SUPPLEMENTARY INFORMATION

A tuff cone erupted under frozen-bed ice (northern Victoria Land, Antarctica): linking glaciovolcanic and cosmogenic nuclide data for ice sheet reconstructions

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Analytical methods

Geochemistry

Major elements (Table 1, main text) were determined by X-ray fluorescence (XRF-ARL 9400XP) on glass beads, at Dipartimento di Scienze della Terra, Università di Pisa, with precision between 1% and 4% RSD for most elements, except TiO_2, MnO, CaO, Na_2O, (5–8% RSD; Tamponi et al. 2003).

^{40}Ar-^{39}Ar dating

For dating, a sample of fresh lava was crushed and sieved to extract groundmass. Sample preparation and ^{40}Ar–^{39}Ar data collection were completed at Istituto di Geoscienze e Georisorse, CNR, Pisa (Italy). The groundmass was leached in an ultrasonic bath (heated to c. 50°C) for 1 h in HCl 3.5 N and 1h in HNO_3 1N (Koppers et al. 2000). The groundmass was wrapped in aluminum foil and irradiated for 3 h in the core of the TRIGA reactor at the University of Pavia (Italy) along with the dating standard Fish Canyon sanidine (FCs). Laser step-heating experiment was performed using an infrared Nd:YAG laser beam defocused to a c. 2 mm spot size and homogenized by a beam-homogenizer lens which produces a flat power distribution. Steps were carried out at increasing laser power until complete melting occurred. More details on the analytical procedures are given in Di Vincenzo et al. (2010). Data corrected for post-irradiation decay, mass discrimination effects, isotope derived from interfering neutron reactions and blank, are listed in Table S1. Errors on single runs are 2σ analytical uncertainties, including in-run statistics and uncertainties in the discrimination factor, interference corrections and procedural blanks. Uncertainties on total gas ages and on error-weighted mean ages also include the uncertainty in the fluence monitor (2σ internal errors). Ages were calculated using the IUGS recommended constants (Steiger and Jäger 1977) and an age of 28.03 Ma for FCs (Jourdan and Renne 2007). We adopted old constants due to the lack of general consensus regarding new ^{40}K decay constants.

Table S1. ^{40}Ar–^{39}Ar laser step-heating data on sample T5.5.4, Harrow Peaks, Antarctica

laser power (W)	$^{36}Ar_{atm}$	$^{37}Ar_{Ca}$	$^{38}Ar_{Cl}$	$^{39}Ar_{K}$	$^{40}Ar_{Tot}$	Age (ka)	±2σ	$^{40}Ar^*$ %	$^{39}Ar_K$ %	K/Ca	±2σ
0.20	0.00326	0.02370	0.00090	0.01966	1.019	1361	653	5.4	1.1	0.4397	0.0266
0.40	0.00325	0.2418	0.00407	0.2149	1.318	799.9	56.1	27.0	12.5	0.4710	0.0281
0.60	0.00154	0.3640	0.00408	0.2514	0.7824	630.9	28.0	41.9	14.6	0.3660	0.0221
0.80	0.00127	0.3673	0.00380	0.2132	0.6663	660.4	37.5	43.6	12.4	0.3077	0.0186
1.10	0.00131	0.4247	0.00359	0.2325	0.7052	658.2	45.5	44.8	13.5	0.2901	0.0174
1.50	0.00136	0.4166	0.00383	0.1877	0.6419	615.8	57.4	37.2	10.9	0.2388	0.0143
2.20	0.00162	0.4658	0.00486	0.1428	0.6225	481.0	55.3	22.8	8.3	0.1625	0.0098
6.0	0.00262	1.987	0.0127	0.3857	1.136	454.0	48.1	31.8	22.4	0.1029	0.0062
15.0	0.00093	0.6286	0.00178	0.07512	0.3782	667.6	92.3	27.4	4.4	0.0633	0.0038
Total gas age						*615.6*	*20.1*			*0.186*	*0.010*
weighted mean (4 out of 9, MSWD = 0.98)						***641.6***	***19.9***		*51.4*		
isochron age (steps 0.6 to 1.5 W), ($^{40}Ar/^{36}Ar)_i$ = 246±77						*788*	*213*				

Notes: Argon isotope concentrations are in Volts. Mass spectrometer sensitivity: ~2.0*10-14 moles/V.

Cosmogenic nuclide surface exposure dating

The volcanic outcrop is strewn with abundant granitoid erratics showing pronounced edge abrasion which contrasts with the unmodified angular detritus derived from the volcanic outcrop itself (Fig. S1). The samples analysed are slab-like boulders collected from gentle hill slopes, where there was minimal possibility of rolling or rotation. Both boulders show ample signs of edge rounding presumably caused by the original host ice, which should favour the removal of inherited nuclides.

Analysis of $^{10}Be/^{9}Be$ ratios was undertaken by the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, USA. Sample $^{10}Be/^{9}Be$ ratios were measured relative to the 07KNSTD3110 standard with a $^{10}Be/^{9}Be$ ratio of 2.85 x 10^{-12} (Nishiizumi et al. 2007). The analytical background was controlled using procedural blanks, carrier splits containing the same amount of ^{9}Be atoms than added to the samples and processed and measured identically to the samples. Blank corrections for these samples were less than 1%. We calculated topographic shielding using the online geometric shielding calculator, v. 1.1 (Balco et al. 2008), assumed zero erosion, and used a quartz density of 2.7 g cm^{-3} and the Antarctic pressure-altitude relation (Stone 2000). We applied the ^{10}Be production rate from a calibration site in New Zealand (Putnam et al. 2010), calculated ^{10}Be exposure ages using the CRONUS-Earth online calculator version 2.2 (available at http://hess.ess.washington.edu/) and report those ^{10}Be ages using the 'St' scaling scheme (Lal 1991; Stone 2000). We report 1 sigma 'propagated' errors on the ^{10}Be ages (Table S2), which include both analytical uncertainties and uncertainty on the production rate (2.3 %; Putnam et al. 2010).

Table S2. Analytical data for ^{10}Be exposure ages from Harrow Peaks erratics

Sample ID	AMS ID	Latitude (S)	Longitude (W)	Altitude (m a.s.l.)	Thickness (cm)	Shielding factor	^{10}Be/^{9}Be
T11.8.1	BE37468	-74.04755	164.79062	368	3.58	0.9934	1.8781E-13
T11.8.2	BE37469	-74.04735	164.79093	366	3.62	0.9743	1.521E-13

[Table S2, continued]

1σ error	Quartz weight (g)	^{9}Be carrier (mg)	^{10}Be conc. (at.g^{-1})	1σ error (at.g^{-1})	^{10}Be age$^{\$}$ (yr)	1σ error$^{\$}$ (yr)	1σ propagated error*$^{\$}$ (yr)
3.5023E-15	15.0410	0.1900	1.586E+05	2.958E+03	22,900	400	680
3.4892E-15	15.1598	0.1892	1.269E+05	2.911E+03	18,700	400	609

$ rounded to nearest 100 years

* error propagated with production rate uncertainty of 2.3% (Putnam et al. 2010)

Description of erratics sampled for cosmogenic surface exposure dating

Sample 1 (T11.8.1) is a white granodiorite with numerous cm-wide mica-bearing schlieren (muscovite, possibly biotite) that impart a foliated appearance to the sample though it lacks a prominent alignment of the quartz and feldspar crystals. Dominant crystal size outside of the schlieren is c. 5-10 mm. Pegmatite veins with crystals up to 3 cm in length are also present. The slab surface is strongly red-brown stained, less so on its sides and only faintly so on the lower surface. It shows clear corner abrasion and has a subangular morphology (Fig. S2).

Sample 2 (T11.8.2) is a different granodiorite, lacking micaceous schlieren and thus massive in appearance, and the crystal size is finer (c. 5-8 mm). A single pegmatite vein is present. Red-brown surface coloration is present, not as strongly developed as in sample 1 but with a similar distribution. Sample 2 is somewhat more angular than sample 1, although also subangular overall (Fig. S3).

References

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Figure S1. Photos of representative granitoid erratics present at the Harrow Peaks volcanic outcrop. The red circles in the first image mark the locations of erratics (many > 1 m

across) on the summit of the central plug-like outcrop, to illustrate their abundance. Note the subrounded shapes of the erratics in the other images, due to pronounced abrasion, which contrast with the conspicuously angular shapes of the surrounding basalt debris derived from the volcanic outcrop.

Figure S2. View of sample T11.8.1; the hammer is 50 cm long

Figure S3. View of sample T11.8.2