A recent volcanic eruption beneath the West Antarctic ice sheet

HUGH F. J. CORR* AND DAVID G. VAUGHAN

British Antarctic Survey, Natural Environment Research Council, Cambridge CB3 0ET, UK
***e-mail: h.corr@bas.ac.uk**

Indirect evidence suggests that volcanic activity occurring beneath the West Antarctic ice sheet influences ice flow and sheet stability[1–3]. However, only volcanoes that protrude through the ice sheet[4] and those inferred from geophysical techniques[1,2] have been mapped so far. Here we analyse radar data from the Hudson Mountains, West Antarctica[5], that contain reflections from within the ice that had previously been interpreted erroneously as the ice-sheet bed. We show that the reflections are present within an elliptical area of about 23,000 km^2 that contains tephra from an explosive volcanic eruption. The tephra layer is thickest at a subglacial topographic high, which we term the Hudson Mountains Subglacial Volcano. The layer depth dates the eruption at 207 BC ± 240 years, which matches exceptionally strong but previously unattributed conductivity signals in nearby ice cores. The layer contains 0.019–0.31 km^3 of tephra, which implies a volcanic explosive index of 3–4. Production and episodic release of water from the volcano probably affected ice flow at the time of the eruption. Ongoing volcanic heat production may have implications for contemporary ice dynamics in this glacial system.

Unlike the East Antarctic ice sheet, which lies on generally aseismic continental crust that shows little volcanic activity[6], the West Antarctic ice sheet (WAIS) lies over a crustal rift that has volcanism on its flanks and associated elevated geothermal heat flux[6,7]. Indeed, several active volcanoes outcrop above the ice sheet[4] and the most recent eruption from these occurred at 7.5 kyr BP (ref. 4). However most of the WAIS is blanketed by a thick ice sheet and so far only a few subglacial volcanic centres have been inferred from geophysical data[1,2,8]. Most of these are highly eroded and may be relict features[8], but one, Mount Casertz, shows signs of recent activity. It has an associated surface depression, indicating high geothermal heat flux[1], was the focus of recent earthquake activity[9] and is believed to produce subglacial water that is responsible for rapid ice flow nearby[3].

Elsewhere in the WAIS, ice cores and ice-sounding radar (see for example ref. 10) contain evidence of fallout from volcanic eruptions, but these are usually chemical signatures transported great distances in aerosols. Thus, although there is indirect evidence for subglacial volcanic edifices, one of which may have elevated geothermal heat flux, there is no direct evidence for recent subglacial eruptive activity beneath the WAIS, and no evidence of episodic subglacial water production that would change ice flow[3].

Hudson Mountains (Fig. 1) are located close to Pine Island Glacier within West Antarctica. Their geology is poorly known, but among the exposed nunataks are three extensively eroded Miocene volcanoes and young, slightly eroded parasitic cones[11]. Furthermore, the presence of breccia and consolidated ash cones suggests the occurrence of hydromagmatic or steam-blast eruptions. Evidence of recent volcanic activity is, however, confined to a report of the ‘possible presence of steam’ at an unspecified nunatak in 1974, and an eruption reportedly seen in satellite data in 1985 (ref. 11).

We have analysed data from a 2004/05 US/UK airborne geophysical survey that yielded ice-sounding radar and gravity- and magnetic-anomaly data[5,12] (Fig. 1). Radar sections (Fig. 2) from ten sorties over Hudson Mountains show an extremely bright internal reflection mid-depth (100–700 m) in the ice sheet. This bright reflection is, in places, 30 dB stronger than any other internal reflection we have seen from any part of Antarctica; in places, it is stronger than the underlying ice-bed echo.

Re-examination of a photographic radar echogram acquired in 1981 (ref. 13) showed the bright reflection (Fig. 1), but this had been misidentified as the ice bottom; erroneous ice-thickness data arising from this interpretation have been used many times (for example in ref. 14). The same misidentification was made of radar data acquired in late 2001 and used in subsequent analyses[15,16].

In our data, the bright reflection does not intersect the weaker internal layers that lie above and below it, suggesting that the reflection arises from a layer of material deposited over a short period on the ice surface and subsequently buried by snowfall. We have estimated the age of the layer at three ice divides using an idealized Dansgaard–Johnsen model[17]. The calculated ages closely agree with one another, confirming that the layer is isochronous, but uncertainty in the rate of snow accumulation[18] limits our confidence in assigning an absolute age (207 BC ± 240 yr).

The bright reflection occurs across a 156 × 190 km elliptical area (23,000 km^2) (Fig. 1). The power of the reflection is strongest at the centre and fades exponentially towards the margins (Fig. 3), where it becomes indistinguishable from other internal layers. The reflection occurs everywhere within the elliptical area, except on the trunk and Tributary 6 of Pine Island Glacier. The absence of the reflections here is, however, to be expected; in two millennia, ice velocities of 20–2,000 m yr^{-1} would have transported the layer to the ice-shelf front, where it would have been lost to iceberg calving.

Together, the unusual strength of the reflection, the elliptical shape of the area over which it is visible, the way it fades towards the margins, its isochronous nature and the reports of nearby volcanic activity all lead us to conclude that the reflection derives from a layer of tephra deposited as air-fall on the ice surface from a single, volcanic eruption.

We have mapped the absolute power of the reflection, which should be related to the thickness of the tephra layer, together with relative along-track variance in this power (Fig. 1b), which should be related to the typical clast size (see the Supplementary

Information). Both show well-defined maxima close to the centre of the elliptical area; we take this to indicate the eruptive centre. The symmetry of the plume around this point indicates that the eruption took place in low-wind conditions[19].

The volcanic explosive index (VEI) is a measure of the significance of an eruption on the basis of volume (V) of tephra ejected. It has been shown[20] that the total volume of erupted material is related to the maximum thickness of the tephra layer, T_0, the ratio of axes of the mapped tephra, α, and the distance over which the tephra thins by half, b_t,

$$V = 13.08\,T_0\frac{b_t^2}{\alpha}.$$

Here we have no direct measurement of the tephra-layer thickness, but we estimate that the minimum detectable layer is equivalent to a layer of solid tephra ~0.3 mm thick, and we extrapolate this to the eruptive centre on the basis of reflected power. These calculations also show that the strength of the reflection is largely unaffected by whether the tephra is mixed into ice in dilutions down to 0.5%. However, below this dilution, even a thick layer would be difficult to distinguish (see the Supplementary Information).

Figure 3 confirms the exponential reduction in reflected power over 40 km and provides a good estimate for b_t at ~8 km. Using the above relationship we estimate the total tephra volume to be between 0.019 and 0.31 km^3, which implies a VEI of 3 or 4. Antarctica has produced no reported Holocene eruptions greater than VEI-3 (ref. 21).

Satellite imagery[22] shows no current rock exposure within 50 km of the eruptive centre, but immediately beneath it there is a subglacial topographic high (>20 km wide, ~1,000 m high)[5], where the ice is less than 100 m thick. Although we cannot identify the precise centre of the eruption, we refer to this feature as Hudson Mountains Subglacial Volcano (HMSV).

VEI-3 subglacial eruptions were produced from beneath a similar thickness of ice at Grímsvötn, Iceland, in 1996 (ref. 23), 1998 and 2004 (ref. 24). These were highly explosive and the 2004 eruption produced a column more than 12 km in height[24]. They also produced large quantities of melt water, which eventually escaped by flowing under and through the surrounding ice. However, because it escaped relatively quickly, this water seems to have had only transient impact on the ice flow[23].

Given the similar size of these subglacial eruptions, we expect a comparable column height from the HMSV eruption, which would have transported its chemical signature many hundreds of kilometres. Indeed, two ice cores from the WAIS contain evidence of the eruption. Byrd Station ice core (~1,100 km from HMSV) contains ten spikes in acid concentration associated with eruptions younger than 10 kyr (ref. 25). The strongest of these occurred at 315 BC. Similarly, the Siple Dome ice core (~1,300 km from HMSV) contains a volcanic signal from an unknown source at 325 BC (ref. 26). This, together with another at 7,900 yr BP attributed to Mount Takahe[4], are by far the strongest in the last 10 kyr of this record. The eruptive source of the 315 BC and 325 BC layers is unknown, but their dates are within the uncertainty of each other and of our date for the HMSV eruption. We conclude that these layers have the same source, and thus the most certain date for the HMSV eruption is that from the Siple Dome ice core, 325 BC.

The existence of a subglacial volcano within the WAIS, whose most recent eruption can be mapped, dated and given a VEI, is a unique finding, and its location now extends by ~500 km the zone of active volcanism along the margin of the WAIS. A single eruptive event of the type we have seen would be unlikely to influence the future of the entire WAIS. However, such widespread volcanism could indicate either elevated geothermal heat fluxes, or the episodic production and release of subglacial melt water.

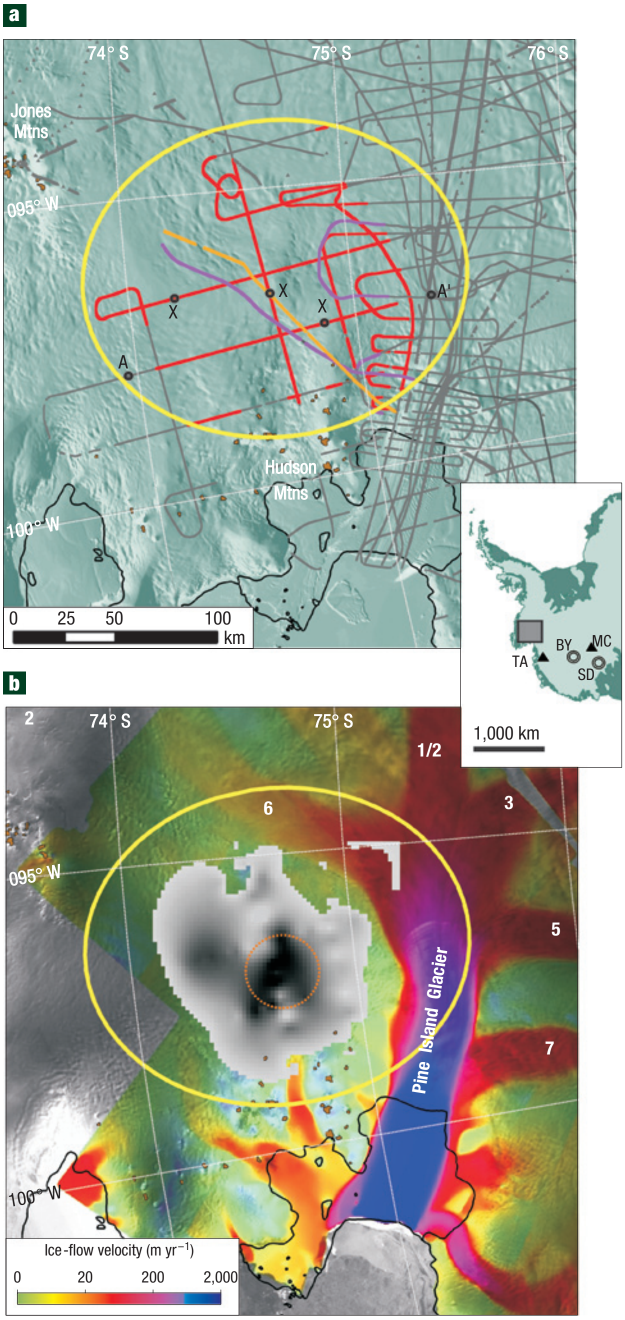

Figure 1 Distribution and interpretation of airborne radar data. The inset shows the location of frames **a** and **b**, and features mentioned in the text. BY, Byrd Station; SD, Siple Dome. Triangles indicate volcanoes: TA, Mount Takahe; MC, Mount Casertz. **a**, Tracks of the airborne radar sorties in the Hudson Mountain region. Grey lines, sorties by British Antarctic Survey (BAS) in 2004/05 (ref. 5) on which the bright internal reflector is absent; coloured lines are sorties on which the bright internal reflector is present (orange, BAS/1981 (ref. 13); purple, NASA and Centro de Estudios Científicos/2001; red, BAS/2004/05). The yellow line shows the elliptical domain in which the layer is present. Rock outcrops, ice-sheet grounding lines and ice-fronts are also shown. The background is a mosaic of Modis images[22]. A–A′ is the segment of flight line shown in Fig. 2, and three points at which the layer-age calculations were made are marked X. **b**, Relative variance in the power of the internal reflection in dB. The background image is a determination of ice-flow velocity from SAR interferometry[16]. Pine Island Glacier tributaries are numbered following ref. 29. The dotted orange line shows the likely location for the eruptive centre, HMSV.

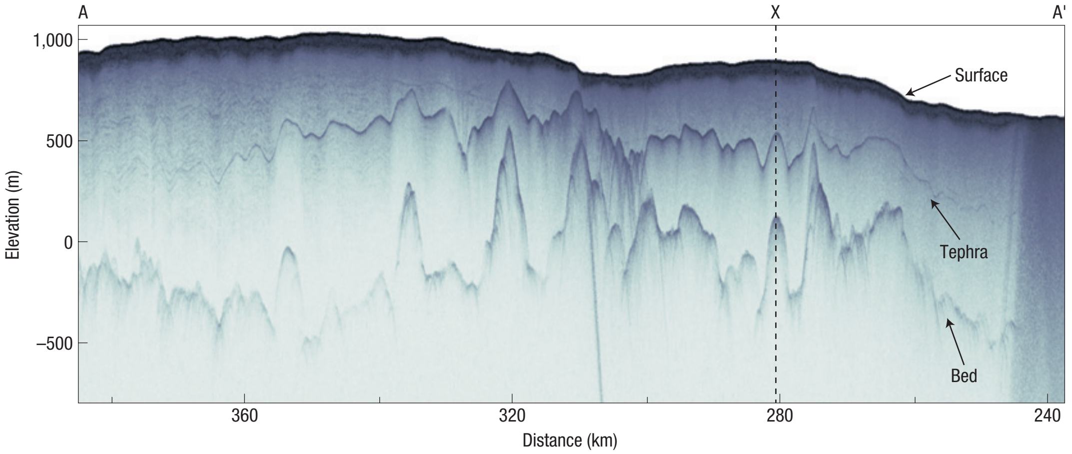

Figure 2 Terrain-corrected radar echogram (vertical exaggeration × 35) for flight segment A–A′ shown in Fig. 1. The dashed line indicates the location of an ice divide: one of the three locations at which the layer age was calculated. Note the visible fading of reflection power towards the edges of the image.

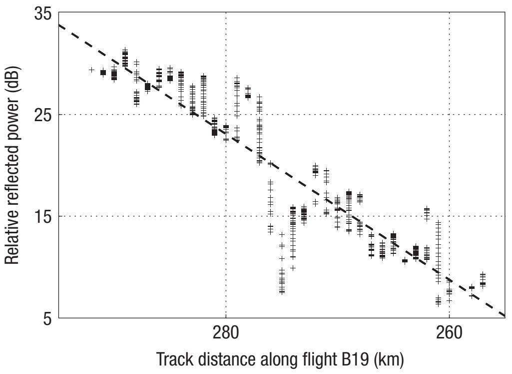

Figure 3 The relative reflected power of the tephra-layer echo for a section of profile A–A′ shown in Fig. 2, calculated for individual radar traces (crosses). The regression line (dashed) shows how the echo amplitude falls by $\sim$50% (6 dB of power) over each 8 km interval. This is taken as the tephra half-distance, b_t. Similar values were obtained from other flight segments.

Such factors need to be addressed in formulating projections of the contribution of this ice sheet to future sea-level rise. More specifically, the proximity of HMSV to Pine Island Glacier, which has shown two abrupt episodes of acceleration in recent decades[27] and is part of a wider area of ice-sheet thinning[28], compels us to consider what effect HMSV has had and is having on ice flow.

Ice-surface and bed topography[5] indicate that if subglacial water were generated near HMSV some of it would drain into Tributary 6 (ref. 29) and then under Pine Island Glacier itself. Water released during the HMSV eruption probably affected the flow of Pine Island Glacier, although if the water release was rapid, as it was in Iceland[23], this may have been transitory.

The depression in the ice surface over Mt Casertz is strong evidence that high geothermal heat flux[1] exists there today. However, the fact that no similar depression exists over HMSV cannot be taken to show that similar conditions do not exist there, because HMSV lies beneath an ice divide and so it is not clear that such a depression should exist. We assert, however, that, given such recent eruptive activity, high geothermal heat flux may exist above HMSV today, and may be delivering subglacial water to Pine Island Glacier. However, Pine Island Glacier lies in a deep subglacial trough[5], and this will isolate its subglacial hydrological system from neighbouring glaciers (Thwaites, Smith and Kohler). Therefore, even if continuous or episodic production of melt water from HMSV affects Pine Island Glacier, there is little likelihood that it could affect these neighbouring glaciers. It is thus possible that volcanic activity over HMSV contributed to some of the recent changes in velocity of Pine Island Glacier[27], but it cannot explain the widespread thinning that has been observed across these glacier basins in recent decades. We follow previous authors[30] in favouring an oceanic driver as the likely cause for these changes.

Received 5 November 2007; accepted 18 December 2007; published 20 January 2008.

References

1. Blankenship, D. D. *et al.* Active volcanism beneath the West Antarctic ice sheet and implications for ice-sheet stability. *Nature* **361**, 526–529 (1993).
2. Behrendt, J. C., Finn, C. A., Blankenship, D. D. & Bell, R. E. Aeromagnetic evidence for a volcanic caldera complex beneath the divide of the West Antarctic ice sheet. *Geophys. Res. Lett.* **25**, 4385–4388 (1998).
3. Vogel, S. W. & Tulaczyk, S. Ice-dynamical constraints on the existence and impact of subglacial volcanism on West Antarctic ice sheet stability. *Geophys. Res. Lett.* **33**, L23502 (2006).
4. Wilch, T. I., McIntosh, W. C. & Dunbar, N. W. Late Quaternary volcanic activity in Marie Byrd Land: Potential Ar-40/Ar-39-dated time horizons in West Antarctic ice and marine cores. *Geol. Soc. Am. Bull.* **111**, 1563–1580 (1999).
5. Vaughan, D. G. *et al.* New boundary conditions for the West Antarctic ice sheet: Subglacial topography beneath Pine Island Glacier. *Geophys. Res. Lett.* **33**, L09501 (2006).
6. Shapiro, N. M. & Ritzwoller, M. H. Inferring surface heat flux distributions guided by a global seismic model: particular application to Antarctica. *Earth Planet. Sci. Lett.* **223**, 213–224 (2004).
7. Winberry, J. P. & Anandakrishnan, S. Crustal structure of the West Antarctic rift system and Marie Byrd Land hotspot. *Geology* **32**, 977–980 (2004).
8. Behrendt, J. C., Blankenship, D. D., Morse, D. L. & Bell, R. E. Shallow-source aeromagnetic anomalies observed over the West Antarctic Ice Sheet compared with coincident bed topography from radar ice sounding—new evidence for glacial "removal" of subglacially erupted late Cenozoic rift-related volcanic edifices. *Glob. Planet. Change* **42**, 177–193 (2004).
9. Winberry, J. P. & Anandakrishnan, S. Seismicity and neotectonics of West Antarctica. *Geophys. Res. Lett.* **30**, 1931 (2003).
10. Welch, B. C. & Jacobel, R. W. Analysis of deep-penetrating radar surveys of West Antarctica, US-ITASE 2001. *Geophys. Res. Lett.* **30**, 1444 (2003).
11. Rowley, P. D., Laudon, T. S., La Prade, K. E. & LeMasurier, W. E. in *Volcanoes of the Antarctic Plate and Southern Oceans* (eds LaMasurier, W. E. & Thomson, J. W.) 289–293 (American Geophysical Union, Washington, 1986).
12. Holt, J. W. *et al.* New boundary conditions for the West Antarctic ice sheet: Subglacial topography beneath Thwaites and Smith glaciers. *Geophys. Res. Lett.* **33**, L09502 (2006).
13. Crabtree, R. D. & Doake, C. S. M. Pine Island Glacier and its drainage basin: Results from radio echo-sounding. *Ann. Glaciol.* **3**, 65–70 (1982).
14. Lythe, M., Vaughan, D. G. & The BEDMAP Consortium, BEDMAP: A new ice thickness and subglacial topographic model of Antarctica. *J. Geophys. Res.* **106**, 11335–11352 (2001).
15. Thomas, R. *et al.* Accelerated sea-level rise from West Antarctica. *Science* **306**, 255–258 (2004).
16. Rignot, E. *et al.* Improved estimate of the mass balance of glaciers draining into the Amundsen Sea of West Antarctica from CECS/NASA 2002 campaign. *Ann. Glaciol.* **39**, 231–237 (2004).
17. Paterson, W. S. B. *The Physics of Glaciers* (Elsevier, Oxford, 1994).
18. Arthern, R. J., Winebrenner, D. P. & Vaughan, D. G. Antarctic snow accumulation mapped using polarization of 4.3 cm wavelength microwave emission. *J. Geophys. Res.* **111**, D06107 (2006).

19. Papale, P. & Rosi, M. A case of no-wind Plinian fallout at Pululagua Caldera (Ecuador)—Implications for models of clast dispersal. *Bull. Volcanol.* **55**, 523–535 (1993).
20. Pyle, D. M. The thickness, volume and grainsize of tephra fall deposits. *Bull. Volcanol.* **51**, 1–15 (1989).
21. Siebert, L. & Simkin, T. *Volcanoes of the World: An Illustrated Catalog of Holocene Volcanoes and their Eruptions* (http://www.volcano.si.edu/world/) (Smithsonian Institution, Washington, 2002).
22. Haran, T., Bohlander, J., Scambos, T., Fahnestock, M. & compilers, *MODIS Mosaic of Antarctica (MOA) Image Map: Digital Media* (National Snow and Ice Data Center, Boulder, 2005).
23. Gudmundsson, M. T., Sigmundsson, F. & Bjornsson, H. Ice–volcano interaction of the 1996 Gjalp subglacial eruption, Vatnajokull, Iceland. *Nature* **389**, 954–957 (1997).
24. *Icelandic Meteorological Office*. <http://hraun.vedur.is/~hs/myndir/vinna/vinna/Grimsvotn_report_November4.doc> (Reykavik, Iceland, 2004).
25. Hammer, C. U., Clausen, H. B. & Langway, C. C. 50,000 years of recorded global volcanism. *Clim. Change* **35**, 1–15 (1997).
26. Kurbatov, A. V. *et al*. A 12,000 year record of explosive volcanism in the Siple Dome Ice Core, West Antarctica. *J. Geophys. Res.* **111**, D12307 (2006).
27. Joughin, I., Rignot, E., Rosanova, C. E., Lucchitta, B. K. & Bohlander, J. Timing of recent accelerations of Pine Island Glacier, Antarctica. *Geophys. Res. Lett.* **30**, 1706 (2003).
28. Shepherd, A., Wingham, D. J. & Mansley, J. A. D. Inland thinning of the Amundsen Sea sector, West Antarctica. *Geophys. Res. Lett.* **29**, 1364 (2002).
29. Stenoien, M. D. & Bentley, C. R. Pine Island Glacier, Antarctica: A study of the catchment using interferometric synthetic aperture radar measurements and radar altimetry. *J. Geophys. Res.* **105**, 21761–21779 (2000).
30. Shepherd, A., Wingham, D. J. & Rignot, E. Warm ocean is eroding West Antarctic Ice Sheet. *Geophys. Res. Lett.* **31**, L23402 (2004).

Acknowledgements

The field campaign received logistical support from the British Antarctic Survey and US National Science Foundation and was conducted in collaboration with the University of Texas. We acknowledge the support from field personnel who assisted us, and discussions from many researchers who improved the manuscript.
Correspondence and requests for materials should be addressed to H.F.J.C.
Supplementary Information accompanies this paper on www.nature.com/naturegeoscience.

Author contributions

H.F.J.C and D.G.V. contributed equally to this work.