A GLACIAL STAGE SPANNING THE ANTARCTIC COLD REVERSAL IN TORRES DEL PAINE (51° S), CHILE, BASED ON PRELIMINARY COSMOGENIC EXPOSURE AGES

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ABSTRACT. Initial cosmogenic ^{10}Be results from a former ice limit in Torres del Paine indicate a short-lived stillstand or readvance of Patagonian ice culminating at 12–15 kyr BP with a mean age of 13.2 ± 0.8 kyr BP. The glacier extended some 40 km beyond the present ice margin and was within 15 km of the presumed Last Glacial Maximum limits. The timing of the glacier stage spans the cooling event recorded in Antarctic ice cores, termed the Antarctic Cold Reversal (14.5–12.9 kyr BP). This result implies that glaciers at these latitudes were out of phase with those in the northern hemisphere; instead they mirrored the climate structure of Antarctica during the last glacial to interglacial transition.

Key words: Antarctic Cold Reversal, South America, Patagonia, Late Glacial, geomorphology, cosmogenic

Introduction

The nature and timing of the last glaciation in central Patagonia remains poorly constrained, yet landforms constitute some of the clearest records of Pleistocene glacial expansion in southern South America (Caldenius 1932; Ferugilio 1949–1950; Mercer 1976; Marden and Clapperton 1995). Past glacier fluctuations provide a proxy record of climatic conditions because ice dynamics are principally controlled by regional precipitation and temperature. As such, improved chronological data from a variety of sites may allow us to distinguish between local and global patterns of environmental change, thus improving our understanding of how the ocean–atmosphere systems of the two hemispheres interact (Denton *et al.* 1999; Clapperton *et al.* 1995; Hubbard 1997).

Background

In his seminal work Caldenius (1932) was able to trace the position of most major moraine systems throughout Patagonia and Tierra del Fuego, By teleconnecting glacial lake varves in Patagonia with the Swedish varve chronology of De Geer (1927 1929), he attempted to construct a temporal framework for these advances. Caldenius attributed the largest moraine limits to late-glacial stadial events, the Finiglacial, Gotiglacial and the Daniglacial. Subsequent work has demonstrated that, although the mapped limits are broadly correct, the chronology is unresolved between regions and individual lobes of the once-expanded Patagonian ice sheet. This is particularly true in the central latitudes of the Patagonian Icefield (45–50°) where considerable disagreement exists (Clapperton *et al.* 1995; Wenzens 1999, 2001, 2003; McCulloch *et al.* 2000; McCulloch and Sugden 2001; Hulton *et al.* 2002). This paper reports the initial results of cosmogenic exposure analyses of erratics located on a late glacial limit in Torres del Paine at 51°S (Fig. 1).

Marden (1993, 1997) identified eight moraine limits or drift stages in Torres del Paine that he related to glacial advances from the Neoglacial to the **Last Glacial Maximum (LGM)**. Of these eight advances, six were ascribed to the Late Glacial and are identified in Fig. 1 as limits A to F, with Limit A being the oldest and Limit F correlated with the Younger Dryas. Chronological control was provided by a combination of absolute and relative dating techniques and in particular the stratigraphic relationships with a dated airfall and pumice tephra from an eruption of Volcan Reclús at 12 638 ± 60 ^{14}C yr BP (14 348–15 507 BP; Mc-

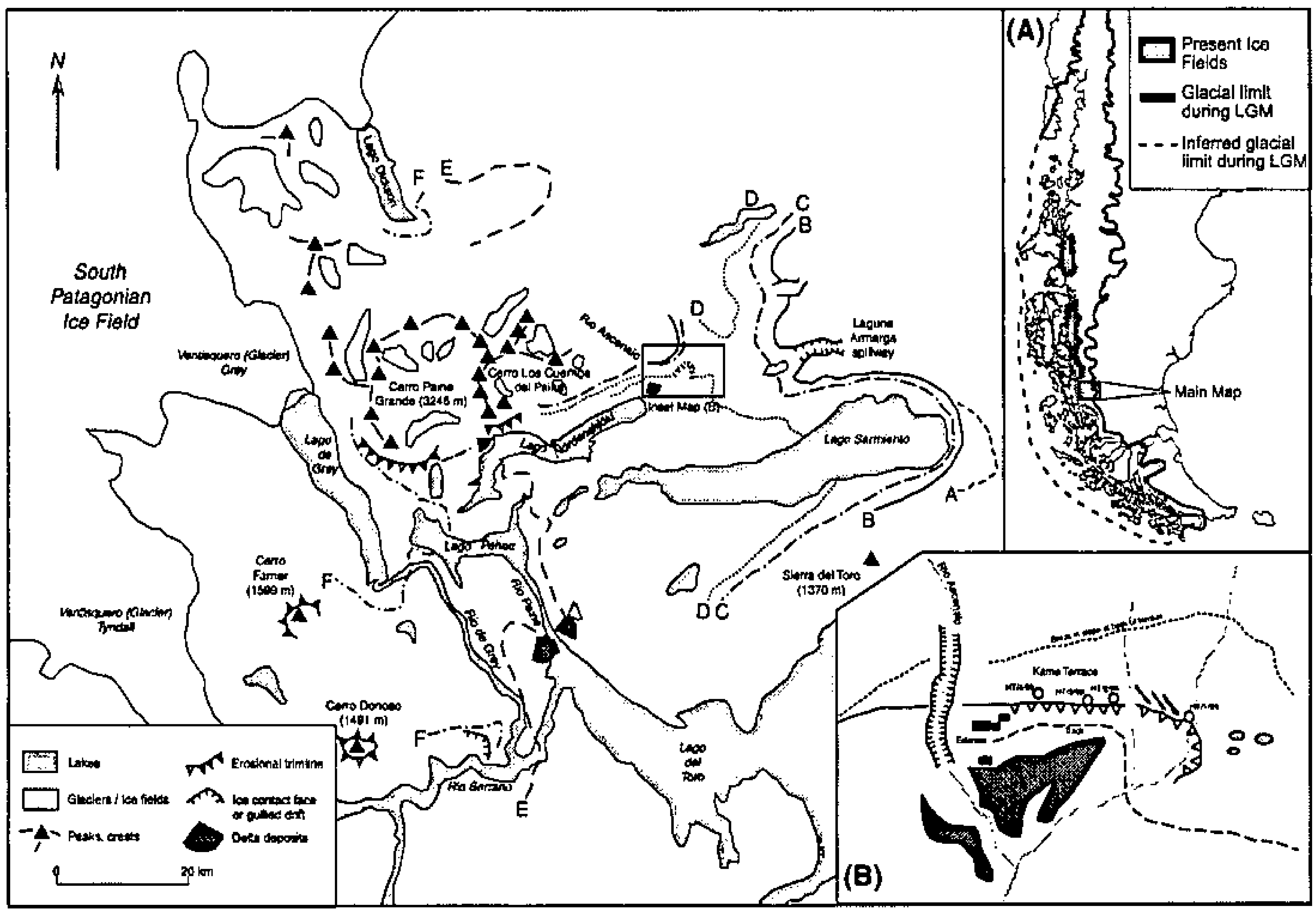

Fig. 1. Ice limits A-F at Torres del Paine (51°S), after Marden and Clapperton (1995). Inset (A) location of Torres del Paine in relation to present and the Last Glacial Maximum extent of Patagonian glaciers. Inset (B) detail of sampling sites at Estancia Cerro Paine (after Marden 1993). The lateral limit extending along the flanks of Cerro Los Cuernos del Paine grades into the ice-contact face and kame terrace described by Marden (1997)

Culloch *et al.* 2005). The chronological control for this tephra comes from minimum and maximum radiocarbon dates from cores located in the Strait of Magellan, over 250 km to the southwest (McCulloch and Davies 2001). Within the Torres del Paine area, the only available chronological control on the Reclús tephra is from radiocarbon-dated organic material just above the tephra itself, providing a minimum age of 9 180 ± 120 ^{14}C yr BP (10 221–10 430 cal yr BP) (Stern 1990). The outer limits (A, B and C) still have no direct dating in Torres del Paine, but they can be correlated with those in the Magellan region where they have been ascribed to the LGM (17–26 kyr) by both radiocarbon dating and cosmogenic exposure dating (McCulloch *et al.* 2005). Around 15 km inside these outer limits Marden (1997) identified evidence of Limit D in two separate valleys (Fig. 1). Clapperton (1993) assigned Limit D to cooling during the final stages of the LGM, at a similar time to Heinrich Event 1 in the North Atlantic and also to advances further north in the Chilean Lake District constrained by inter-till organic layers to 14 550–14 850 ^{14}C yr BP (17 166–18 033 cal yr BP (Denton *et al.* 1999). This paper tests this latter correlation.

The clearest evidence for Limit D is in the vicinity of Estancia Cerro Paine (Fig. 1). A clear lateral moraine descends obliquely towards the mouth of Rio Ascensio. The moraine is an asymmetric ridge *c.* 5 m high with abundant surface boulders. East of the Ascensio valley the ridge merges with a gently sloping terrace falling at an angle of <4° towards the east and with a prominent 30 m escarpment face to the south. The proximal part of the terrace is characterised by small moraine ridges, hummocks, boulders and kettle holes. The escarpment face continues as an arc 2 km east of the estancia buildings. The terrace has been dissected by stream erosion in places. The landform assemblage indicates a former ice marginal position. The presence of kettle holes, hummocks and large boulders along the upper edge of the escarpment slope indicate an ice-contact

Table 1. Cosmogenic radionuclide data and exposure ages, Estancia Cerro Paine, Torres del Paine, Chile

Sample	Elv (m a.s.l.)	Lat.	Long.	Mass of quartz (g)	Carrier (Be(mg)[a]	$^{10}Be/^{9}Be$ ratio (* 10^{-13})[b]	Error (%)[b]
HT/1/99	215	51°02'	72°92'	70.2160	0.50701	2.00	7.0
HT/2/99	215	51°02'	72°92'	47.9444	0.50701	1.49	7.3
HT/3/99	193	51°02'	72°92'	84.9210	0.50701	2.36	8.3
HT/4/99	256	51°02'	72°92'	79.3881	0.50701	2.51	7.0

Shielding correction[c]	Atoms of ^{10}Be[d]	Error) (%)[d]	^{10}Be exposure age (kyr)[e]	Exposure age (kyr)[f]	Mean landform age[g]
0.99	84532	8.3	13.1 ± 1.4	13.4 ± 1.4	13.2 ± 0.8
0.99	76315	9.3	11.8 ± 1.6	11.9 ± 1.6	
0.99	77793	9.5	12.2 ± 1.6	12.4 ± 1.6	
0.99	96530	8.0	14.5 ± 1.6	14.8 ± 1.6	

Note: All samples prepared at the Institute of Geography, School of GeoSciences, University of Edinburgh, and analysed at the AMS accelerator mass spectrometry (AMS) facility of the Paul Scherrer Institute and the ETH Zurich, Switzerland

[a] Carrier addition measured by calibrated pipette.
[b] Reported ratio from AMS measurement, corrected to ETH in-house AMS standards
[c] Depth shielding calculated following the methods outlined in Dunne *et al.* (1999)
[d] Corrected for shielding and laboratory blanks and reported absolute error from AMS analyses.
[e] Calculated using a ^{10}Be production rate of 5.1 ± 0.3 at/g/yr^{-1} and scaled following the methods outlined by Stone (2000), which are a reformulation of those of Lal (1991).
[f] At 1.7 mm/kyr; based on similar studies from Patagonia (M. Kaplan; unpublished data)
[g] Error weighted mean age of this landform with erosion correction for all samples with at an erosion rate of 1.7 mm/kyr

slope. The gently sloping lateral deposit is a kame terrace. The broad accumulation of sediments is a proglacial outwash deposit originating from a glacier terminating at the 30 m escarpment.

Exposure dating

Exposure dating with *in situ* cosmogenic nuclides provides a means of directly measuring the time elapsed since the deposition of an erratic (Gosse and Phillips 2001). Four samples were obtained for cosmogenic exposure dating from erratics on the upper surface of the terrace (Fig. 1). The boulders are composed of quartz diorite and quartz monzonite, with some signs of plucking and striations indicating their former transport at the base of a glacier. They were deposited in close proximity to one another and should provide a close age for the glacier limit. The concentration of ^{10}Be in four boulders was measured in samples taken from the upper few centimetres of their top surfaces. By choosing the largest boulders from those available, any problems related to exhumation or significant coverage by snow or vegetation were minimised. Sampling was restricted to boulders in stable positions to avoid the risk of post-depositional movement. Altitudes were obtained by a hand-held digital altimeter, which was calibrated from known spot heights in the area, and measurements are likely to have an error of ± 10 m.

The isotope ^{10}Be was selectively extracted from the quartz component of the whole rock sample following the standard procedures described by Kohl and Nishizumi (1992) and Ivy-Ochs (1996). The isotope ratios were measured at the PSI/ETH AMS facility in Zurich, Switzerland. For this study the ^{10}Be production rate used is 5.1 ± 0.3 atoms/g(qtz)/yr at 1013.25 hPa air pressure at latitude >60° (Gosse and Stone 2001). The reference production rate was scaled to the latitude and altitude of the site following the methods outlined by Stone (2000). The total production at the site was corrected for attenuation of cosmic radiation due to the thickness of the sample itself and any shielding due to the surrounding topography, following the procedures of Dunne *et al.*, (1999).

In order to provide a realistic age envelope, the ages have been calculated allowing for the effect of surface erosion. Cosmogenic exposure studies on similar lithologies at Lago Buenos Aires (46.5°S), Argentina, suggest a rate of 1.7 mm per 1 000 years is realistic at sites east of the South Patagonian icefields (M. Kaplan, personal communication). This will vary with lithology and environmental conditions and therefore is only a guide to the possible magnitude of the age envelope. The other bound of

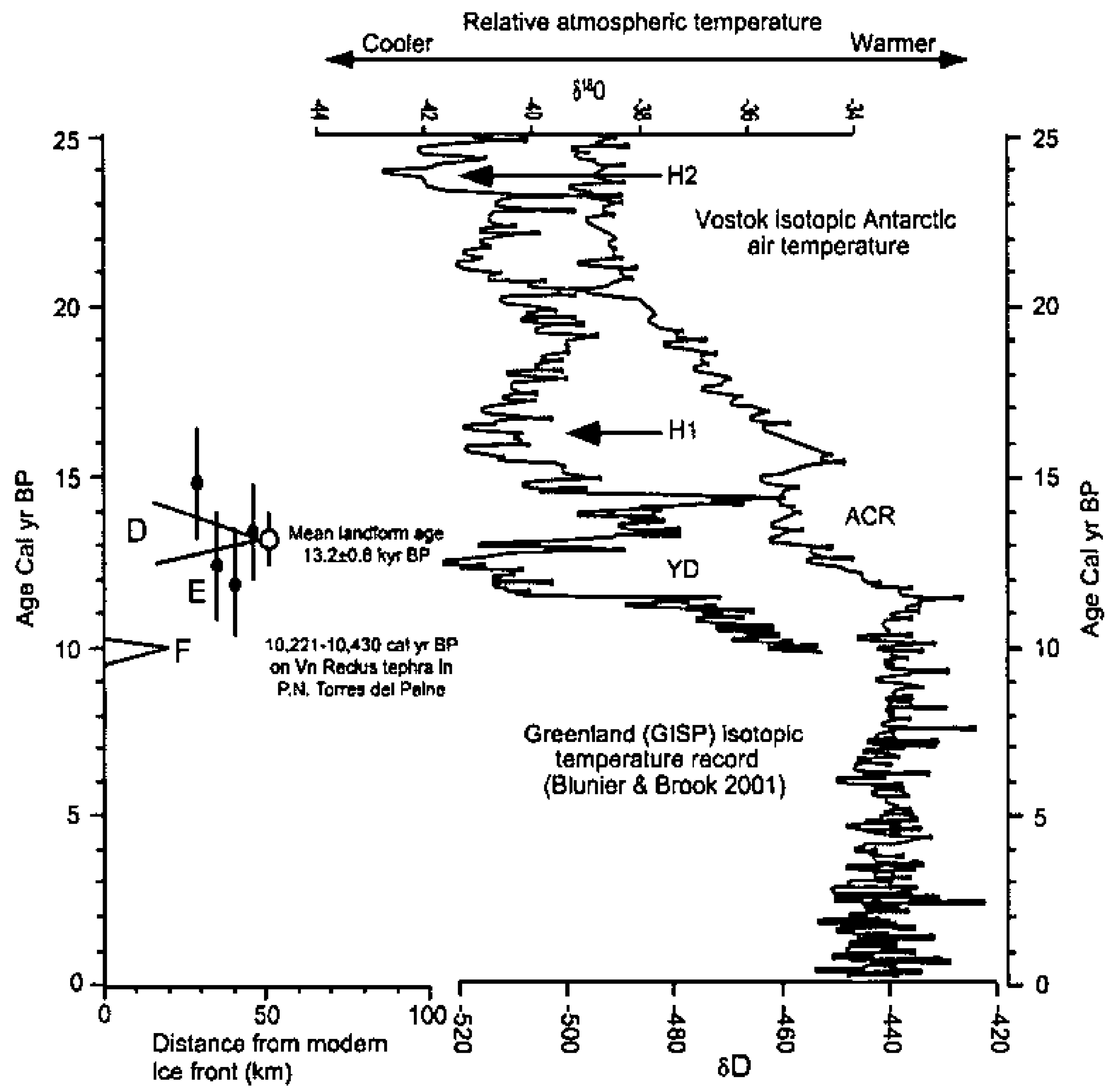

Fig. 2. Exposure ages for Limit D in Torres del Paine plotted against the suggested timing of two eruptions of Volcan Reclús. These data are compared with ice core records of relative atmospheric temperature from GISP II (Greenland) and Vostok (Antarctica) after Blunier *et al.* (1997) and Petit *et al.* (1999). The timing of Heinrich Event 1, the Antarctic Cold Reversal and the Younger Dryas are also highlighted, after Steig *et al.* 1998 and Raynaud *et al.* 2000)

the envelope is constrained by the preservation of some striations, which implies that parts of the erratics have experienced only modest erosion since deposition.

Results

Table 1 lists the cosmogenic ^{10}Be radionuclide data, the location and type of sampling site and the conventional exposure ages of each sample. The AMS analyses indicate that the data set is internally consistent and that the four exposure ages are indistinguishable within 1σ error. Ages vary between 11 900 ± 1 600 and 14 800 ± 1 600 yr BP. This most likely represents a minimum age range if one allows for the effects of surface weathering and temporary shielding by seasonal snow, soils, vegetation or volcanic ash falls. By selecting the largest boulders available, we aimed to minimise the effects of temporary shielding and suggest that it had a negligible effect on the lee side of the Andes, with its low annual precipitation and strong winds throughout most of the year, at least in these latitudes. Surface erosion of 1.7 mm per 1000 years leads to an increase of *c.* 1.8% in the exposure ages. Applying this erosion rate to the boulders of the kame terrace produces ages of 12 000–15 000 yr BP with a mean age of 13 200 ± 800 yr BP.

Discussion

Figure 2 compares the results from this study with regional glacial chronologies and global climate records from both the northern and southern hemispheres. The exposure ages suggest that the glacial stage in Torres del Paine did not coincide with cooling during the final stages of the LGM, as suggested by Clapperton (1993). Rather, allowing for surface erosion, glacier expansion or a stillstand culminated between 12 000 and 15 000 cal yr BP, with a mean age of 13 200 ± 800 cal yr BP. This coincides with the time of general atmospheric warming recorded by a rise in δ^{18}O recorded in the GISP II ice core in Greenland. This suggests that at this latitude glacial expansion was not in phase with atmospheric warming in the northern hemisphere. Rather the timing coincides with and, indeed, overlaps the lower temperatures recorded in Antarctic ice cores, termed the **Antarctic Cold Reversal (ACR)** at 12 700–14 800 yr BP (Raynaud *et al.* 2000; Blunier *et al.* 1997).

Taken at face value, the mean landform age of the four boulders is inconsistent with the presence of the older Reclús tephra (12 638 ± 60 ^{14}C yr BP (14 348–15 507 cal yr BP) in laminated glaci-lacustrine sediments within the ice limit. The exposure ages presented here could be interpreted as being too young in relation to the tephra. There are several possible explanations for such an apparent discrepancy. First, the ages are indistinguishable statistically and it may be that the inherent dating errors are too large to unpick the sequence of deglacial events. Secondly, the cosmogenic exposure ages may be too young as a result of underestimating the amount of shielding or surface erosion, in spite of the use of sampling procedures and analyses to minimise the effects. Thirdly, it may reflect the effect of another as yet unsuspected factor. Perhaps glacio-isostatic recovery has modified the cosmogenic production rate at the site. Such effects are known from exposure studies on the fringes of the former Scandinavian ice sheet (Tschudi *et al.* 2000). If one assumes that the Torres del Paine site has been raised isostatically by 70 m since deglaciation, and the effect is integrated over the exposure period, then the altitudinal change increases the calculated age by almost 1000 years, due to the relationship between cosmogenic nuclide production and altitude.

An alternative line of argument is to suggest that it is the age ascribed to the Reclús tephra that is incorrect. Evidence for a single regional event is based on the correlation of a tephra in Torres del Paine with a geochemically similar tephra that is well dated in cores some 250 km to the south in the Strait of Magellan. The correlation depends on a core taken by Porter, analysed by Stern (1990) within Limit F near the western end of Lago Nordenskjöld (Marden 1997). The lower part of the core contains a tephra which is similar to that in the Strait of Magellan region, dated at 12 638 ± 60 ^{14}C yr BP (McCulloch *et al.* 2005). However, the core in Torres del Paine revealed a minimum date of 9180 ± 120 ^{14}C yr BP from organic material 1 cm above the tephra layer. Thus the possibility exists that the latter tephra is the product of a later eruption occurring just before 9180 ± 120 yr BP. We suspect that this is the most likely explanation of the discrepancy between the cosmogenic exposure ages and the previously assumed age of the tephra.

Conclusions

Our ^{10}Be data provide the first direct dating of a late glacial stage in this sector of the former Patagonian ice sheet. The exposure ages, allowing for surface erosion, suggest that the glacier advance or stillstand culminated after the end of the LGM between 12 000 and 15 000 cal yr BP (mean 13 200 ± 800 cal yr BP), a time when most global climate records, especially in the northern hemisphere, indicate atmospheric and oceanic warming. Instead, the advance or stillstand coincides with the Antarctic Cold Reversal, a cooling event recorded in Antarctic ice cores, and ends during the Younger Dryas. Thus the implication is that this part of southernmost South America was responding to an antiphase Antarctic climatic signal during the Late Glacial.

Acceptance of the exposure ages has led us to suggest a reinterpretation of the age of a tephra from Volcan Reclús present within the sediments and landforms in Torres del Paine. In line with previous age estimates from Torres del Paine itself, we suggest this tephra was deposited immediately prior to 9 180 ± 120 ^{14}C yr BP (10 221–10 430 cal yr BP). There was an earlier tephra from the same volcano which is recorded at sites further south in the Strait of Magellan at 12 638 ± 60 ^{14}C yr BP (15 348–15 507 cal yr BP). This latter tephra is not recorded within the study area of Torres del Paine, probably due to the combination of more extensive ice cover and prevailing wind direction.

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References

Blunier, T., Schwander,J., Stauffer,B., Stocker,T.F., Dällenbach, A., Indermühle, A.,Tschumi, J., Chappelaz, J.,Raynaud, D., *and Barnola, J-M.*, 1997: Timing of the Antarctic Cold Reversal and the atmospheric CO_2 increase with respect to the Younger Dryas event. *Geophysical Research Letters*, 24: 2683–2686.

Caldenius, C.M., 1932: Las glaciaciones cuaternarias en la Patagonia y Tierra del Fuego. *Geografiska Annaler*, 14: 1–164.

Clapperton, C.M., 1993: Quaternary Geology and Geomorphology of South America. Elsevier. 779 p.

Clapperton, C.M., Sugden, D.E., Kauffman, D. and McCulloch, R.D., 1995: The last glaciations in central Magellan Strait, southernmost Chile. *Quaternary Research*, 44: 133–148.

De Geer, G., 1927: Late glacial clay varves in Argentina, measured by Dr. Carl Caldenius, dated and connected with the solar curve through the Swedish time scale. *Geografiska Annaler*, 9.

De Geer, G., 1929: Gotiglacial clay varves in southern Chile, measured by Dr. Carl Caldenius, identified with synchronous varves in Sweden, Finland and the USA. *Geografiska Annaler*, 11.

Denton, G.H., Heusser, C.J., Lowell, T.V., Moreno, P.I., Andersen, B.G., Heusser, L.E., Schlüchter, C. and Marchant, D.R., 1999: Interhemispheric linkage of paleoclimate during the last glaciations. *Geografiska Annaler*, 81A: 107–153.

Dunne, J., Elmore, D. and Muzikar, P., 1999: Scaling factors for the rates of production of cosmogenic nuclides for geometric shielding and attenuation at depth on sloping surfaces. *Geomorphology*, 27: 3–11.

Ferugilio, E., 1949–50: Description geologica de la Patagonia. Buenos Aires, Direccion General Yacimientos Petroloiferos Fiscals. Volumes 1, 2, 3.

Gosse, J.C. and Phillips, F.M., 2001: Terrestrial in situ cosmogenic nuclides: theory and application. *Quaternary Science Reviews*, 20: 1475–1560.

Gosse, J.C. and Stone, J., 2001: Terrestrial cosmogenic nuclide methods passing milestones toward paleo-altimetry. *Transactions of the American Geophysical Union*, 82(7): 81.

Hubbard, A.L., 1997: Modelling climate, topography and palaeoglacier fluctuations in the Chilean Andes, *Earth Surface Processes and Landforms*, 22: 79–92.

Hulton, N.R.J., Purves, R.S., McCulloch, R.D., Sugden, D.E., and Bentley, M.J., 2002: The Last Glacial Maximum and deglaciation in southern South America. *Quaternary Science Reviews*, 21: 323–341.

Ivy-Ochs, S., 1996: The dating of rock surfaces using the in situ produced ^{10}Be, ^{26}Al, and ^{36}Cl, with examples from Antarctica and the Swiss Alps. PhD thesis. Swiss Federal Institute of Technology, Zurich. 196 p.

Kohl, C.P. and Nishizumi, K., 1992: Chemical isolation of quartz for measurement of in situ produced cosmogenic nuclides. *Geochemica et Cosmochemica Acta*, 56: 3583–3587.

Lal, D., 1991: Cosmic ray labelling of erosion surfaces: in situ nuclide production rates and erosion rates. *Earth and Planetary Science Letters*, 104: 424–439.

McCulloch, R.D. and Davies, S.J., 2001: Late-glacial and Holocene palaeoenvironmental change in the central Strait of Magellan, southern Patagonia. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 173: 143–173.

McCulloch R.D. and Sugden, D.E., 2001: Climatic inferences from glacial and palaeoecological evidence at the last glacial termination, southern South America: a reply. *Journal of Quaternary Science*, 16: 291–294.

McCulloch, R.D., Bentley, M.J., Purves, R.S., Hulton, N.R.J., Sugden, D.E. and Clapperton, C.M., 2000: Climatic inferences from glacial and palaeoecological evidence at the last termination, southern South America. *Journal of Quaternary Science*, 15: 409–417.

McCulloch, R.D., Fogwill, C.J., Sugden, D.E., Bentley, M.J. and Kubik, P.W., 2005: Chronology of the last glaciation in central Strait of Magellan and Bahía Inútil, southernmost South America. *Geografiska Annaler*, 87A (2): 289–312

Marden, C.J., 1993: Late Quaternary glacial history of the South Patagonian Icefield at Torres del Paine, Chile. PhD thesis. University of Aberdeen. 298 p.

Marden, C.J., 1997: Late-glacial fluctuations of the South Patagonian Icefield, Torres del Paine National Park, southern Chile. *Quaternary International*, 38/39: 61- 68.

Marden, C.J. and Clapperton, C.M., 1995: Fluctuations of the South Patagonian Icefield during the last glaciation and the Holocene. *Journal of Quaternary Science*, 10: 197–210.

Mercer, J.H., 1976: Glacial history of southernmost South America. *Quaternary Research*, 6: 125–166.

Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J.M., Basile, I., Bender, M., Chapellaz, J., Davis, J., Delaygue, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V., Lorius, C., Pépin, L., Ritz, C., Saltzman, E. and Stievenard, M., 1999: Climate and armospheric history of the past 420 000 years from the Vostok ice core, Antarctica, *Nature*, 399: 429–436.

Raynaud, D., Barnola, J-M., Chappellaz, J., Blunier, T., Indermühle, A. and Stauffer, B., 2000: The ice record of greenhouse gases: a view in the context of future changes. *Quaternary Science Reviews*, 9, 17–00.

Steig, E.J., Brook, E.J., White, J.W.C., Sucher, C.M., Bender, M.L., Lehman, S., Morse, D.L., Waddington, E.D. and Clow, G.D., 1998: Synchronous climate changes in Antarctica and the North Atlantic. *Science*, 282: 92–95.

Stern, C.R., 1990: Tephrochronology of southernmost Patagonia, *National Geographic Research*, 6: 110–126.

Stone, J.O., 2000: Air pressure and cosmogenic isotope production. *Journal of Geophysical Research*, 105: 23,753–23,759.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.W., Hughen, K.A., Kromer, B., McCormac, F.G., v.d. Plicht, J. and Spurk, M. 1998: INTCAL98 radiocarbon age calibration, 24 000–0 cal. BP. *Radiocarbon*, 40: 1041–1083.

Tschudi, T., 2000: Surface exposure dating: a geologist's view, with examples from both hemispheres. PhD thesis. Swiss Federal Institute of Technology, Zurich. 125 pp.

Wenzens, G., 1999: Fluctuations of outlet and valley glaciers in the southern Andes (Argentina) during the past 13 000 years. *Quaternary Research*, 51: 238–247.

Wenzens, G., 2001: Climatic inferences from glacial and palaeoecological evidence at the last termination, southern South America: comment. *Journal of Quaternary Science*, 16: 291–294.

Wenzens, G., 2003: Comment on: The Last Glacial Maximum and deglaciation in southern South America. *Quaternary Science Reviews*, 22: 751–754.

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