Preservation of Miocene glacier ice in East Antarctica

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ANTARCTIC climate during the Pliocene has been the subject of considerable debate. One view holds that, during part of the Pliocene, East Antarctica was largely free of glacier ice and that vegetation survived on the coastal mountains[1-4]. An alternative viewpoint argues for the development of a stable polar ice sheet by the middle Miocene, which has persisted since then[5-10]. Here we report the discovery of buried glacier ice in Beacon valley, East Antarctica, which appears to have survived for at least 8.1 million years. We have dated the ice by $^{40}Ar/^{39}Ar$ analysis of volcanic ash in the thin, overlying glacial till which, we argue, has undergone little (if any) reworking. Isotope and crystal fabric analyses of the ice show that it was derived from an ice sheet. We suggest that stable polar conditions must have persisted in this region for at least 8.1 million years for this ice to have avoided sublimation.

Beacon valley (77° S, 161° E) is near the peripheral Taylor dome of the East Antarctic ice sheet. The present-day mean annual temperature is −30 to −35 °C and precipitation is less than 10 mm water equivalent per year[11,12]. The valley is bordered by mountains rising to 3,011 m (Mount Feather), which consist of late Palaeozoic and early Mesozoic sandstones and dolerite (Fig. 1*a*). The mouth of Beacon valley is dammed by a lobe of Taylor glacier, an outlet glacier that drains Taylor dome on the periphery of the East Antarctic ice sheet. Ablation on Taylor glacier is entirely from sublimation and averages ~0.18 m water equivalent per year at 1,000 m elevation[13]. The glacier is cold-based in its upper ablation zone, although part of the basal ice beneath the lower ablation zone may be at the pressure melting point[13]. Modern $\delta^{18}O$ values for ice on Taylor dome range[14,15] from −40‰ to −42‰ (with respect to the SMOW standard); in contrast, $\delta^{18}O$ values for local glaciers at the head of Beacon valley range from −30‰ to −40‰, reflecting a mix of local snowfall and wind-drifted snow from the ice sheet. (See Fig. 2 legend for definition of $\delta^{18}O$.) These local glaciers lead down-valley into extensive debris-covered rock glaciers. In between the rock glaciers and Taylor glacier at an altitude of 1,300–1,450 m is a flattish boulder-covered valley floor. It is in this latter area that the buried ice extends over an area of at least 4 km^2. The thickness of the ice is unknown. But the amplitude of the stagnant ice surface morphology, such as kettle holes, implies a depth of at least 15 m.

The till overlying the buried ice is derived from Taylor glacier and is part of an extensive granite-bearing deposit marking the former expansion of East Antarctic outlet glaciers into the Dry valleys[5,6,10]. The presence of granite shows the till is not local because this lithology does not crop out in the Beacon valley area and is absent from the deposits of local rock glaciers. Excavation revealed that beneath a surface layer of stones the till is 50 cm thick and consists of a thin upper sandy layer, with angular fragments of local sandstone and dolerite, and a thicker, lower, fine-grained layer containing granite and glacially striated stones in a silt and clay-sized matrix.

TABLE 1 Isotope data and ages of ash deposits from Beacon valley

Analysis no.	$^{40}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	$^{40}Ar^*/^{39}Ar$	$^{40}Ar^*$ (%)	Age (Myr)	s.d.
Sample DMS91-107 (sanidine)							
7182-02	12.5394	1.55483	0.01119	9.368	74.6	8.055	0.293
7182-04	10.7856	0.02569	0.00474	9.387	87.0	8.071	0.222
7182-05	10.4854	0.01234	0.00372	9.387	89.5	8.072	0.184
7182-06	9.5960	0.04598	0.00133	9.206	95.9	7.916	0.158
7182-08	10.4079	0.00000	0.00368	9.319	89.5	8.013	0.477
7182-09	9.6967	0.07168	0.00089	9.439	97.3	8.116	0.080
7182-10	10.7869	0.13244	0.00477	9.389	87.0	8.073	0.208
					Weighted mean	8.07	± 0.06
					Arithmetic mean	8.05	± 0.07
Sample NPS88-2 (sanidine)							
2497-01	4.4866	0.06351	0.00638	2.985	61.3	8.026	0.402
2497-02	3.1188	0.04201	0.00051	2.968	95.2	7.981	0.083
2497-03	7.9987	0.23502	0.01614	3.247	40.6	8.729	0.346
2497-04	3.1251	0.04416	0.00117	2.779	88.9	7.475	0.123
2497.08	3.1431	0.02010	0.00097	2.855	90.8	7.676	0.093
2497-09	3.3614	0.15182	0.00188	2.817	83.8	7.577	0.170
2497-10	3.1806	0.03697	0.00120	2.826	88.9	7.601	0.196
					Weighted mean	7.87	± 0.43
					Arithmetic mean	7.78	± 0.05
Contaminant or detrital grain							
2497-07	4.7721	0.04123	0.00153	4.323	90.6	11.611	0.191

Laser total-fusion $^{40}Ar/^{39}Ar$ analyses of individual euhedral crystals from ash deposits overlying buried ice in Beacon valley, carried out by the Berkeley Geochronology Center, Berkeley, California. Pristine euhedral crystals were hand-picked from each ash sample using a binocular microscope, treated with 7% hydrofluoric acid in an ultrasonic cleaner for 5 min to remove any altered clays or attached glass, followed by 10 min in distilled water, and then irradiated in the core of the Omega West research reactor at Los Alamos National Laboratory. For sample DMS-91-107, obtained in 1991 from the wedge illustrated in Fig. 1*b*, the weighted mean age of 8.07 ± 0.06 Myr is based on seven separate single-crystal analyses using a Mass Analyzer Product 215 noble-gas mass spectrometer, calibrated with monitor minerals Fish Canyon Sanidine and MMhb-1; the weighted mean age of 7.87 ± 0.43 Myr for sample NPS88-2 is also based on seven separate analyses. This latter sample was collected from an adjacent relic wedge in 1988. Asterisk describes radiogenic ^{40}Ar.

The till surface is marked by contraction-crack polygons[16]. Active forms are characterized by V-shaped troughs 2–3 m deep, which penetrate into the underlying ice and are commonly filled with wedges of vertically stratified sand and gravel deposits. In addition there are traces of relict wedges, recognizable only in stratigraphic section in the overlying till, which reflect abandoned crack patterns. We have discovered volcanic ash in four such relict wedges. In one well preserved wedge shown in Fig. 1*b*, the ash has a uniform geochemistry and contains <10% non-volcanic contaminants. Its grain size distribution is bimodal with peaks at 23 and 250 μm but with a coarse component up to 1,000 μm in size. The ash fines upwards within the wedge. It contains glass shards with fragile bubble vesicles and delicate spires. There is no chemical etching of volcanic anorthoclase crystals, and glass shards show no evidence of weathering when viewed under a scanning electron microscope.

The high concentration of ash, the uniform geochemistry, the bimodal grain-size distribution, the stratification by grain size, and the preservation of delicate features on glass shards all point to an origin by direct airfall into an open crack[17]. Moreover, the preservation of details of the wedge structure and the lack of mixing and abrasion of ash particles suggests that there has been little subsequent disturbance. These observations provide compelling grounds for arguing that the ash is in situ, apart from any settling associated with sublimation of the underlying ice. Further, on the basis of examination of 75 volcanic ash sites in the area, we can preclude alternative explanations for the stratigraphic position of the ash[17]. Aeolian action produces an abraded, unimodal deposit mixed with non-volcanic material, whereas down-slope mass movement or rock glacier flow distorts the initial wedge form, and likewise causes grain abrasion and mixing.

Laser-fusion $^{40}Ar/^{39}Ar$ dating of individual crystals shows that the ashes are 7.9–8.1 Myr old (Table 1). This means that the granite-bearing till in which they are emplaced must be older than 8.1 Myr, a conclusion which agrees with other minimum dates for the same till elsewhere in the Dry valleys, also obtained by isotopic dating of volcanic ashes. The latter yield minimum ages of 11.3 Myr in the adjacent Arena valley, and 13.6 and 12.0 Myr in two separate locations in the Asgard Range[5,6]. The ash dates imply that the granite-bearing till is Miocene or older in age.

The surface of the ice beneath the ash wedge is approximately horizontal, and truncates a plunging fold (Fig. 1*c*). The ice, which consists of equigranular 10-mm crystals, is clouded by dispersed rock debris, and contains several debris bands up to 150 mm in thickness (Fig. 2*a*). Granulometric analyses indicate that the debris is composed of 3% gravel (a small percentage of which is granite), 72% sand and 15% silt and clay. Enveloping the debris-bearing layers are bands of clear ice and white, bubbly foliated ice. Alternating debris-rich and debris-poor sequences are typical of basal regelation and debris entrainment, and reflect the former presence of basal ice at the pressure melting point[18,19]. Detailed laboratory analysis of thin sections from each of the ice types reveals a fabric with a strong maximum caused by shearing at depth with some compressive flow (Fig. 2*b*). The preservation of this type of fabric and the small crystal size may reflect the ability of dirt content to impede recrystallization processes[20,21]. The direction of movement is up-valley and oblique to the longitudinal axis of Beacon valley; this is consistent with the presence of granite, and shows that the ice is derived from an expanded Taylor outlet glacier rather than local glaciers.

Oxygen-isotope analyses of the fossil ice give $\delta^{18}O$ values that cluster around −33‰. They yield less negative values than exist at higher altitudes on Taylor dome today. Because $\delta^{18}O$ values for the fossil ice fall within the range obtained for modern ice at the head of Beacon valley, we suggest that

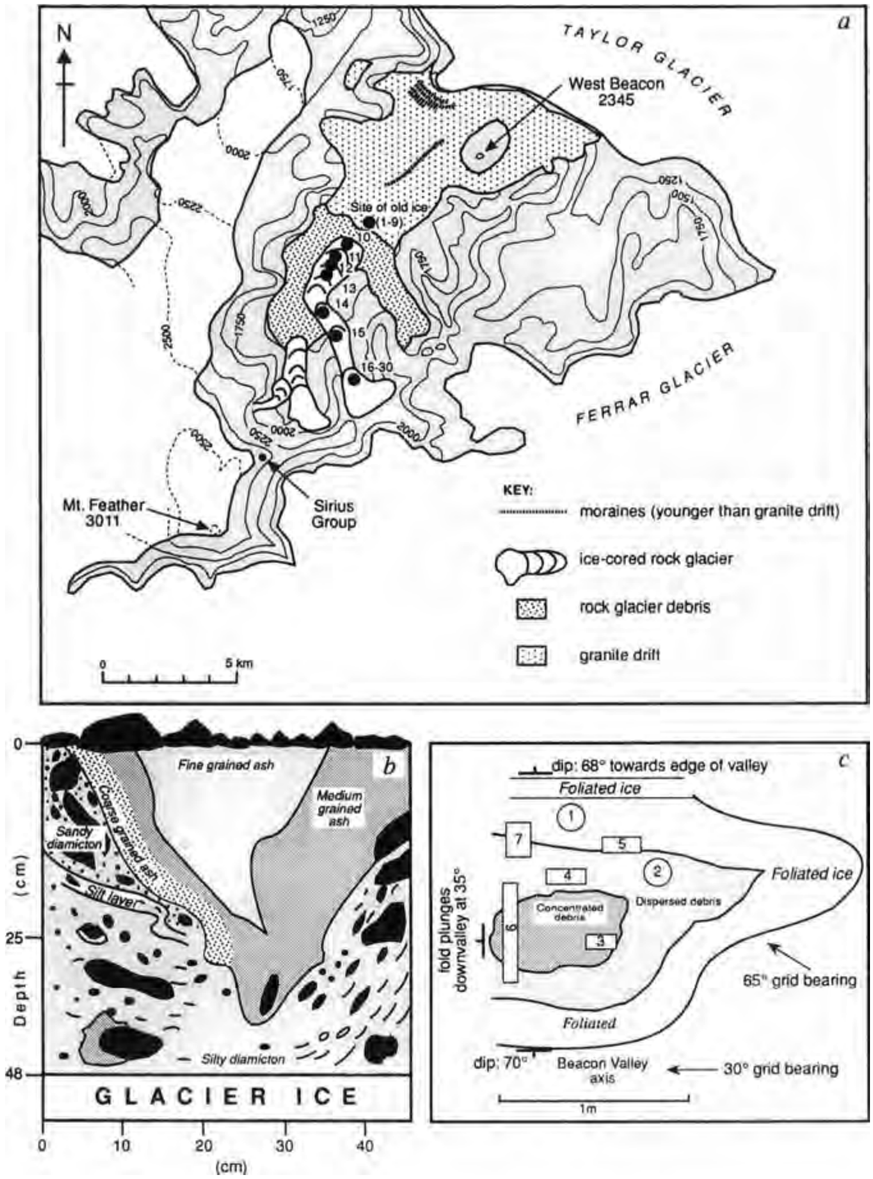

FIG. 1 *a*, Map showing Beacon valley and the sites (filled circles, numbered 1–30) where ice was sampled. Heights are shown in metres. The old ice underlies much of the granite drift on the floor of Beacon Valley. *b*, Excavation showing the vertical relationships between the till, the wedge of volcanic ash and the underlying ice. The ash-filled wedge, which tapers with depth, is bounded by vertically oriented stones and has been little disturbed since formation. The lower, granite-bearing, silty diamicton has a matrix with 1.7 wt% clay-sized particles (<0.004 mm). The coarse stratification of the ash by size is typical of a direct airfall deposit. *c*, Plan view of the ice exposed in the bottom of the excavation beneath the ash wedge, showing sampling sites and how the surface truncates a plunging fold. Ice was transferred, without melting, to Brussels for analysis.

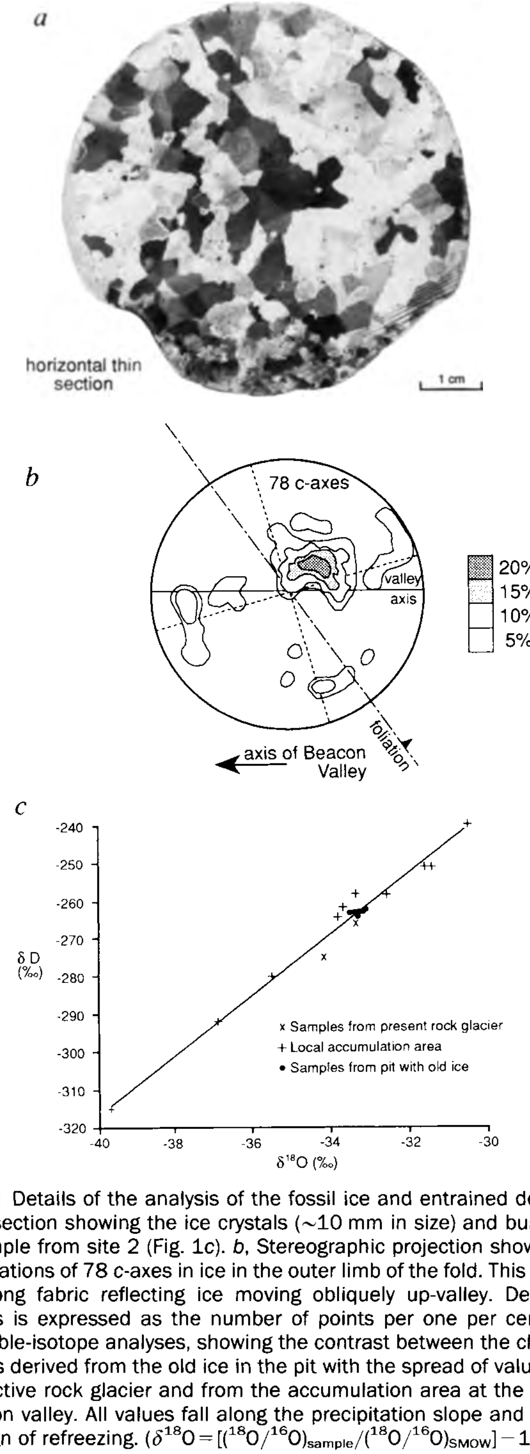

FIG. 2 Details of the analysis of the fossil ice and entrained debris. *a*, Thin section showing the ice crystals (~10 mm in size) and bubbles in a sample from site 2 (Fig. 1*c*). *b*, Stereographic projection showing the orientations of 78 c-axes in ice in the outer limb of the fold. This reveals a strong fabric reflecting ice moving obliquely up-valley. Density of c-axes is expressed as the number of points per one per cent area. *c*, Stable-isotope analyses, showing the contrast between the cluster of values derived from the old ice in the pit with the spread of values from the active rock glacier and from the accumulation area at the head of Beacon valley. All values fall along the precipitation slope and there is no sign of refreezing. ($\delta^{18}O = [(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{SMOW}] - 1$ per mil and $\delta D = [(D/H)_{sample}/(D/H)_{SMOW}] - 1$ per mil.)

climate conditions on the ice dome of the Miocene-age ice were similar to those of Beacon valley today. All ice samples, fossil and modern, are aligned on a precipitation slope, implying that phase changes in the fossil ice have not significantly modified the initial isotopic composition.

Overall, the debris and ice characteristics suggest that this is a remnant of basal glacier ice. The nature of the debris shows that the glacier was sliding over its bed; the ice fabric and the presence of granite erratics suggest that the remnant glacier ice was derived from an expanded Taylor glacier. The isotopic analyses suggest that the ice accumulated under cold climate conditions similar to those of Beacon valley today. These findings all point to the preservation of a remnant of an ancient outlet glacier of the East Antarctic ice sheet for at least 8.1 Myr.

At first sight it might seem surprising that glacier ice can avoid sublimation beneath a thin layer of till over a period of 8 Myr. However, if one assumes that the soil is 100% saturated with water vapour and that the water partial-pressure gradient is determined on average by the geothermal heat flux[22], it is found that the amount of sublimation is consistent with 1 m of settling. A problem arises in that relative humidities below 100% have been observed in soils elsewhere in the Dry valleys[23]; if these lower values applied to Beacon valley then they could lead to moisture fluxes three orders of magnitude greater. At this stage, when little is understood about the role of sublimation in frozen sediments[24], it is useful to highlight three points in support of our assumptions: the observed relative humidity fluctuations[23] were restricted to near the surface, and saturation persisted at a depth of 30–40 cm; the readings are atypical in that they were taken in summer when surface temperatures were highest and relative humidities lowest; the presence of snow causes the underlying soil to be saturated, and in Beacon valley drifting snow collects preferentially in the depressions associated with wedges. We conclude that lowering of a few metres is plausible. It is consistent with the preservation of the overlying ash-wedge structure and would also explain the loss by settlement of any traces of the lower part of the wedge which may originally have been 2–3 m deep.

The implication of this discovery of ancient glacier ice is that a polar ice sheet, sufficiently big to nourish outlet glaciers flowing into the Dry valleys, existed in East Antarctica by 8.1 Myr ago. There is a further implication for Pliocene climate. The survival of ancient glacier ice beneath a thin layer of unconsolidated till suggests that the cold polar climate of Beacon valley has persisted at least for the past 8.1 Myr, and supports those who argue for the long-term stability of the East Antarctic ice sheet[5–10]. □

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