Age *vs* depth of glacial ice at South Pole

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Abstract.

A knowledge of age as a function of depth in glacial ice is important for both glaciology and paleoclimatology. For sites near a ridge or dome, an ice flow model together with information on accumulation rate provides a first approximation. If the accumulation rate is high enough, annual layering of isotopes and dust measured in a solid core can provide a precise age *vs* depth relationship. For South Pole, the flow geometry is not simple and no deep core exists. Nevertheless, by remotely sensing peaks in scattering and absorption of light from pulsed sources buried at depths down to 2200 m, we have been able to determine age *vs* depth for ages up to 65,000 years. Radar isochrons of Siegert and Hodgkins (this issue) provide a crude extension of the age *vs* depth model to $\sim$140,000 years.

Introduction

There is ample motivation for wanting to obtain a deep ice core at or near the South Pole. First is the accumulation rate, which during the last 2000 years has been about three times as high as at Vostok Station. If the high accumulation rate were to be shown to persist throughout the last glacial-interglacial cycle, one could carry out a number of palaeochemical studies with higher resolution than at Vostok, where the most detailed palaeoclimatological studies in Antarctica have been carried out. Furthermore, aeolian volatiles such as nitric acid, which tend to escape from the firn at a site with a low accumulation rate, are retained more completely at South Pole.Second is its geographic location

− farther inland than any other ice core sites and fed by air from several oceans and continents. Third is the likely synergism with a variety of other existing and proposed projects that exploit the deep ice at South Pole: the AMANDA and IceCube neutrino observatories; a proposed Very Large Seismic Array; and proposed study of a subglacial lake within a few kilometers of the Pole. Finally, there is its proximity to the superb infrastructure of the South Pole Station − which would reduce the expense of setting up a field camp. Clearly it would be desirable, in planning experiments, to know age *vs* depth in South Pole ice.

Two upstream sources of the ice that reaches the South Pole have been proposed, based on topography and bedrock elevations: the high plateau at the western edge of the Gamburtsev Subglacial Mountains 980 km from South Pole, at 82 ^{0}S 71 ^{0}E, and Titan Dome, ∼200 km to the south [McInnes and Radok, 1984]. The only facts we have about the accumulation rate are an old measurement, based on annual layering, of an age of ∼2000 yr for a shallow core to a depth of 202.4 m [Kuivinen *et al*., 1982], and a recent measurement, calibrated with volcanic reference layers, of 0.082 m ice equivalent per year over the last 730 years [Legrand and Kirchner, 1990]. Because of the large horizontal flow rate − about 9 m/yr at the surface − to calculate age *vs* depth at greater depths would be nontrivial: it would require obtaining and analyzing a deep solid core, making field measurements of ice particle paths with shallow cores along the two flowlines, and estimating accumulation rates in the past along the flowlines. Previous estimates of accumulation rate as a function of distance upstream differ markedly. To match the present-day accumulation rate and sideways flow velocity at Pole, McInnes and Radok [1984] derived horizontal balance velocities that dropped gradually from the value of 9 m/yr at Pole to 0.1 m/yr at the origin of the flowline on the high plateau, an accumulation value of 0.02 m ice/yr at all distances greater than 300 m upstream (which is surely in error), and a set of particle paths based on an assumption that the vertical velocity in the ice decreased linearly with depth. They neglected flow from Titan Dome to the South Pole.

At our request, M. Giovinetto carried out interpolations of accumulation rates between isopleths on the map of Giovinetto and Bentley [1985]. He inferred 1.5 to 2 times higher values than those of McInnes and Radok at all upstream distances greater than 200 km.

Determining peaks in dust concentration by light scattering and absorption

Since 1994 the Antarctic Muon and Neutrino Detector Array collaboration (AMANDA) has been using intense light sources including pulsed lasers, pulsed blue LEDs, and D. C. sources of tunable wavelengths to measure scattering and absorption of light as a function of wavelength and depth in South Pole ice [Askebjer *et al*., 1995; AMANDA Collaboration, 1999]. They concluded that scattering of visible light is due almost entirely to the presence in the ice of insoluble mineral dust grains, sea salt grains, and possibly liquid acid droplets deposited in snow as aerosols and subsequently compressed into the growing ice sheet; and absorption of visible light is due to the sum of absorption by pure ice and by insoluble mineral dust grains. In a series of papers [AMANDA collaboration, 1995, 1997, 1999; Price and Bergstrm, 1997; He and Price, 1998] we and our colleagues used Mie theory to give a semi-quantitative account of the measured scattering and absorption coefficients as a function of wavelength and at two distinct depth intervals: $800 - 1000$ m and $1600 - 1850$ m. As input parameters we used the same concentrations of dust, salts, and acids that were measured in the Vostok ice core [Legrand *et al*., 1988; Legrand, 1999], together with tabulations of their size distributions as aerosols [He and Price, 1998], and related the depth dependence of the concentrations of dust, salts and acids at Vostok to that at the South Pole through an assumed one-parameter age *vs* depth relationship at the South Pole. Until now we have had no way to check on the validity of that age *vs* depth relationship.

We now show that by matching five peaks in light scattering and absorption as a function of depth, obtained by the AMANDA collaboration [1999], with corresponding peaks in the concentration of dust at known depths and ages at Vostok [Legrand *et al*., 1988; Legrand, 1999] and Dome Fuji [Watanabe *et al*., 1999], we can derive the age *vs* depth relationship for South Pole ice at depths from 1300 to 2100 m, corresponding to ages from 23,000 to 65,000 years. As described in Askebjer *et al*. [1995], the method involves measuring arrival time distributions for nanosecond light pulses that propagate from each of many sources frozen at various depths in the ice to receiving photomultiplier tubes frozen at other locations at known distances from those sources. Both the effective scattering coefficient, b_e, and the absorption coefficient, a, were extracted from such time distributions. (In the absence of scattering, all photons would arrive at a phototube at the same time; in the absence of absorption, the fluence would fall off as r^{-2}; in dusty ice the time distribution is broadened and delayed, as discussed quantitatively by Askebjer *et al*. [1995].) To determine variations with depth of concentrations of grains of dust, salts, and acids, we used sets of data for pairs of sources and receivers at nearly the same depths and separated by horizontal distances of 30 to 100 meters. As an example, Fig. 1 shows data [AMANDA collaboration, 1999] for b_{eff} and a as a function of depth, derived using pulses of laser light at a wavelength of 532 nm. In Fig. 1a the monotonically decreasing values of b_{eff} at depths from 800 to ∼1200 m are due mainly to scattering from air bubbles, which gradually undergo a phase transformation into air hydrate clathrate crystals as depth increases [Price, 1995]. In contrast to air bubbles, which scatter strongly, air hydrate crystals undergo essentially no scattering, because their refractive index is almost the same as that of ice. Figure 1b shows absorption at 532 nm as a function of depth. Neither bubbles nor air hydrate crystals contribute to absorption. The major feature in Fig. 1b is a broad absorption peak centered at 1300 m, superimposed on a nearly featureless background that slowly increases with depth. As discussed elsewhere [AMANDA collaboration, 1999], the peak at 1300 m is due to the very large concentration of insoluble mineral dust corresponding to the Last Glacial Maximum (LGM). In both Vostok ice [Petit *et al*., 1990] and Greenland ice [De Angelis *et al*., 1997] the huge dust peak has been found to correspond to an age of $\sim$23,000 years. None of the peaks in dust concentration at greater depths contributes enough to absorption at 532 nm to stand out above background.

It has been shown elsewhere [Woschnagg and Price, 1999] that intrinsic absorption by perfectly pure ice increases with temperature at a rate of 1 % per Kelvin, and that this property explains the gradual increase with depth. No dependence of absorption of visible light on temperature has previously been reported for ice. Nevertheless, the interpretation of the smooth increase with temperature is consistent with measurements by others of a temperature dependence of absorptivity of $\sim$1 % per Kelvin in both the ultraviolet and the infrared, and we regard this explanation of the trend in the visible as established.

In Fig. 1a the contribution by dust to scattering at 1300 m is concealed by the contribution by bubbles, which falls to zero at a depth of $\sim$1400 m. We identify the four scattering peaks at greater depths, labeled A, B, C, and D, with dust peaks seen in Vostok and Dome Fuji data, shown in Fig. 2 and labeled A, B, C, and D. In Fig. 2, the concentration of Ca^{2+} ions serves as a proxy for dust. Also labeled in Fig. 2 are the peaks at the LGM for Vostok and Dome Fuji. Independent measurements of concentrations of insoluble dust particles in Vostok and Dome Fuji show the same five peaks but with differences in substructures. The ages at which the dust peaks at Vostok and Dome Fuji occur are 38,000 yr (A), 46,500 yr (B), 53,500 yr (C), and 65,000 yr (D). Significant variations in the Ca^{2+} and dust concentration occur on a depth scale of meters, whereas our resolution of peaks in scattering and absorption is only some tens of meters. It is not surprising, therefore, that the optical data in Fig. 1 do not track all the substructure in Fig. 2.

Measurements at wavelengths of 470 and 337 nm, though not as complete as the ones in Figs. 1a and b, support our assignment of ages. The main difference is that at 532 nm absorption is featureless, except for the peak at the LGM, whereas at 470 and 337 nm the contribution from dust grains dominates over intrinsic absorption by ice. The analysis at those wavelengths will be reported in a later paper.

Age *vs* depth in South Pole ice from 1300 to 2100 m

Figure 3 shows our assignments of age as a function of depth for the five peaks labeled LGM, A, B, C, and D. The solid curve is a smooth fit to the five points and to the measurement of age for the 200-m core. We derived the dashed curve using the simple model of Dansgaard and Johnsen [1969], which applies best to flow near a divide. The curve is for a constant accumulation rate of 0.08 m ice/yr and for a vertical strain rate that is uniform from the surface down to a depth 430 m above bedrock and that then decreases linearly to zero at bedrock. The Dansgaard-Johnsen curve should not be expected to represent well the actual age *vs* depth: the South Pole ice is far from a divide, the accumulation rate was not constant in time or location of upstream parcels of ice, and the juxtaposition of flow from both the high plateau and Titan Dome no doubt creates turbulence. The inflection of the solid curve is evidence of the complexity of ice flow into the South Pole region.

Estimates of age using radar isochrons

In the accompanying paper, Siegert and Hodgkins [1999] succeeded in tracing three prominent radar isochrons all the way from Vostok Station to Titan Dome, which is ∼200 km from South Pole. Unfortunately, between Titan Dome and South Pole the isochrons were indistinct, and a direct link from Vostok to Pole could not be established. Following a suggestion by Siegert, we assumed that the ratio between the depth-age of ice and total ice thickness is constant between South Pole and Titan Dome, and scaled the depths of the three isochrons from 1400, 1800, and 2050 m at Titan by the ratio of 2900 m (depth of South Pole ice) to 2180 m (depth of Titan ice). The resulting values, represented by triangular points corresponding to ages of 70, 105, and 142 kyr based on Vostok depth chronology, are shown in Fig. 3. The points lie rather close to an extension of our curve. For comparison, the dot-dashed curve shows the age *vs* depth curve for Vostok [Salamatin *et al*., 1998].

Error bars are absent from the depth-age points derived from internal radar layering traced from the Vostok ice core to Titan Dome. Although the layers around South Pole are continuous in the top 1000 m, at greater depths the layers become increasingly buckled. Such layering is not possible to trace across the ice sheet. It is clear that, in contrast to the rather orderly flow of ice near Vostok, the flow increases near the South Pole, probably due to the confluence of ice from the Gamburtsev Mountains and from Titan Dome. The layer buckling, which may be related to this flow of ice, precludes the evaluation of reliable errors in the radar-layering depth-age relationship between Titan Dome and South Pole. However, the general pattern of layering in other central regions of the ice sheet shows that the relationship between the depth of known isochrons is related linearly to total ice thickness (across short distances as a first order approximation).

Significance of the South Pole age *vs* depth relationship

The main conclusion, which can be seen by comparing the solid curve for South Pole with the dot-dashed curve for Vostok in Fig. 3, is that at any given depth the ice at South Pole is much younger than that at Vostok: by a factor five at depths up to $\sim$1 km, a factor 3.3 at 1.5 km, and a factor 2.4 at 2 km. As a consequence, annual layers will be much better resolvable. For example, for Holocene ice the annual layers are $\sim$3 to 4 times as thick at South Pole as at Vostok, and for ice at a depth of 2.1 km, annual layers are $\sim$2 cm thick at South Pole compared with $\sim$1 cm at Vostok. The significance of this depth *vs* age relationship for AMANDA is that at depths below 2200 m the dust concentration is extremely low, which means that the optical properties of the ice are outstanding for neutrino astrophysics.

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Figure Captions

1. Effective scattering coefficient, b_{eff}, and absorption coefficient, a, as a function of depth in South Pole ice, measured in situ with a pulsed laser at a wavelength of 532 nm. The labeling of the peaks is the same as in Fig. 2.

2. Dust concentration (using Ca^{2+} concentration as a proxy) as a function of depth in cores at Vostok Station and at Dome Fuji. Total mineral dust is estimated by dividing the non-marine calcium concentration by its relative abundance, 0.0415.

3. Age *vs* depth relationships for South Pole ice (this work) and for Vostok [Salamatin *et al*., 1998]. See text for a discussion of the radar data and the Dansgaard-Johnsen model (dashed curve). Bedrock is at 2900 m.

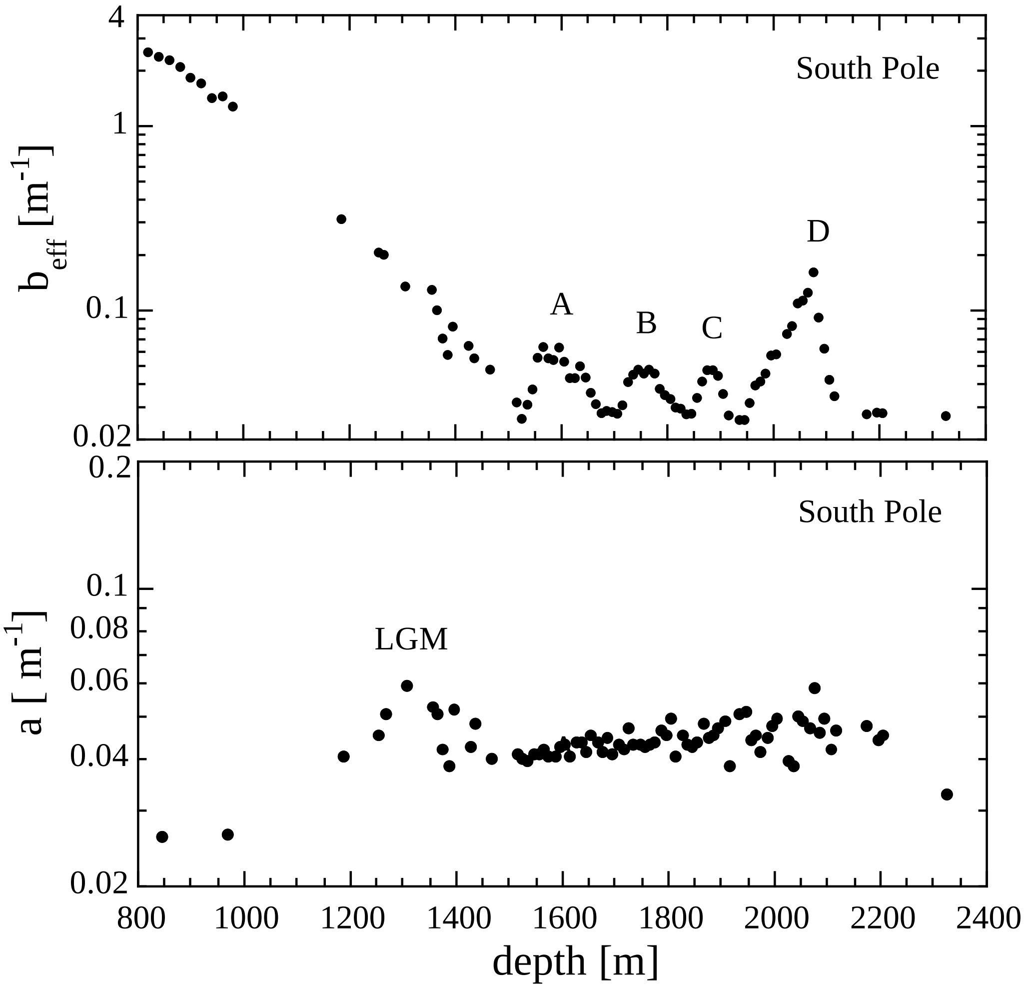

Figure 1

1. Effective scattering coefficient, b_{eff}, and absorption coefficient, a, as a function of depth in South Pole ice, measured in situ with a pulsed laser at a wavelength of 532 nm. The labeling of the peaks is the same as in Fig. 2.

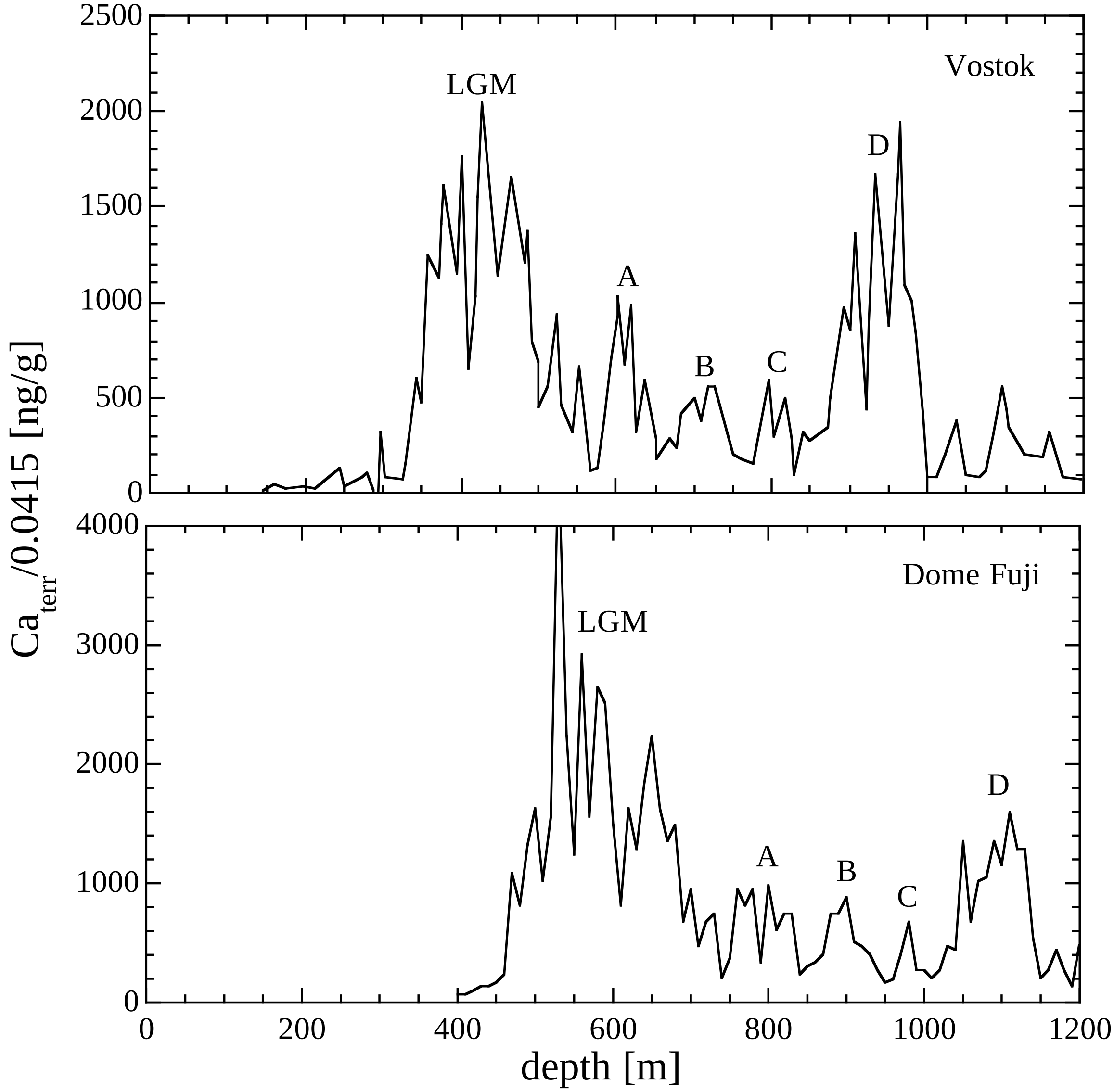

Figure 2

2. Dust concentration (using Ca^{2+} concentration as a proxy) as a function of depth in cores at Vostok Station and at Dome Fuji. Total mineral dust is estimated by dividing the non-marine calcium concentration by its relative abundance, 0.0415.

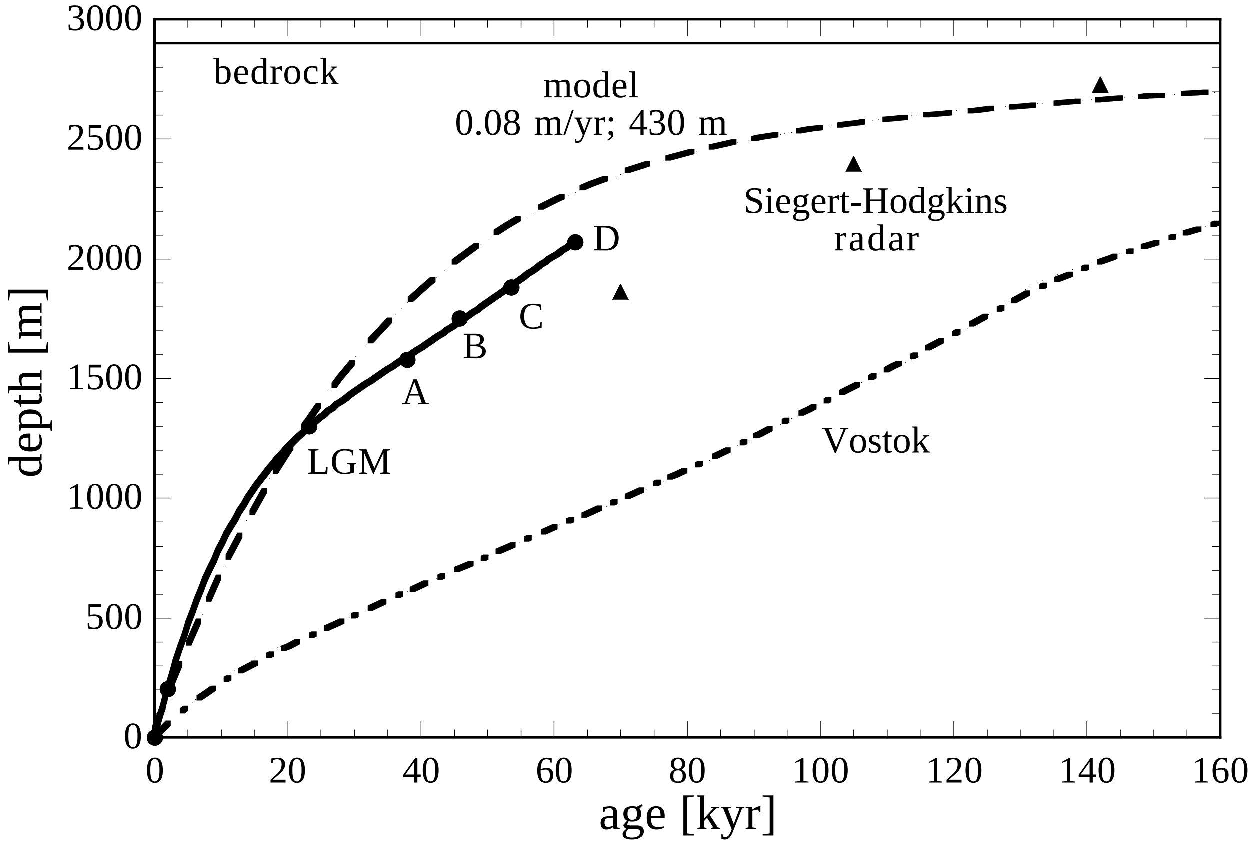

Figure 3

3. Age *vs* depth relationships for South Pole ice (this work) and for Vostok [Salamatin *et al*., 1998]. See text for a discussion of the radar data and the Dansgaard-Johnsen model (dashed curve). Bedrock is at 2900 m.