LETTERS
nature geoscience
PUBLISHED ONLINE: 26 SEPTEMBER 2010 | DOI: 10.1038/NGEO962

Glacier advance in southern middle-latitudes during the Antarctic Cold Reversal

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During the last deglaciation, warming over Antarctica was interrupted by a return to colder conditions from about 14,540 to 12,760 yr ago. This period, known as the Antarctic Cold Reversal, is well documented in Antarctic ice cores[1], but the geographic extent of the cooling throughout the Southern Hemisphere remains unclear[2]. Here we use ^{10}Be surface-exposure ages from two glacial moraine sets from the Southern Alps, New Zealand, to assess whether the glacier advance was associated with the Antarctic Cold Reversal. We find that widespread glacier resurgence culminated 13,000 years ago, at the peak of Antarctic cooling. Subsequent glacier retreat in the Southern Alps coincided with warming in Antarctica. We conclude that the climate deterioration associated with the Antarctic Cold Reversal extended into the southern mid-latitudes of the southwestern Pacific Ocean. We suggest that the extensive cooling was caused by northward migration of the southern Subtropical Front, and concomitant northward expansion of cold Southern Ocean waters.

New Zealand glacier fluctuations are a proxy for former atmospheric conditions, specifically summer temperature[3] (see Supplementary Note). Glacial landforms document former ice extent and, together with surface-exposure dating, can be used to infer the regional history of atmospheric temperatures. We targeted the exceptionally well-defined Birch Hill moraine complex (44° S, 170° E; Fig. 1), which represents resurgence of an extensive ice tongue, here called the Pukaki glacier. This tongue drained a combination of catchments that today feed four of the largest valley glaciers in New Zealand (Fig. 2). When it stood at the Birch Hill moraines, the Pukaki glacier had a total catchment of 595 km^2. As a test for regional coherence of glacier resurgence, we report ^{10}Be dates of the mid-Macaulay moraine complex, located 50 km northeast of the Birch Hill moraines. The mid-Macaulay moraines were formed by an ice tongue, here called the Macaulay glacier, that drained a catchment of 33 km^2 and that was independent of the Pukaki glacier (Fig. 2). The Birch Hill and mid-Macaulay moraine chronologies incorporate recent analytical improvements[4] with a precise local ^{10}Be production rate[5] resulting in centennial resolution of late-glacial climate events integrated over a total of ~628 km^2 of former ice catchment (Fig. 2).

The Birch Hill moraines lie about two-thirds the distance from the end moraines of the Last Glacial Maximum (LGM) to the present-day glacier termini (Fig. 1; see Supplementary Note). Birch Hill landforms comprise well-defined lateral moraine complexes on both flanks of the Tasman River valley, set against LGM ice-smoothed valley walls with subdued morphology. The strong morphologic contrast between the sharp-crested outermost Birch Hill ridges ('Birch Hill I' (ref. 6); Fig. 1) and the subdued outboard topography implies moraine construction at the culmination of a post-LGM glacier advance (see Supplementary Note). The Birch Hill moraine complex contains an inboard flight of discontinuous moraine ridges ('Birch Hill II' (ref. 6); Fig. 1) that record ~150 m of ice-surface lowering (see Supplementary Note).

The mid-Macaulay terminal moraines lie in the Macaulay River valley, a tributary of Lake Tekapo, midway between the valley mouth and small cirque glaciers at the valley head (Fig. 2; see Supplementary Fig. S2). These prominent, well-defined moraines were formed at the culmination of a post-LGM glacier advance. They have been correlated to the Birch Hill moraines on the basis of geomorphology and valley position[6].

Our chronology consists of 27 high-precision ^{10}Be surface-exposure dates of samples collected from the tops of quartzofeldspathic sandstone ('greywacke') boulders embedded in the Birch Hill and mid-Macaulay moraines (respectively 24 and 3 dates; Supplementary Tables S1 and S2). The dates are based on a precise ^{10}Be production rate measured at a nearby radiocarbon-dated early Holocene debris-flow deposit and verified locally at a nearby radiocarbon-dated LGM moraine set[5]. Of the 27 dates, 15 are from the outermost Birch Hill I right-lateral moraine ridge, and yield a mean exposure age of 12,970 ± 300 yr (arithmetic mean ± standard error of the mean propagated with production-rate uncertainty; see Supplementary Methods, Fig. S4). One age (BH-07-11) plots outside the 99% confidence level (3σ) and is rejected (see Supplementary Methods). Seven dates are from Birch Hill II inboard moraine ridges and afford a mean exposure age of 13,120 ± 300 yr (Supplementary Fig. S4). Thus the ages of the Birch Hill moraine sets are indistinguishable within the ~300 yr uncertainty. Two boulders on a small moraine remnant immediately outboard of the Birch Hill I ridge afford a mean exposure age of 14,090 ± 300 yr, suggesting an earlier phase of moraine construction. Finally, three boulders embedded on the most prominent ridge of the mid-Macaulay terminal moraines yield a mean exposure age of 13,310 ± 290 yr ago (see Supplementary Methods and Supplementary Fig. S4).

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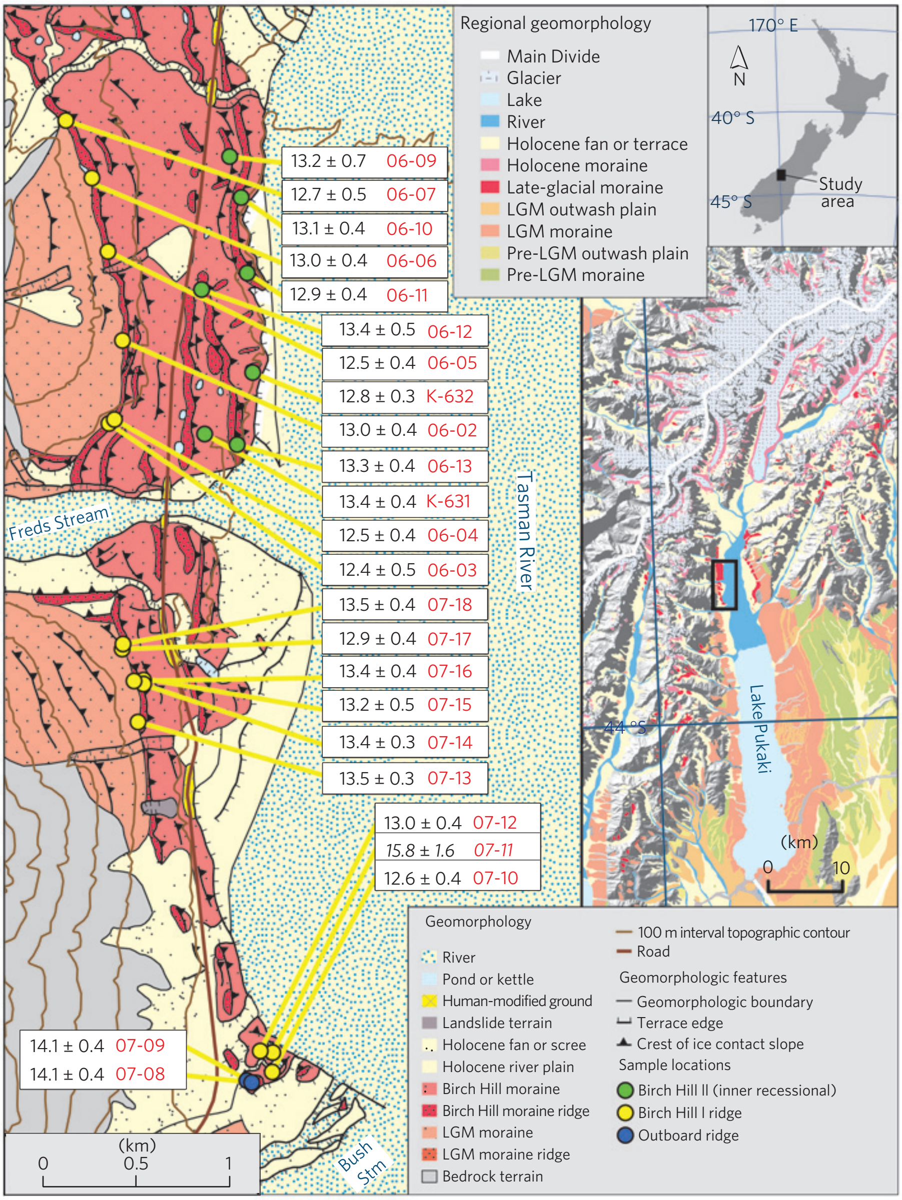

Figure 1 | Detailed glacial geomorphic map of the Birch Hill right-lateral moraine complex. A New Zealand location map and a regional map of the Lake Pukaki region are inset, with the box denoting the extent of the detailed map. Coloured circles show sample locations, annotated with ^{10}Be surface-exposure ages in white boxes (in kyr, errors are 1σ). An outlier age is shown in italics.

Our surface-exposure chronology of the Birch Hill moraines indicates that an advance of the former Pukaki glacier culminated at 12,970±300 yr ago. Within the next few centuries the glacier surface had lowered by at least 150 m, implying a terminus retreat of ~5 km (see Supplementary Methods). These ice-margin fluctuations attest to a positive mass balance of the Pukaki glacier, interpreted most simply as reflecting cooler summer temperatures integrated over its ablating tongue before 12,970 ± 300 yr ago, followed immediately by the onset of a negative mass balance due to the effect of consistently warmer summer temperatures. The age determined for the mid-Macaulay moraines is indistinguishable, within error, from that of the Birch Hill ridges, implying an independent response of the former Macaulay glacier to the same climate signal.

Northwest of the main drainage divide ('Main Divide'), calendar-year converted radiocarbon ages on wood buried beneath till at Canavans Knob document an advance of Franz Josef Glacier over the knob towards the Waiho Loop moraine at ~13,000 yr ago[7,8] (Fig. 2; Supplementary Table S3; Note). When it stood at the Waiho Loop moraine, Franz Josef Glacier drained an ice catchment of at least 85 km^2 (Fig. 2). If interpreted as a response to climatic forcing (see Supplementary Note), the late-glacial expansion of Franz Josef Glacier, taken together with concurrent glacier advances reported here from southeast of the Main Divide, indicates regionally coherent cooling that impacted at least ~715 km^2 of the glaciated Southern Alps and that culminated about 13,000 yr ago (Fig. 2).

The moraine chronology presented here extends the geographic footprint of the Antarctic Cold Reversal (ACR) atmospheric signal from the East Antarctic plateau at 75° S to the central Southern Alps at 44° S in the southwest Pacific region. In both localities, the coldest part of the late-glacial reversal was close to 13,000 yr ago, followed immediately by warming (Fig. 3; Supplementary Table S3). Further evidence for the ACR climate signal in southern mid-latitudes comes from proxy-inferred sea-surface temperatures (SSTs) derived from marine cores situated close to the Subtropical Front (STF) south of Australia at 36° S (ref. 9), in the southeastern Pacific Ocean near Chile at ~41° S (ref. 10), and in the South

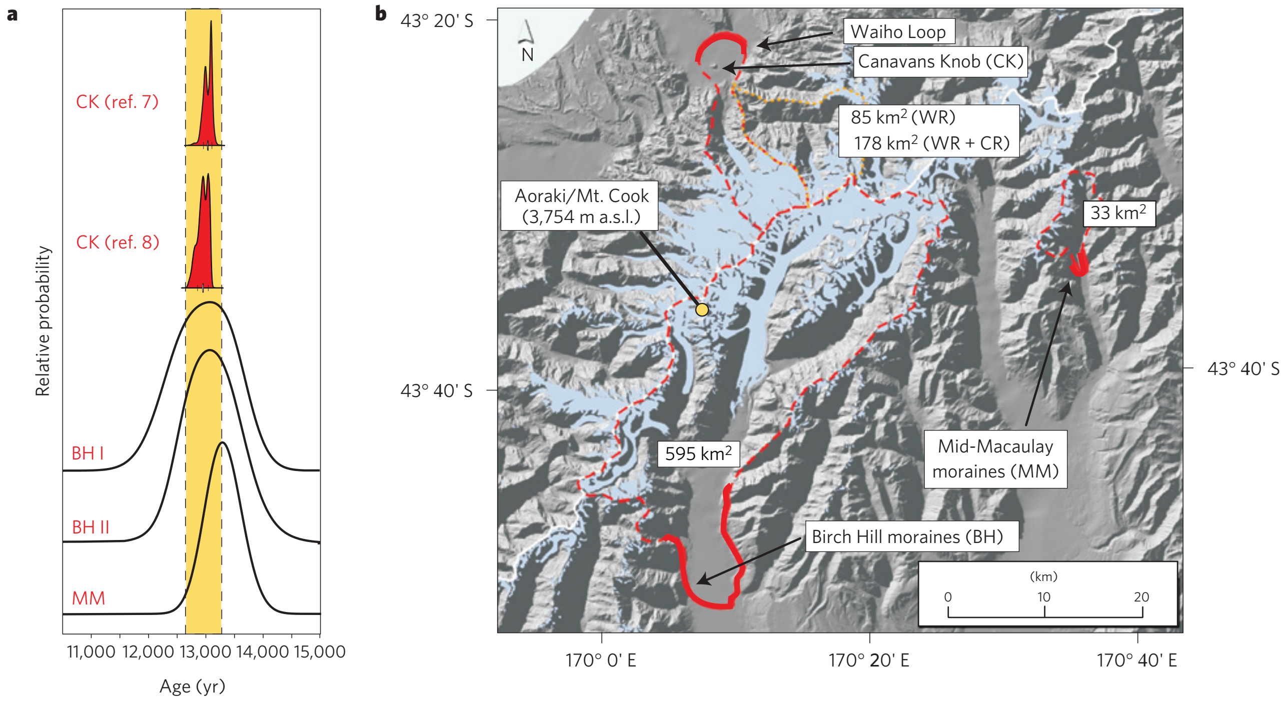

Figure 2 | Central Southern Alps about 13,000 yr ago. a, Summed probability curves of Canavans Knob (CK) radiocarbon dates[7,8] and ^{10}Be surface-exposure ages of the Birch Hill (BH) and mid-Macaulay (MM) moraine sets. Yellow band = arithmetic mean and propagated uncertainty for the Birch Hill I ridge. **b**, Map showing former catchments of Franz Josef Glacier, Pukaki and Macaulay glaciers, when they sat at the Waiho Loop, Birch Hill and mid-Macaulay moraines, respectively. Solid red lines = known ice margins. Dashed red lines = inferred ice-catchment perimeters. Dotted orange line = Callery valley catchment, which may have contributed ice to the Franz Josef Glacier when it produced the Waiho Loop moraine. White boxes = catchment areas. Light-coloured regions = present-day glacier configuration. CR = Callery River. WR = Waiho River.

Atlantic at 41° S (ref. 11) (Fig. 3; Supplementary Table S3). Thus the ACR signature is evident in both atmospheric and oceanic proxies spanning at least ~40° of the southern latitudes.

The timing of the widespread southern cold reversal corresponds in timing with the Greenland ice core signature[12,13] of the Bølling/Allerød (B–A) interstadial, but ended at the onset of the Younger Dryas (YD) stadial (Fig. 3; Supplementary Table S3). Tenable drivers of late-glacial climate change must accommodate widespread synchrony of the ACR in the southern quarter of the globe, as well as asynchrony with North Atlantic climate signals.

First, we consider mechanisms for the contrast in climate between the hemispheres during the ACR/B–A interval. One possibility is that southern cooling during the northern B–A interstadial was due to heat transfer between the hemispheres by an ocean-based bipolar see-saw[14–16]. B–A strengthening of North Atlantic overturning could have increased northward ocean heat transport across the equatorial Atlantic Ocean, leading to cooling in the Southern Ocean[17]. But to explain our data, this mechanism would need to have spread atmospheric cooling from Southern Hemisphere mid-latitudes to Antarctic ice-core sites (1,000–4,000 m a.s.l.). Modelled perturbations to North Atlantic deepwater (NADW) formation produce only gradual, weak and patchy surface air-temperature responses over the Southern Ocean and Antarctica (for example, refs 17,18). Nor is it clear whether changes in NADW will alter the position of the STF, making it difficult to explain the indicated shifts of the STF during the late-glacial period (for example, refs 9–11,19,20) by way of an oceanic bipolar see-saw.

A second possibility is that latitudinal migrations of global wind belts contributed to north–south antiphasing[20,21]. Wind stress within the southern westerly wind belt is considered a major determinant of the location of the STF, and shifts of the locus of the westerlies may induce concomitant migration of the STF (for example, refs 19,20,22). The potential significance of sustained shifts in atmospheric circulation was highlighted in the 1950's by Harrington[23], who pointed out that glaciers in the Southern Alps straddle the boundary zone between the tracks of subtropical highs and Southern Ocean lows associated with the southern westerly wind belt. He recognized that a sustained southward shift of the southern westerlies would decrease the frequency of cold, moist Southern Ocean air masses flowing over the Southern Alps, and that such a phenomenon provides a possible mechanism for glacier retreat in the Southern Alps.

Warm conditions in the North Atlantic during the B–A/ACR could have promoted northward-shifted wind belts in both hemispheres, leading to an expanded polar cell in the south[21]. ACR-like SST signatures at southern mid-latitude sites have been attributed to equatorward movement of the STF (refs 9–11), consistent with northward-shifted westerlies[20]. Reduced upwelling south of the Antarctic Circumpolar Current during the ACR has also been attributed to an equatorward shift of the southern hemisphere westerlies[24]. In the opposite sense, proxy-inferred southward migration of the STF, as well as invigorated Southern Ocean upwelling during the YD (ref. 24), are consistent with a poleward shift of the southern westerly wind belt. In the Southern Alps, the culmination of ice advance 13,000 yr ago and the subsequent rapid ice retreat is compatible with an equatorward expansion, followed by a poleward retreat, of the southern westerlies and STF, possibly attributable to the transition from North Atlantic interstadial (B–A) to stadial (YD) conditions.

The ACR appears to be an expression of an interhemispheric see-saw, but whether this see-saw was primarily oceanic, atmospheric, or both, remains elusive. Northward migration of the STF would enlarge the Southern Ocean, as defined by the position of the

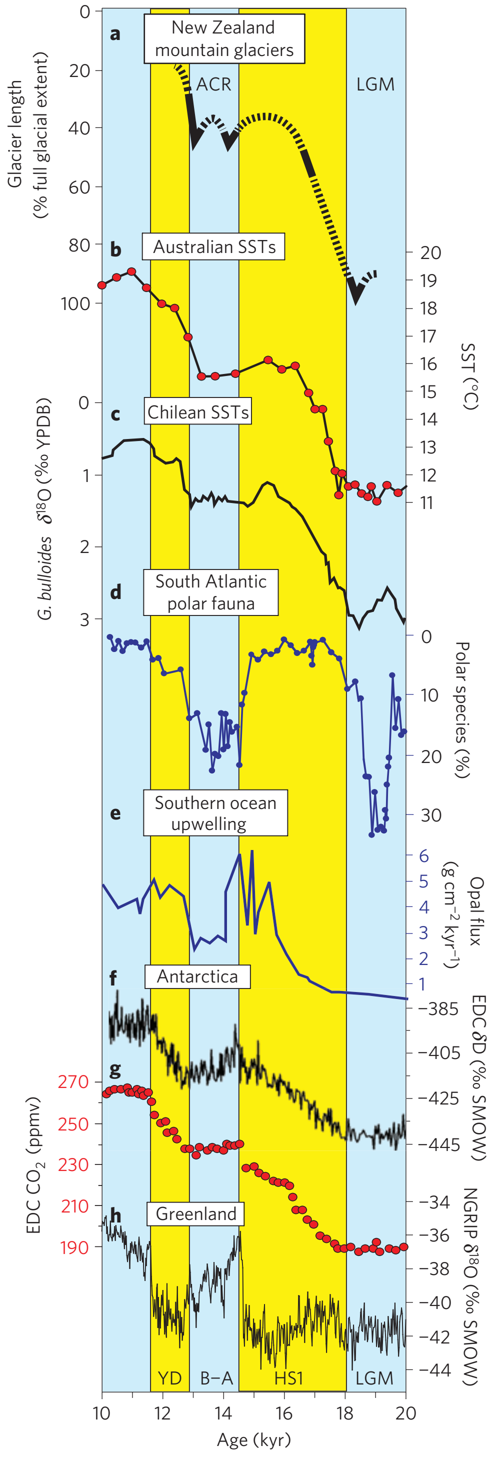

Figure 3 | Deglacial records mentioned in text. a, Time-distance diagram based on Pukaki valley moraines and ^{10}Be surface-exposure chronology (see Supplementary Methods). Bold lines denote where age control exists, dotted lines are interpretations. **b**, South Australian alkenone-derived SSTs from core MD03-2611 (ref. 9). **c**, *Globigerina bulloides* δ^{18}O (water temperatures) from core ODP 1233 (ref. 10). **d**, Cryophilic foraminifera from South Atlantic core TNO57-21 (water temperatures; ref. 11). **e**, Biogenic opal flux (wind-driven upwelling; ref. 24). **f**,**g**, EPICA Dome C ice-core deuterium (Antarctic air temperature; ref. 28) (**f**) and atmospheric carbon dioxide concentrations[28] (atmospheric indicator of Southern Ocean processes[24,29]) (**g**), placed on the NGRIP methane-synchronized timescale of ref. 1. **h**, NGRIP ice-core δ^{18}O (refs 12,13). Yellow bands = YD and Heinrich Stadial-1 (HS1) (ref. 11) periods.

STF, and reduced upwelling offers a mechanism for ocean-surface cooling and expansion of circum-Antarctic sea ice. Such feedbacks could explain the ACR signature in Antarctic ice-core records[20,24–27]. Put simply, we propose that the ACR occurred because the Southern Ocean grew larger and cooler in response to B–A warmth in the North Atlantic region. As a consequence, cooler conditions over New Zealand stimulated glacier growth while interior Antarctica also cooled. The opposite would have occurred at the onset of North Atlantic YD cooling.

On the basis of recent progress in the ^{10}Be surface-exposure dating method, we present a moraine chronology that places the culmination of late-glacial cooling in the Southern Alps between 12,970 ± 300 and 13,310 ± 290 yr ago. Our moraine records show that mid-latitude southwest Pacific deglacial atmospheric warming reversed during the ACR/B–A interval, and that marked warming and glacier retreat resumed at the onset of the YD cold snap in Greenland. Taken together with evidence from marine cores, our results from New Zealand suggest a unified expression of late-glacial climate throughout the ocean and atmosphere of middle and high southern latitudes that was of opposite sign to the B–A/YD oscillation in the North Atlantic region. Of the possible mechanisms that could explain the occurrence of ACR glacier resurgence in New Zealand, we consider that the explanation most compatible with available Southern Hemisphere data, spanning nearly 40° of latitude, is that of interlocked migrations of southern westerlies and the STF. Modulation of southern middle-to-high latitude late-glacial temperatures by such an atmospheric see-saw would have complemented any Southern Ocean cooling by an oceanic see-saw. Continued efforts to map and date precisely the geographical footprint of the ACR will clarify the interhemispheric linkages that ushered Earth's climate from ice-age to interglacial conditions.

Received 22 March 2010; accepted 18 August 2010;
published online 26 September 2010

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Acknowledgements

We thank the Gary C. Comer Science and Education Foundation and the National Oceanographic and Atmospheric Administration for support. D.J.A.B. was supported by Foundation for Research, Science and Technology contract CO5X0701. C.S. was supported by the Swiss National Fund proposal no. 200020-105220/1. This work was partially supported by National Science Foundation awards EAR-0746190 (to R.C.F.), 074571, 0936077, 0823521 (to M.R.K., J.M.S. and G.H.D.). We thank the staff of the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory for their devoted and meticulous work. R. F. Anderson, W. S. Broecker, R. B. Alley, J. D. Hays, G. R. M. Bromley, B. L. Hall, and U. Ninnemann contributed helpful insights. We thank B. Lemieux-Dudon for providing the most recent ice-core chronologies. H. and R. Ivey of Glentanner Station graciously allowed us access to the Birch Hill moraines. We thank the Department of Conservation—Te Papa Atawhai, te Rünanga o Ngäi Tahu for access to the Macaulay valley and inner Birch Hill moraines. This is LDEO contribution no. 7396.

Author contributions

A.E.P. helped design the project, conducted field work and laboratory analyses, and wrote the paper. G.H.D., J.M.S. and C.S. helped design the project and participated in the field work. D.J.A.B. and B.G.A. conducted geomorphic mapping. R.S. carried out laboratory work. A.M.D. participated in the field work. R.C.F. conducted AMS analyses. G.H.D., D.J.A.B., J.M.S., M.R.K., and C.S. helped write the paper.

Additional information

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