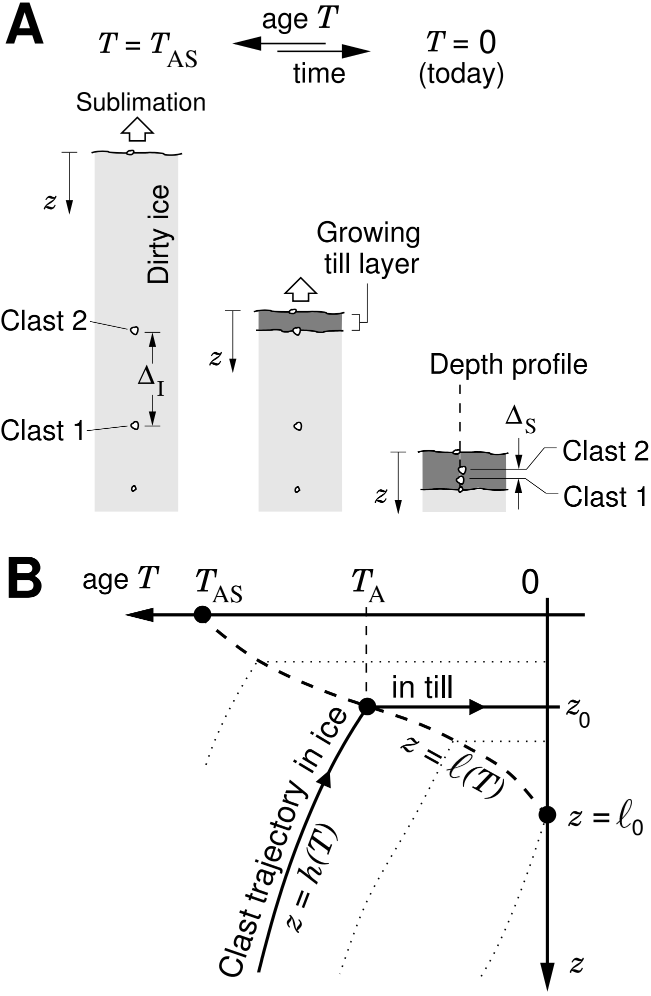


**Figure 1 (65%)**

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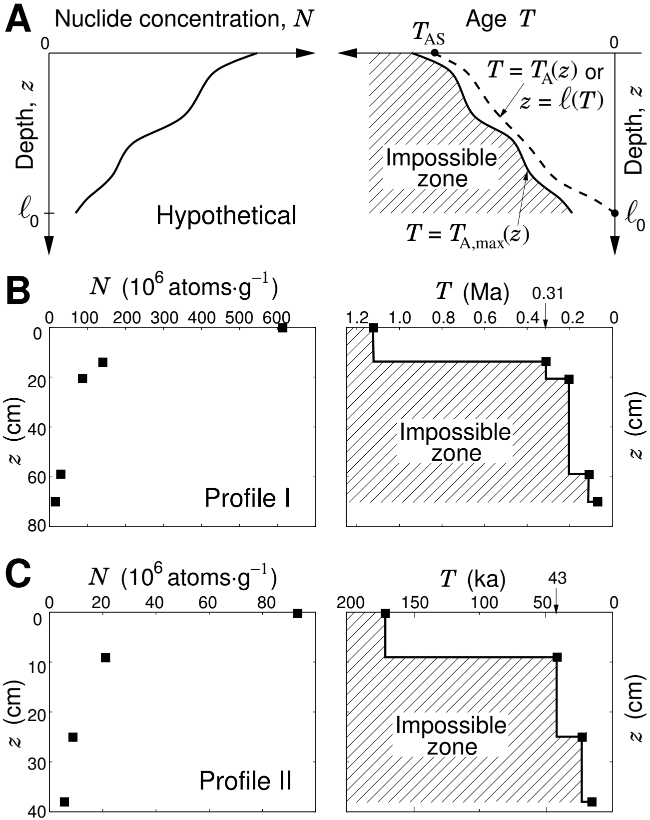


**Figure 2 (44.5 %)**

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