Glacial dynamics in southernmost South America during Marine Isotope Stage 5e to the Younger Dryas chron: a brief review with a focus on cosmogenic nuclide measurements

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ABSTRACT: The timing of major glacial changes between Marine Isotope Stage (MIS) 5e and the Younger Dryas chron (YD) in southern South America is reviewed. Focus is placed on studies that use cosmogenic nuclide measurements. However, other dated records and modelling results are also discussed to provide the broader glacial geological context. Limits on the state of glacial geologic knowledge are examined and suggestions are made as to how some of these can be addressed in future studies. Studies show that on the east side of the Andes at Lago Buenos Aires (45° S) there is evidence indicating that following a MIS 6 glaciation ice was less extensive during MIS 4 than MIS 2. In contrast, on the west side of the Andes in the Chilean Lake District area, MIS 4 ice may have been more extensive than during MIS 2. Although Patagonia experienced an MIS 2 glaciation broadly in phase with that in other areas around the globe, there are differences in glacial histories between areas on millennial timescales. Climate reversals are evident in many records between ca. 17 and 10 ka. The timing of such Lateglacial activity, which included less extensive advances than during the local Last Glacial Maximum (LGM), varies somewhat between areas. This could be due to the relative influence of middle- to high-latitude climatic regimes. At present, chronological uncertainties prevent confident assignment of cosmogenic ages for glacial events at the millennial timescale and defining associated climate variability between different study areas.

KEYWORDS: Last Glacial Maximum; South America; climate change; surface exposure dating; GCM modelling.

Introduction

The purpose of this paper is to discuss briefly the knowledge of glacial fluctuations during Marine Isotope Stage (MIS) 5e to the Younger Dryas chron (YD) in southernmost South America (Fig. 1). Rather than summarise all prior research efforts to date, the focus here is on glacial geological records. Furthermore, to distinguish this paper from recent reviews of a similar nature (e.g. Heusser, 2003; Coronato *et al.*, 2004a,b; Harrison, 2004; Rabassa *et al.*, 2005), we focus on those studies that used cosmogenic nuclide measurements, although exceptions are made to help place such efforts in a broader context. Lastly, some outstanding problems are discussed, specifically those due to current limitations or uncertainties ('roadblocks') in the techniques of surface exposure measurements.

Early work (pre-1980 or pre-accelerator mass spectrometry (AMS) technology) recognised that southern Patagonia was unique in terms of the Quaternary geological record because a variety of dating approaches could be applied (Mercer, 1983). Basaltic lava flows interbedded with the glacial drift and landforms allows the application of K–Ar or ^{40}Ar/^{39}Ar, ^{14}C, cosmogenic nuclide and optically stimulated luminescence (OSL) techniques (Rabassa *et al.*, 2000, 2005). As discussed in detail below, ^{10}Be, ^{3}He, ^{26}Al and ^{36}Cl measurements have been valuable in dating directly individual moraines and landforms, adding a different and complementary approach to the (largely) 'stratigraphic-based' dating techniques (e.g. radiocarbon). For convenience, the discussion is separated into the glacial history from MIS 5e to MIS 2, during MIS 2 or the local Last Glacial Maximum (LGM), and the Lateglacial (i.e. 17–10 cal. ka) intervals. The term 'local LGM' is used for the last major glaciation in Patagonia unless otherwise noted, which occurred during MIS 2, but it may be distinct from the 'global' (ice sheet) Last Glacial Maximum (LGM) (Mix *et al.*, 2001).

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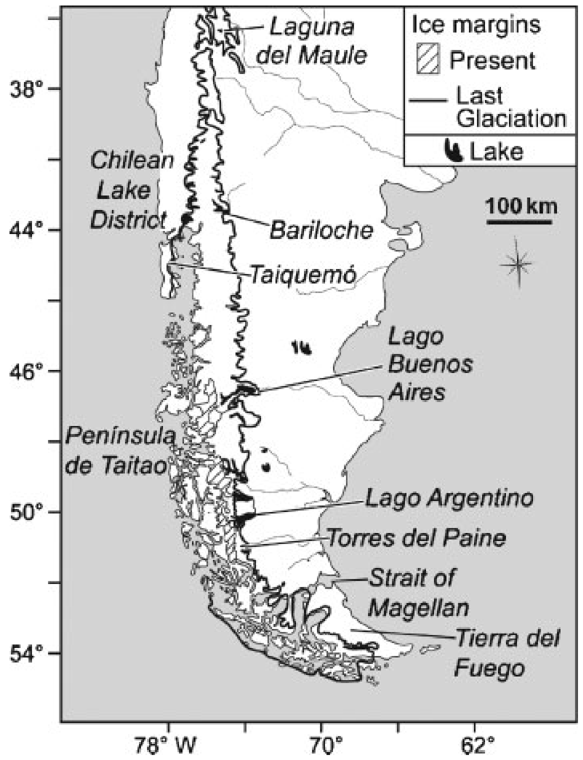

Figure 1 Southern Patagonia and sites mentioned in the text (also see Fig. 7)

Glacial history

MIS 5e to 2 (ca. 128–28 ka)

There is limited knowledge about the glacial and climate history during MIS 5e, 4 and 3, as in other regions around the world. This is due to (1) poor or a lack of preservation of relevant deposits and (2) the ca. 35 ^{14}C ka limit of radiocarbon dating. Although pre-MIS2 moraines and landforms have been a focus of numerous comprehensive investigations (e.g. Coronato *et al.*, 2004a,b; Rabassa *et al.*, 2005), a lack of quantitative data has prohibited confident assignment of ages to many of the associated deposits (Clapperton, 1993). Two records that do provide quantitative age data and valuable insight into southern Patagonian glacial conditions between MIS 5e and 2 are in the southern Chilean Lake District/Isla Grande de Chiloé (CLD/IGC, 40–42° S) (Denton *et al.*, 1999; Heusser, 2003) and around Lago Buenos Aires (LBA) (Kaplan *et al.*, 2004, 2005; Singer *et al.*, 2004; Douglass *et al.*, 2006).

Based on a radiocarbon-dated pollen and sediment record from the Taiquemó site (IGC), Heusser *et al.* (1999) and Heusser and Heusser (2006) reconstructed palaeotemperatures and inferred environmental conditions from ca. 60 to 10 ka (Fig. 2). The basal age of the Taiquemó core is assumed to be beyond the limit of radiocarbon dating. Below the prominent LGM section of the core, interglacial conditions are not again encountered. In addition, there is no evidence for hiatuses in the core. These findings led Heusser *et al.* (1999) and Denton *et al.* (1999) to infer that the base of the core was MIS 4 in age, and thus also the nearby moraines, locally termed the 'outer Llanquihue deposits'. Although the terminal positions of the ice margins through much of MIS 3 or 'middle Llanquihue time' are unknown, unweathered till or outwash in stratigraphic sections in the CLD, beneath radiocarbon-dated levels, could be due to glacial advances between MIS 4 and the LGM (Denton *et al.*, 1999). Late MIS 3 advances in the CLD are dated to 29 400 and 26 800 ^{14}C a BP (~35 and 32 ka, respectively; Fairbanks *et al.*, 2005). It is important to note that the MIS 2 moraines are less extensive than the inferred MIS 4 drift limit. This finding, if correct, indicates that on the north-west side of the Patagonian Andes MIS 4 glaciers were more extensive than during MIS 2. This conclusion, however, is based only on a minimum age limit provided by a single core, the chronology for which is derived from extrapolation beyond the limits of the radiocarbon technique (Fig. 2).

The first quantitative direct dating (i.e. non stratigraphic-based) of pre-LGM or MIS2 moraines in southern South America was undertaken at LBA (~46° S; Kaplan *et al.*, 2004; Douglass *et al.*, 2006) (Fig. 3). Previously, stratigraphic-based dating had provided age constraints for the pre-LGM landforms

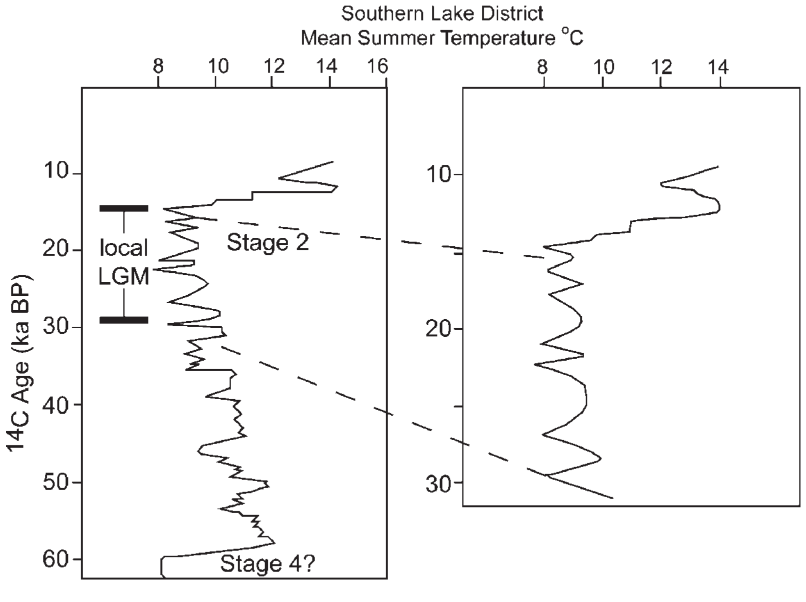

Figure 2 Palaeotemperatures in the Lake District of Chile (CLD) from Heusser *et al.* (1999) and Denton *et al.* (1999). *Y*-axis scale is in ^{14}C a BP. The record is from the Taiquemó core. Below the Holocene section, no interglacial material or pollen is observed again down-core, leading to the conclusion that the basal sediments are MIS 4 in age. Full-glacial or near-full-glacial conditions existed from ca. 29 400 to 14 550 ^{14}C a BP, and the duration of the inferred local LGM is shown (Denton *et al.*, 1999)

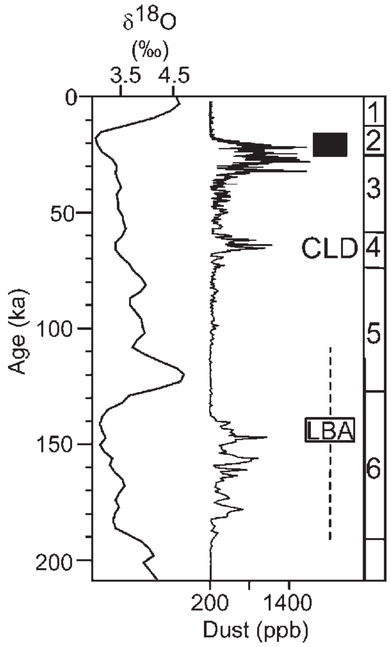

Figure 3 Records of glacial events in Patagonia for the last 200 ka compared with changes in the Northern Hemisphere ice sheets (i.e. $\delta^{18}O$; Shackleton *et al.*, 1990) and EPICA dust concentration (EPICA, 2004). MIS 6 to 1 labelled on the right side. The dust has been isotopically fingerprinted to a Patagonian source with peak concentrations possibly corresponding to windblown material produced during glacial maxima (Basile *et al.*, 1997). For LBA, for MIS 6 time the dashed line reflects the entire possible age range obtained for the two moraines, ca. 190–109 ka, and the best age estimate for the glaciation is 150–140 ka (Kaplan *et al.*, 2005). For MIS 4, a glacial event is inferred for the CLD, but not for LBA. Peak dust concentrations in Antarctic ice imply that ice was active during MIS 4 time, but at LBA it was less extensive than that during MIS 2. The finding for LBA is the opposite of that for the CLD (Heusser *et al.*, 1999). The MIS 2 glaciation, which is found throughout Patagonia, is represented by the black rectangle

in this area and elsewhere (Heusser, 2003; Coronato *et al.*, 2004; Singer *et al.*, 2004; Rabassa *et al.*, 2005). The evidence indicates that a major glacial advance occurred during MIS 6 with a best age-estimate of ca. 150–140 ka (Kaplan *et al.*, 2004; Douglass *et al.*, 2006). Subsequently, the next major glaciation occurred during the LGM or between ca. 23 and 16 ka (Douglass *et al.*, 2006). Wenzens (2006) questioned the findings at LBA, specifically the documented stratigraphic relations between lava flows and cosmogenic ages. Also, he inferred ages for the glacial deposits based on geomorphic arguments and *a priori* correlations to other field sites. His concerns were addressed in Kaplan *et al.* (2006a), who provided additional field relation data and also pointed out that Wenzens (2006) provided no reason for invalidating the cosmogenic-based results.

On the east side of the Patagonian Andes, glacial deposits dating to MIS 4 are not found at LBA. However, Antarctic ice cores show a distinct peak in glacial-age dust concentration at ca. 75 ka (Fig. 3), which has a Patagonian Sr, Nd and Pb isotope signature (Basile *et al.*, 1997; Petit *et al.*, 1998). Based on the ice core data, Kaplan *et al.* (2005) inferred that a major MIS 4 glacial advance or event occurred at LBA, but was obliterated by the more extensive MIS 2 glacial advances. Alternatively, it is possible that increased aridity, wind strength or changing fluvial processes, without a glacial advance, could cause the Antarctic dust peak. Nonetheless, on the east side of the Andes at ~46° S, MIS 6 ice was larger than that during MIS 2, which were both more extensive than that during MIS 4. The findings at LBA are of particular interest in comparison to those in the CLD on the north-west side of the Patagonian Andes, 850 km farther north, where it was inferred that the MIS 4 ice sheet was more extensive than the MIS 2 moraine belts.

MIS2 or local LGM (ca. 28–16 ka)

Much inquiry has focused on glacial activity during MIS 2, in part due to the ability to apply radiocarbon and cosmogenic nuclide techniques. The highest concentrations of data are in the CLD/IGC (Denton *et al.*, 1999), at LBA (Singer *et al.*, 2004; Kaplan *et al.*, 2004, 2005; Douglass *et al.*, 2006) and in the Magallanes/Tierra del Fuego area (Fig. 5; e.g. McCulloch *et al.*, 2000; Heusser, 2003; Coronato *et al.*, 2004b; Sugden, 2005). In addition, numerous studies have been carried out elsewhere. These are summarised, for example, in Heusser (2003), Harrison (2004) and Coronato *et al.* (2004a).

The findings in the CLD are primarily presented and reviewed in Denton *et al.* (1999), including work by Bentley (1997) and Lowell *et al.* (1995). Denton *et al.* (1999) summarised that full-glacial or near-full-glacial conditions persisted from ca. 29 400 to 14 550 ^{14}C a BP, with well-defined advances during that interval (Fig. 5). Mean summer temperature was depressed 6–8°C compared to modern values during the coldest phases, thought to be contemporaneous with the major glacial advances into the outer moraine belt. The maximum at 22 300–22 600 ^{14}C a BP was probably the most extensive of the LGM in the northern part of the CLD, whereas that at 14 800–14 900 ^{14}C a BP was the most extensive in the IGC. The equilibrium line altitude (ELA) depression during these maxima was about 1000 m (Denton *et al.*, 1999).

Studies in LBA revealed five MIS 2 moraines that formed between ca. 23 and 16 ka (Figs. 3 and 5) (Kaplan *et al.*, 2004; Douglass *et al.*, 2006). Subsequently a lake formed, which was followed by a glacial readvance. The maximum extent of glaciation was ca. 23 ka (Fenix V) although it is highlighted that the subsequent advance (Fenix IV) was of a similar extent. Modelling simulations provided a 'best-fit' ELA depression of ~900 m compared to present in order to drive the maximum ice extent to Fenix V (Hubbard *et al.*, 2005).

The Strait of Magellan region (~52–54° S) has a long history of study (Nordenskjöld, 1899; Caldenius, 1932; Meglioli, 1992; Porter *et al.*, 1992; Clapperton *et al.*, 1995; Jackofsky *et al.*, 2000; McCulloch *et al.*, 2000; Heusser, 2003; Coronato *et al.*, 2004a; Sugden, 2005). Recent efforts around the Magallanes region have focused on refining the chronology of events during the local LGM and deglaciation (Fig. 4; Sugden, 2005; Kaplan *et al.*, 2008). The local LGM occurred broadly between ca. 25 and 17 ka (McCulloch *et al.*, 2005; Kaplan *et al.*, 2008). The former age is based on cosmogenic nuclide data and the latter on radiocarbon data. The most extensive ice front occurred at ca. 25 ka. Subsequently, overall glacial retreat was limited until ca. 20 ka. The ice front retreated and ice surface lowered before the last major set of moraines were built, prior to 17 ka (Benn and Clapperton, 2000; McCulloch *et al.*, 2005; Kaplan *et al.*, 2008).

Other areas in southernmost South America where research has focused, but where the quantitative age data are not as extensive as the above regions, include Torres del Paine, Lago Argentino and adjacent valleys to the north, San Carlos de Bariloche and Laguna del Maule (Caldenius, 1932; Rabassa and Clapperton, 1990; Clapperton, 1993; Marden and Clapperton, 1995; Singer *et al.*, 2000; Coronato *et al.*, 2004a; Wenzens, 2005). In the Laguna del Maule area (Fig. 5), Singer

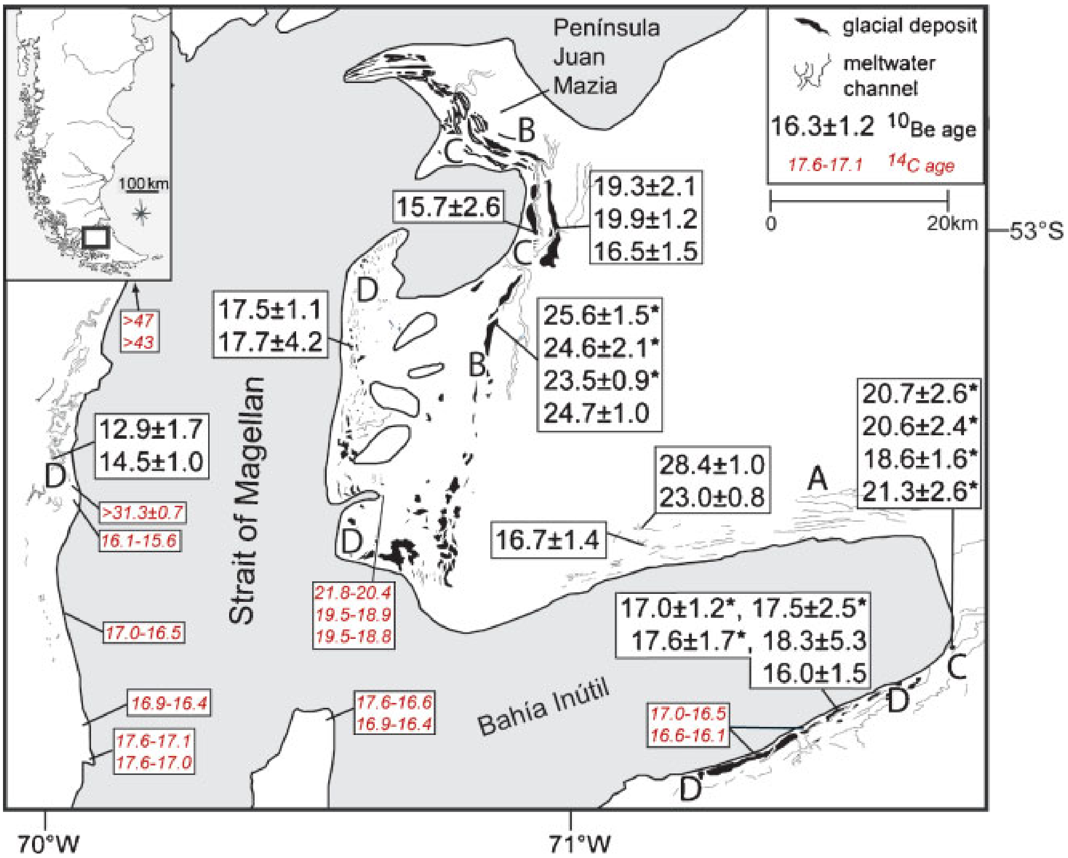

Figure 4 ^{10}Be and ^{14}C chronology from the Strait of Magellan and Bahía Inútil along with mapping of glacial deposits (from Kaplan *et al.*, 2008, and McCulloch *et al.*, 2005). Ages with asterisk are from McCulloch *et al.* (2005). The ^{10}Be ages are used in Fig. 5 and they are calculated using the CHRONUS Calculator (Balco *et al.*, 2008; hess.ess.washington.edu/math/). Note that ^{14}C data indicate deglaciation of the marine embayments by ca. 17.6–17.0 cal. ka (at 1σ; see McCulloch *et al.*, 2005, and Heusser, 2003, for summaries of ^{14}C chronologies). Taken at face value, the ^{10}Be and ^{14}C data suggest an advance soon after 18 cal. ka, followed rapidly by deglaciation, a conclusion consistent with evidence in the CLD. This figure is available in colour online at www.interscience.wiley.com/journal/jqs

et al. (2000) documented a glacial advance and retreat between 25.6 and 23.3 ka, which represents the maximum snowline (i.e. 0°C isotherm) depression at that site since ca. 30 ka.

In summary (Fig. 5), recent studies have refined the conclusions of Clapperton and Seltzer (2001) that the LGM was broadly synchronous across Patagonia and with the 'global' ice sheet LGM (Mix *et al.*, 2001). Although all areas experienced 'local LGMs' between ca. 30 and 16 ka, it is possible to recognise millennial-scale variability between the records in terms of glacial events, a topic that is returned to below. It is emphasised that while some of the records rely on stratigraphic-based dating (e.g. CLD/IGC), however, other records rely on landform-based dating (e.g. LBA). Thus, even if two areas responded to the climate forcing, it should not be expected that all of the glacial events documented in one area are observed in the other area. For example, a glacial advance at ca. 28 ka, as documented in the stratigraphic record from the CLD, may have occurred at LBA but it is not preserved in the landform record.

Modelling of local LGM ice and climate

Modelling studies of the entire Patagonian ice sheet or segments have provided valuable insight into former glaciological behaviour, including a 'translation' of the mapped/dated record of glacial fluctuations into a range of possible ELAs and temperature (and precipitation) forcing conditions. Using a glacier–climate model, Hulton *et al.* (2002) found that a ~6°C temperature depression (cf. Denton *et al.*, 1999) could explain the growth and maintenance of the entire Patagonian ice sheet. They also found that a slight drying was required in the southern Patagonia area to match the mapped LGM margins, whereas increased precipitation (in addition to temperature depression) could have occurred in northern Patagonia (also see Sugden *et al.*, 2002). Glasser and Jansson (2005) reconstructed 'models' of former outlet glacial lobes along the Andes based on mapping and chronological studies available. This study outlined the role of former low gradient ice within the Patagonian ice sheet and provided insight into the style and dynamics of glaciation during the local LGM and, by inference, during earlier intervals. They concluded that fast-flowing outlet glaciers would have strongly influenced ice discharge patterns and suggested a partial decoupling of the Patagonian ice sheet from climatically induced glacial changes.

Modelling experiments that focused on specific parts of the former Patagonian ice sheet include Hubbard (1997) and Hubbard *et al.* (2005), which studied the CLD and LBA ice lobes, respectively. In the former study, a depression of ~1000 m relative to present could simulate the mapped ice extent (with no precipitation taken into account). In the latter study, it was found that at the maximum extent, roughly to the limits shown by moraines, an ELA depression of ~900 m reached the 'best fit' in terms of the geological record. Hubbard *et al.* (2005) then scaled the former ELA record to the Vostok palaeotemperature record (Vimieux *et al.*, 2002), for the period 23–17 ka; a modelled ELA depression fluctuated between ~950

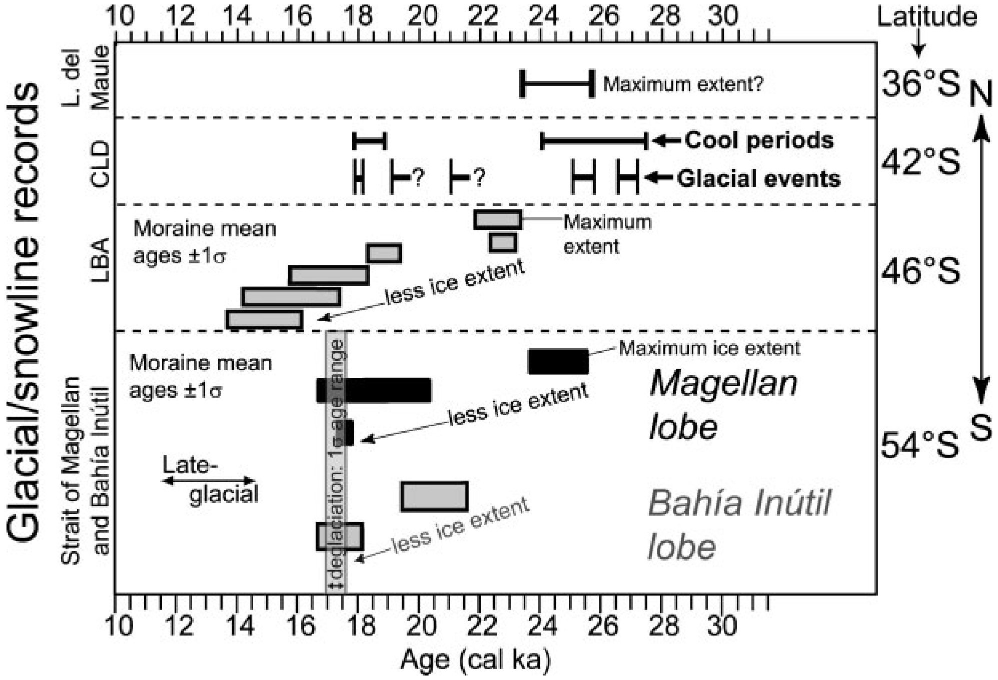

Figure 5 Summary of glacial (i.e. a proxy for snowline change) and palaeoclimatic records spanning the local LGM in southern South America. Shown are the glacial record at Laguna del Maule (Singer *et al.*, 2000), glacial advances and cool periods in the Chilean Lake District (CLD) (Denton *et al.*, 1999, Heusser *et al.*, 1999; Moreno *et al.*, 1999; Moreno, 2002; calendar ages based on Calib 5.02 (Reimer *et al.*, 2004) and Fairbanks *et al.*, 2005), moraine ages at LBA (Douglass *et al.*, 2006; Kaplan *et al.*, 2004), and chronology of moraines and deglaciation in the Strait of Magellan and Bahía Inútil (McCulloch *et al.*, 2005; Kaplan *et al.*, 2008). In the northern and southern parts of the CLD/IGC region, the maximum ice extent was during the first and last advances, respectively. For LBA, grey bars indicate mean moraine ages at one standard deviation. For the purposes of this paper, it does not matter if weighted means are used, as in Douglass *et al.* (2006). In addition, 1σ uncertainty is shown based on analytical uncertainties, in comparison to that in Douglass *et al.* (2006), to highlight the relative differences in moraine ages within the area. For example, the technique can clearly be used to distinguish the oldest two moraines from the younger three moraines. For the Strait of Magellan and Bahía Inútil the black and grey bars, respectively, represent mean moraine ages also (Fig. 4) at one standard deviation, and the timing for the Lateglacial (see Fig. 7) is from Sugden (2005) and McCulloch *et al.* (2005). The age range for deglaciation (grey vertical bar), 17.6–17.0 cal. ka, is the 1σ calibrated age range for radiocarbon data in Fig. 4 and from McCulloch *et al.* (2005). For LBA and Strait of Magellan, the arrows point out that the moraines, from right to left, reflect decreasing ice extent (maximum extent is dated for the Magellan lobe). Cosmogenic nuclide data for LBA and the Magellan/Inútil sites were calculated using version 1 of the CRONUS Calculator (hess.ess.washington.edu/math/; Balco *et al.*, 2008); thus, for LBA, there may be slight differences from that in Table 2 in Douglass *et al.* (2006). Various scaling factors produce differences of <5% for cosmogenic ages in southern Patagonia; however, it is highlighted that at present the production rate value itself may be more uncertain

and 800 m and simulated the ice advance roughly to the moraine-defined limits.

Global Circulation Model (GCM) investigations have focused on the global and South American LGM climate. Most recently, Rojas *et al.* (2008) discussed (Fig. 6) the results of four coupled GCMs conducted by the PMIP2 (Palaeoclimate Modelling Intercomparison Project Phase 2) group for South America during the global LGM (21 ka). They found that all models indicate increased storm activity in winter in the mid latitudes (25–45° S) and south of 60° S over the Pacific Ocean. In addition,

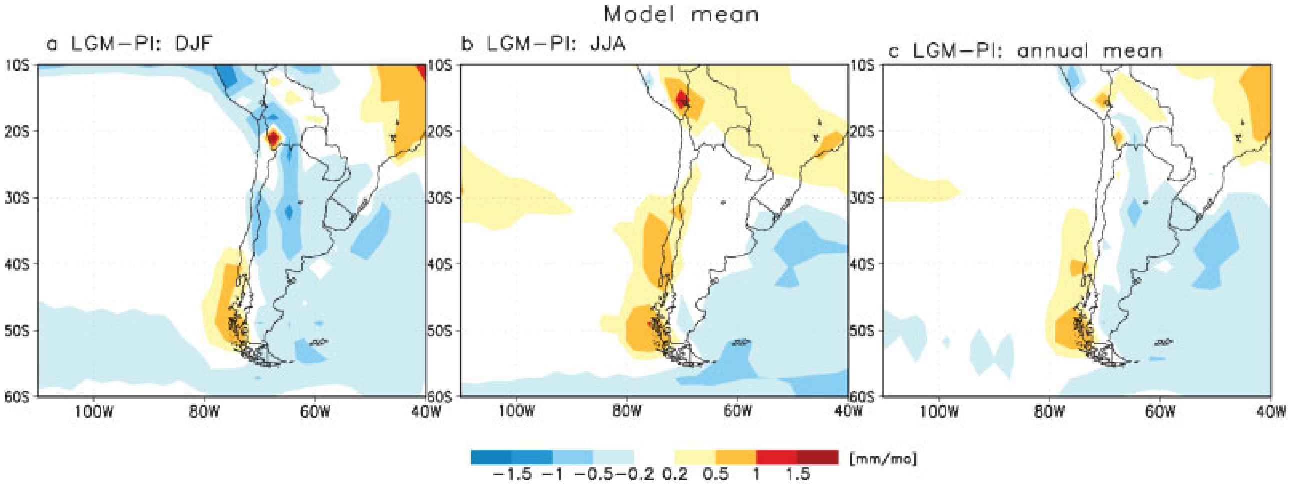

Figure 6 The seasonal mean and annual mean precipitation difference between the global LGM and Pre-Industrial control simulations of five PMIP2 models (Rojas *et al.*, 2008): a) summer mean, b) winter mean, c) annual mean. The following fully coupled atmosphere–ocean models were used to produce global LGM simulations: Hadley Centre HadCM3 model, the Japanese Model for Interdisciplinary Research on Climate MIROC3.2.2, the National Center for Atmospheric Research (NCAR) Community Climate System Model version 3 (CCSM3) model, the Institut Pierre Simon Laplace Climate System Model, IPSL-CM4, and the Institute of Atmospheric Physics, Chinese Academy of Sciences, FGOALS1.0 model

the simulations showed a generally drier LGM compared to present day, both in summer and winter, with some regional heterogeneity over the continents. The HadCM3 and MIROC3.2.2 simulations indicate an increase of precipitation north of 40° S in the Patagonia region during winter, and a decrease south of this latitude. On the lee side of the Andes, all models indicate decreased precipitation. For the summer season the situation is similar to winter at the lee side of the Andes. Along most of the Pacific coast, all models indicate positive anomalies, except CCSM3, which simulates negative changes for the entire region. The model mean of five PMIP2 models indicates positive anomalies in precipitation along the Pacific coast of southern South America (Fig. 6) at 21 ka in both seasons and in the annual mean. Opposite conditions are evident on the lee side of the Andes Cordillera. Another interesting finding from the GCM experiments is that, despite regional heterogeneity and intermodel divergences, there seems to be a climate boundary between the middle and high latitudes of the Southern Hemisphere during the global LGM. This discontinuity, which develops north and south of the zone of maximum wind speeds at 45–50° S, is well expressed in several diagnostic features (maximum sea-level pressure gradient, sea surface temperatures, near-surface wind speeds, precipitation and cyclone density) (Rojas *et al.*, 2008) and may imply a transition to more high-latitude polar climate conditions at these latitudes.

Lateglacial (~17–10 ka)

This part of the last glacial cycle is an ongoing avenue of intense focus by numerous widely distributed investigations using a variety of proxies (Fig. 7). Much of the research efforts have focused on whether cooling intervals overlapped in time with the European YD or Antarctic Cold Reversal (ACR) intervals. Early research led Mercer (1983) to infer that no glacial advances during the Lateglacial time (i.e. renewed snowline depression) occurred in Patagonia, specifically correlative to the YD. Although Lateglacial advances (i.e. ~17–10 ka) have been subsequently documented throughout Patagonia, the precise timing is still debated (Fig. 7). Towards southern Patagonia and Tierra del Fuego, inferred glacial reconstructions are generally more extensive relative to current ice limits. This is likely due to the more southerly latitude and poleward-shift in the westerlies (relative to the LGM condition), which by then were closer to their interglacial position (Moreno *et al.*, 1999; McCulloch *et al.*, 2000; Moreno, 2002; Sugden, 2005). East of the CLD/IGC the glacial limits are not known precisely, but they appear to be in the mountains (e.g. Ariztegui *et al.*, 1997; Heusser, 2003), well behind the local LGM limits.

Some non-glacial proxies on the Pacific coast of central Patagonia do not show variability during this time interval (Fig. 7), specifically around the Taitao Peninsula. Based on the interpretation of pollen records from the Chilean channels, Bennett *et al.* (2000) argued that no climate reversal is evident, a result also found at nearby Laguna Fácil (Massaferro *et al.*, 2005). In contrast, other studies from the Taitao Peninsula have described Lateglacial climate variability (Massaferro and Brooks, 2002; Gilchrist, 2004). Given the overwhelming evidence for Lateglacial climate variability at most sites in Patagonia (whether they are more consistent with the appellations YD or ACR is a different question), this may imply that some lake archives or proxies in the rainforest region of Taitao Peninsula and Chonos Archipelago are different from the majority of the data for this time. In addition, farther south, using high-resolution pollen profiles, Markgraf (1993) argued that much of the environmental variability observed in proxy records was in response to local and regional disturbances by fires.

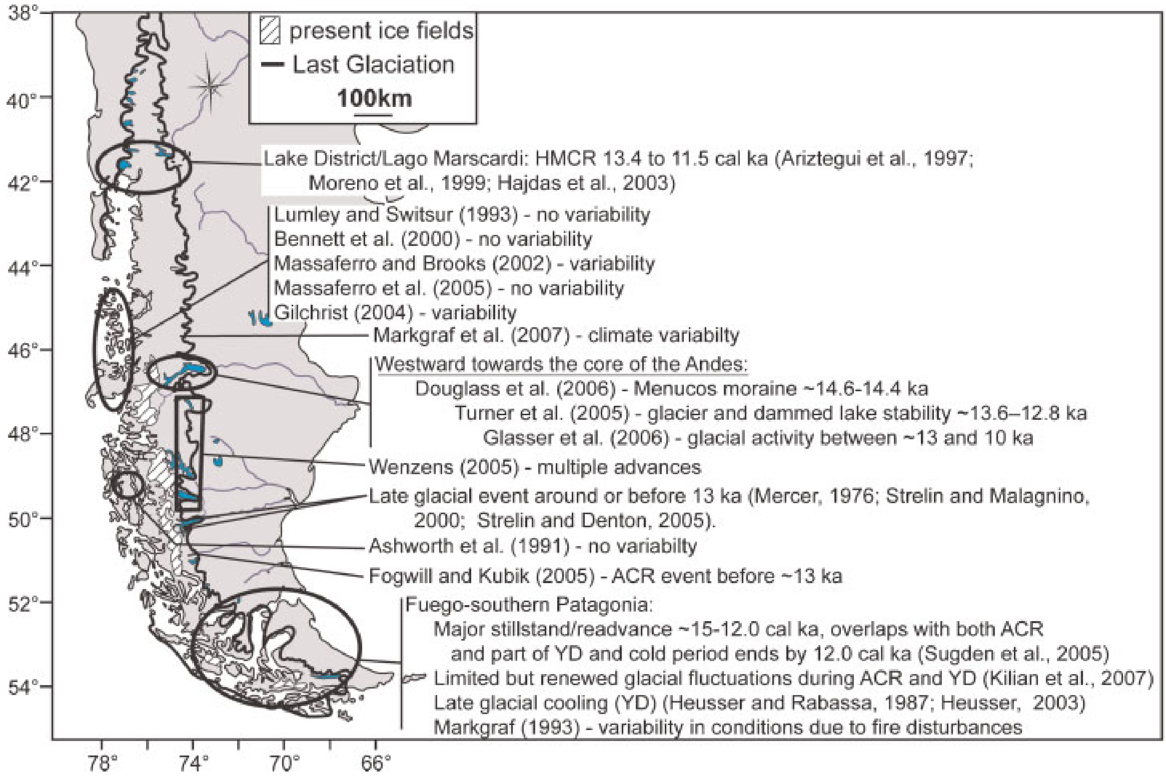

Figure 7 Studies which include numerical ages on proxy records covering the Lateglacial in Patagonia. All ages are in calendar ka BP. For cosmogenic nuclide-based chronologies, various scaling factors produce differences of <5% for southern Patagonia; however, it is highlighted that at present the production rate value itself may be more uncertain. The reader is referred to the comprehensive summaries in Heusser (2003) and Glasser *et al.* (2006) and references cited in the figure for reviews of all prior research in each respective area. HMCR, Huelmo/Mascardi Cold Reversal. This figure is available in colour online at www.interscience.wiley.com/journal/jqs

Recent studies have concluded that south of 52° S, in southern Patagonia–Tierra del Fuego, cooling and renewed glacial activity are characteristic of an 'Antarctic-like' Lateglacial (Sugden, 2005; Sugden *et al.*, 2005; Kaplan *et al.*, 2006b), consistent with marine-based conclusions (e.g., Lamy *et al.*, 2004; Kilian *et al.*, 2007). The basis is that climatic reversals began before the YD interval. Yet cool conditions and glacial fluctuations still persisted during all or part of the subsequent YD; however, compared to the previous millennium, the situation was slightly less cold and there was less extensive ice after ca. 12.6 ka (Fig. 7). Around the east side of the lake at LBA, a prominent moraine is dated around 14.6 ± 1 ka (Douglass *et al.*, 2006); westward from this moraine towards the present icefield, successively less extensive stillstand/advances are inferred overlapping in time with the ACR interval, but younger than 14.6 ka, and during YD time (Turner *et al.*, 2005; Glasser *et al.*, 2006). Hubbard *et al.* (2005) simulated a substantial ELA rise between ca. 17 and 14 ka (following the Vostok temperature reconstruction; Vimeux *et al.*, 2002), which for a time 'levelled off' during the ACR interval. The model simulated glacial changes, specifically ice frontal positions, which were roughly in line with the geomorphic and chronological observations. Farther to the north, around 41–42° S, Moreno *et al.* (2001) and Aritzegui *et al.* (1997) presented evidence for a two-part Lateglacial cooling, the youngest of which was termed the Huelmo Mascardi Cold Reversal (HMCR; Hajdas *et al.*, 2003; Fig. 7).

A hypothesised north–south difference in Lateglacial pattern (McCulloch *et al.*, 2000; Sugden, 2005) predicts testable variability depending on the site and latitude in Patagonia for this important time interval. Glacial activity and cool periods should be observed overlapping with the ACR or YD, with one or the other more prominent depending on the latitude (Sugden *et al.*, 2005; Kaplan *et al.*, 2006b). Southward, 'closer to the Polar Frontal Zone', glacial activity during the ACR interval dominated, whereas to the north that during the YD is more prominent.

Uncertainties and outstanding problems

Observed differences in Patagonia, as summarised in Figs. 5 and 7, may be due to 'genuine' past climate variability or current uncertainties and problems with the proxy techniques, specifically the dating tools. Given a distance of 2000 km from the CLD to the Magellan Straits area (39–54° S), a reasonable hypothesis is that there are at least some spatial differences in glacial histories (Coronato *et al.*, 2004a).

Genuine spatial differences in climate

Some differences between areas are tenable as authentic glacial or climate variability. That is, the inferred millennial and submillennial climate variability is robust and the differences are beyond the uncertainties in respective dating techniques. In addition, when more than one geochronometer is used, and they agree within uncertainties, or a glacial event is reproduced in adjacent valleys, the inferred glacial history can be considered more robust (e.g. McCulloch *et al.*, 2005). Radiocarbon-dated records are comparable to each other, neglecting the uncertainties in converting to calendar years. For example, in the CLD and the Strait of Magellan areas, radiocarbon dating for deglaciation is reproduced using multiple stratigraphic sections and lake cores (Fig. 5). Overall, the CLD chronology is based on radiocarbon dates and, except for during periods of radiocarbon plateaus, the method can date submillennial and century-scale climate events. Maximum glacial extent in the northern side of the CLD, for example, is earlier than in IGC. In addition, in the CLD, MIS 4 ice is perhaps more extensive than that during MIS 2, whereas at LBA evidence of MIS 4 ice is not observed, and at the very least ice is less extensive than that during MIS 6 and 2. If correct, perhaps on the west side of the Andes precipitation worked in combination with temperature to push ice limits farther west during MIS 4 than in MIS 2. On both sides of the Andes these findings must be reproduced.

Whether Patagonia experienced a major glaciation and thus ice age conditions during MIS 2 is not debated, although many critical questions and fine details of the structure of the period still need to be addressed. For example, at the end of local LGM time, some outlet lobes appear to have taken longer to disintegrate. At LBA, a readvance deposited the Menucos moraine (ca. 14.4 ka). This last advance was relatively close to the inner local LGM deposits (Douglass *et al.*, 2006); although the lobe was of lesser extent and had a lower surface slope, it followed a lake phase and a slight ELA rise (Singer *et al.*, 2004; Hubbard *et al.*, 2005). Three radiocarbon ages on carbonate concretions from the lake sediments further define the age of the Menucos advance to after ca. 15.5 cal. ka BP (Kaplan *et al.*, 2004). In contrast, the CLD and Magellan regions deglaciated by ~17.6–17.0 cal. ka BP (1σ calibrated age range), in phase with a near-synchronous termination with other areas around the globe (Schaefer *et al.*, 2006). The differences in timing for complete deglaciation between the CLD (and Magellan) and LBA appears to be beyond known uncertainties in the dating methods used, requiring a climate or ice dynamical mechanism for lingering ice in the latter area.

We hypothesise those areas with a more continental climate on the east side of the Andes deglaciated slightly later than other parts of Patagonia. The LBA moraines are also above 400 m. Perhaps a given warming over Patagonia (e.g. by 17 cal. ka BP) caused less ablation of ice on the east side of the Andes than in more maritime areas on the west side of the Andes or in the Magellan area. The termination in the CLD before 17 cal. ka BP can be explained due to its northern position at 40° S, warm maritime climate (and wet adiabatic lapse rate), and low elevation (near sea level). The Magellan region also experiences a maritime climate and calving dynamics could have played an important role in catastrophic recession of ice before ~17 cal. ka BP (Porter *et al.* 1992; McCulloch *et al.*; 2005, Kaplan *et al.*, 2008), despite its southerly position on the continent. One possibility is that the initial deglaciation at LBA, after Fenix I, corresponds to the second step of warming in the CLD (Denton *et al.*, 1999; Moreno *et al.*, 1999; McCulloch *et al.*, 2000; Moreno, 2002). The above hypotheses can be tested with future studies, both field and modelling-based.

Genuine climate variability or method uncertainties

In contrast to the above examples of 'authentic' climate variability observed in the records, some apparent differences in Figs. 5 and 7, for example, may be due to uncertainties or limitations in the dating techniques. To date, there is a 'roadblock' in dating directly local LGM and Lateglacial moraines at the millennial timescale. An example is the maximum extent of ice during the local LGM (Fig. 5). At LBA, the maximum extent, ca. 23 ka, occurred after that in the northern side of the CLD considering known dating uncertainties; however, such differences between LBA and the Magellan region cannot yet be distinguished because they are well within analytical and systematic uncertainties of the cosmogenic nuclide measurements.

At present, various scaling factors for converting nuclide concentrations to age at a given latitude and elevation vary by less than ~5% for local LGM deposits in central/southern Patagonia. On the other hand, the systematic uncertainty in the production rate value itself may be >5%, especially due to changes in pressure, which likely varied in the past (Ackert *et al.*, 2003). In other words, different production rate and scaling schemes can yield a different timing for a glacier advance, e.g. 600–800 a at 20 ka (Stone, 2000; Dunai, 2000, 2001; Desilets and Zreda, 2003; Lifton *et al.*, 2005; Desilets *et al.*, 2006). However, it is highlighted that when comparing two sites in Patagonia, for relative differences in age, the accuracy is likely better than 5% (assuming geological uncertainties are minimal) as systematic factors are reduced.

In addition, geomorphic processes such as erosion and erratic exhumation add an additional non-systematic uncertainty, which varies in importance depending on locality (Kaplan *et al.*, 2007). For each study area in Patagonia, and elsewhere, each dataset must be treated differently (Douglass *et al.*, 2006; Kaplan *et al.*, 2007) depending on the relative magnitude of landscape processes.

Uncertainties and future research

The outlook for developing a precise glacial chronology throughout Patagonia is promising, especially given the arid conditions that are suitable for cosmogenic dating. Future studies will address at least some present uncertainties and thus 'roadblocks' in understanding millennial timescale (and finer) variability between records. First, improved analytical precision by AMS will allow relative differences within or between nearby sites to become clearer (Schaefer and CRONUS Steering Committee, 2005; Nishiizumi *et al.*, 2007). Second, finer-resolution dating will be possible as systematic uncertainties are reduced with local production rate calibrations and related international efforts (e.g. Balco *et al.* 2008). It cannot be emphasised enough that even if, at present, spatial climatic differences cannot be accurately ascertained (e.g. ACR *versus* YD), cosmogenic nuclide ages can be recalculated in the future as improvements to the techniques are made. Thus, although it is important to be cautious given the current uncertainties, it still pays to gather high-quality (e.g., precise) data now, to address important scientific problems in Patagonia. To address issues related to the affects of geomorphic processes on cosmogenic ages, future studies should make an effort to use a multiple dating approach. For example, radiocarbon data can confirm reconstructed glacial histories or allow production rate 'confirmation' for a given area (McCulloch *et al.*, 2005; Kaplan *et al.*, 2008). Finally, reproducing events in nearby areas allows higher confidence that geomorphic processes particular to either place have minimal affects on the ages and similarities between records may reflect real glacio-climate changes.

Conclusion

Cosmogenic nuclide measurements are invaluable for reconstructing the timing of major glacial changes between MIS 5e and YD time in southern South America, especially east of the Andes. The dating approach also complements previous and ongoing radiocarbon dating campaigns. Together, the chronologies also allow comparison to modelling simulations of past climate. At present, chronological uncertainties prevent confident assignment of cosmogenic ages for glacial events at the millennial timescale. Future refinements, however, to surface exposure dating techniques will refine the method and accuracy of ages.

The data show that Patagonia experienced both MIS 6 and 4 glaciations, although generalising widespread patterns of relative ice extents with that during MIS 2 awaits future work. All of southern South America experienced an MIS 2 glaciation broadly in phase with that in other areas around the globe. Some differences in climate histories between areas appear on a millennial timescale, including for the Lateglacial. All of southern South America experienced climate change during the Lateglacial, except perhaps for some densely forested areas in the Chilean channels.

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References

Ackert RP, Singer BS, Guillou H, Kaplan MR, Kurz MD. 2003. Long-term cosmogenic ^{3}He production rates from ^{40}Ar/^{39}Ar and K-Ar dated Patagonian lava flows at 47°S. *Earth and Planetary Science Letters* **210**: 119–136.

Ariztegui D, Bianchi MM, Masaferro J, Lafargue E, Niessen F. 1997. Interhemispheric synchrony of Late-glacial climatic instability as recorded in proglacial Lake Mascardi, Argentina. *Journal of Quaternary Science* **12**: 333–338.

Ashworth AC, Markgraf V, Villagran C. 1991. Late Quaternary climatic history of the Chilean Channels based on fossil pollen and beetle analyses, with an analysis of the modern vegetation and pollen rain. *Journal of Quaternary Science* **6**: 279–291.

Balco G, Stone J, Lifton N, Dunai T. 2008. A simple, internally consistent, and easily accessible means of calculating surface exposure ages and erosion rates from Be-10 and Al-26 measurements. *Quaternary Geochronology* **3**: 174–195.

Basile I, Grousset FE, Revel M, Petit JR, Biscaye PE, Barkov NI. 1997. Patagonian origin of glacial dust deposited in East Antarctica (Vostok and Dome C) during glacial stages 2, 4 and 6. *Earth and Planetary Science Letters* **146**: 573–589.

Benn DI, Clapperton CM. 2000. Glacial sediment-landform associations and palaeoclimate during the last glaciation, Strait of Magellan, Chile. *Quaternary Research* **54**: 13–23.

Bennett KD, Haberle SG, Lumley SH. 2000. The Last Glacial–Holocene transition in southern Chile. *Science* **290**: 325–328.

Bentley MJ. 1997. Relative and radiocarbon chronology of adjacent former outlet glaciers in the Chilean Lake District. *Journal of Quaternary Science* **12**: 25–33.

Caldenius CC. 1932. Las glaciaciones cuaternarios en la Patagonia y Tierra del Fuego. *Geografiska Annaler* **14**: 1–164 (English summary 144-157).

Clapperton CM. 1993. *Quaternary Geology and Geomorphology of South America*. Elsevier: Amsterdam.

Clapperton C, Seltzer G. 2001. Glaciation during marine isotope Stage 2 in the American Cordillera. In *Interhemispheric Climate Linkages*, Markgraf V (ed.). Academic Press: San Diego, CA.

Clapperton CM, Sugden DE, Kauffman D, McCulloch RD. 1995. The last glaciation in central Magellan Strait, southernmost Chile. *Quaternary Research* **44**: 133–148.

Coronato A, Martinez O, Rabassa J. 2004a. Pleistocene glaciations in Argentine Patagonia, South America. In *Quaternary Glaciations: Extent and Chronology. Part III: South America, Asia, Africa, Australia and Antarctica*, Ehlers J, Gibbard P (eds.) Quaternary Book Series. Elsevier: Amsterdam; 49–67.

Coronato A, Meglioli A, Rabassa J. 2004b. Glaciations in the Magellan Straits and Tierra del Fuego, southernmost South America. In *Quaternary Glaciations — Extent and Chronology. Part III: South America, Asia, Africa, Australia and Antarctica*, Ehlers J, Gibbard P (eds). Quaternary Book Series. Elsevier: Amsterdam; 45–48.

Denton GH, Lowell TV, Heusser CJ, Moreno PI, Andersen BG, Heusser LE, *et al*. 1999. Interhemispheric linkage of paleoclimate during the last glaciation. *Geografiska Annaler* **81**: 107–153.

Desilets D, Zreda M. 2003. Spatial and temporal distribution of secondary cosmic-ray nucleon intensities and applications to in-situ cosmogenic dating. *Earth and Planetary Science Letters* **206**: 21–42.

Desilets D, Zreda M, Prabu T. 2006. Extended scaling factors for in situ cosmogenic nuclides: new measurements at low latitude. *Earth and Planetary Science Letters* **246**: 265–276.

Douglass DC, Singer BS, Kaplan MR, Mickelson DM, Caffee MW. 2006. Cosmogenic nuclide surface exposure dating of boulders on last-glacial and late-glacial moraines, Lago Buenos Aires, Argentina: interpretive strategies and paleoclimate implications. *Quaternary Geochronology* **1**: 43–58.

Dunai T. 2000. Scaling factors for production rates of in situ produced cosmogenic nuclides: a critical reevaluation. *Earth and Planetary Science Letters* **176**: 157–169.

Dunai T. 2001. Influence of secular variation of the magnetic field on production rates of in situ produced cosmogenic nuclides. *Earth and Planetary Science Letters* **193**: 197–212.

EPICA. 2004. Eight glacial cycles from an Antarctic ice core. *Nature* **429**: 623–628.

Fairbanks RG, Mortlock RA, Chiu T-C, Cao L, Kaplan A, Guilderson T, *et al*. 2005. Marine radiocarbon calibration curve spanning 0 to 50,000 years B.P. based on paired ^{230}Th/^{234}U/^{238}U and ^{14}C dates on pristine corals. *Quaternary Science Reviews* **24**: 1781–1796.

Fogwill CJ, Kubik PW. 2005. A glacial stage spanning the Antarctic Cold Reversal in Torres del Paine (51°S), Chile, based on preliminary cosmogenic exposure ages. *Geografiska Annaler* **87A**: 403–508.

Gilchrist SJL. 2004. *Late Quaternary palaeoclimatic reconstructions in Patagonia using chironomid analysis*. PhD thesis, University of Edinburgh.

Glasser NF, Jansson K. 2005. Fast-flowing outlet glaciers of the last glacial maximum Patagonian Icefield. *Quaternary Research* **63**: 206–211.

Glasser NF, Harrison S, Ivy-Ochs S, Duller GAT, Kubik P. 2006. Evidence from the Rio Bayo valley on the extent of the North Patagonian Icefield during the Late Pleistocene–Holocene transition. *Quaternary Research* **65**: 70–77.

Hajdas I, Bonani G, Moreno PI, Ariztegui D. 2003. Precise radiocarbon dating of Late-Glacial cooling in mid-latitude South America. *Quaternary Research* **59**: 70–78.

Harrison S. 2004. The Pleistocene glaciations of Chile. In *Pleistocene Glaciations: Extent and Chronology*, Ehlers J, Gibbard P (eds.) INQUA/Elsevier: Amsterdam; 89–103.

Heusser CJ. 2003. *Ice Age Southern Andes: A Chronicle of Palaeoecological Events*. Elsevier: Amsterdam.

Heusser C, Rabassa J. 1987. Cold climatic episode of Younger Dryas age in Tierra del Fuego. *Nature* **328**: 609–611.

Heusser CJ, Heusser LE. 2006. Submillennial palynology and palaeoecology of the last glaciation at Taiquemó ($\sim$50,000 cal yr, MIS 2-4) in southern Chile. *Quaternary Science Reviews* **25**: 446–454.

Heusser CJ, Heusser LE, Lowell TV. 1999. Paleoecology of the southern Chilean Lake District-Isla Grande de Chiloé during middle–late Llanquihue glaciation and deglaciation. *Geografiska Annaler* **81**: 231–284.

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

Hubbard A, Hein AS, Kaplan MR, Hulton NRJ. 2005. A reconstruction of the late glacial maximum ice sheet and its deglaciation in the vicinity of the Northern Patagonian Icefield, South America. *Geografiska Annaler* **87**: 375–391.

Hulton NRJ, Purves RS, McCulloch RD, Sugden DE, Bentley MJ. 2002. The last glacial maximum and deglaciation in southern South America. *Quaternary Science Reviews* **21**: 233–241.

Jackofsky DS, Gosse JC, Cerling TE, Evenson EB, Klein J, Easterbrook D, Peterson KP, Spies C, Sorenson CJ, Caffee M. 2000. Latitudinal variations in the timing of alpine glacier retreat from LGM, southern South America. In *Thirtieth Arctic Workshop*, Boulder, CO.

Kaplan MR, Ackert RP, Singer BS, Douglass DC, Kurz MD. 2004. Cosmogenic nuclide chronology of millennial-scale glacial advances during O-isotope Stage 2 in Patagonia. *Geological Society of America Bulletin* **116**: 308–321.

Kaplan MR, Douglass DC, Singer BS, Ackert RP, Caffee MW. 2005. Cosmogenic nuclide chronology of pre-last glaciation maximum moraines at Lago Buenos Aires, 46° S, Argentina. *Quaternary Research* **63**: 301–315.

Kaplan MR, Singer BS, Douglass DC, Ackert RP, Caffee MC. 2006a. Response to Wenzens(2006)comment on Kaplan *et al*. (2005) Cosmogenic nuclide chronology of pre-last glaciation maximum moraines at Lago Buenos Aires, 46°S, Argentina. *Quaternary Research* **66**: 367–369.

Kaplan MR, Moreno PI, Villa-Martínez RP, Kubik PW. 2006b. Timing and structure of glacial fluctuations at the end of the last ice age in SW Patagonia. In *American Geophysical Union Fall Meeting*, PP22A-06.

Kaplan MR, Coronato A, Hulton NRJ, Rabassa JO, Stone JO, Kubik PW. 2007. Cosmogenic nuclide measurements in southernmost South America and implications for landscape change. *Geomorphology* **87**: 284–301.

Kaplan MR, Fogwill CJ, Sugden DE, Hulton NRJ, Kubik PW, Freeman SPHT. 2008. Southern Patagonian and Southern Ocean climate during the last glacial period. *Quaternary Science Reviews* **27**: 284–294.

Kilian R, Schneider C, Koch J, Fesq-Martin M, Biester H, Casassa G, Arévalo M, Wendt G, Baeza O, Behrmann J. 2007. Palaeoecological constraints on late Glacial and Holocene ice retreat in the Southern Andes (53°S). *Global and Planetary Change* **59**: 49–66.

Lamy FJ, Kaiser J, Ninnemann U, Hebbeln D, Arz HW, Stoner J. 2004. Antarctic timing of surface water changes off Chile and Patagonian Ice Sheet response. *Science* **304**: 959–1962.

Lifton N, Bieber J, Clem J, Duldig M, Evenson P, Humble J, Pyle R. 2005. Addressing solar modulation and long-term uncertainties in scaling secondary cosmic rays for in situ cosmogenic nuclide applications. *Earth and Planetary Science Letters* **239**: 140–161.

Lowell TV, Heusser CJ, Andersen BG, Moreno PI, Hauser A, Heusser LE, Schlüchter C, Marchant DR, Denton GH. 1995. Interhemispheric correlation of Late Pleistocene glacial events. *Science* **269**: 1541–1549.

Lumley SH, Switsur R. 1993. Late Quaternary chronology of the Taitao Peninsula, southern Chile. *Journal of Quaternary Science* **8**: 161–165.

Marden CJ, Clapperton CM. 1995. Fluctuations of the Southern Patagonian Icefield during the last glaciation and the Holocene. *Journal of Quaternary Science* **10**: 197–209.

Markgraf V. 1993. Younger Dryas in southernmost South America: an update. *Quaternary Science Reviews* **12**: 351–355.

Markgraf V, Whitlock C, Haberle S. 2007. Vegetation and fire history during the last 18,000 cal yr B.P. in southern Patagonia: Mallin Pollux, Coyhaique, Province Aisén (45°41′30″; S, 71°50′30″; W, 640 m elev.). *Palaeogeography, Palaeoclimatology, Palaeoecology* **254**: 292–507.

Massaferro J, Brooks SJ. 2002. Response of chironomids to Late Quaternary environmental change in the Taitao Península, southern Chile. *Journal of Quaternary Science* **17**: 101–111.

Massaferro J, Brooks SJ, Haberle SG. 2005. The dynamics of chironomid assemblages and vegetation during the Late Quaternary at Laguna Fácil, Chonos Archipelago, southern Chile. *Quaternary Science Reviews* **24**: 2510–2522.

McCulloch RD, Bentley MJ, Purves RS, Sugden DE, Clapperton C, Hulton NRJ. 2000. Climatic inferences from glacial and palaeoecological evidence at the last glacial termination, southern South America. *Journal of Quaternary Science* **15**: 409–418.

McCulloch RD, Fogwill CJ, Sugden DE. 2005. Late glacial maxima, the Antarctic Cold Reversal and the Younger Dryas in the Strait of Magellan and Bahía Inútil; a revised chronology. *Geografiska Annaler* **87**: 289–312.

Meglioli A. 1992. *Glacial geology and chronology of southernmost Patagonia and Tierra del Fuego, Argentina and Chile*. PhD dissertation, Lehigh University, Bethlehem, PA.

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

Mercer JH. 1983. Cenozoic glaciation in the southern hemisphere. *Annual Reviews of Earth and Planetary Science* **11**: 99–132.

Mix AC, Bard E, Schneider R. 2001. Environmental processes of the ice age: land, oceans, glaciers (EPILOG). *Quaternary Science Reviews* **20**: 627–657.

Moreno PI. 2002. Western Patagonia: a key area for understanding Quaternary paleoclimate at southern mid-latitudes. In *The Patagonian Icefields: A Unique Natural Laboratory for Environmental and Climate Change Studies*, Casassa G, Sepúlveda F, Sinclair R (eds.) Kluwer Academic/Plenum Publishers: New York; 43–54.

Moreno PI, Jacobson GL, Andersen BG, Lowell TV, Denton GH. 1999. Abrupt vegetation and climate changes during the last glacial maximum and the last termination in the Chilean Lake District: a case study from Canal de la Puntilla (41°S). *Geografiska Annaler* **81A**: 285–311.

Moreno PI, Jacobson GL, Lowell TV, Denton GH. 2001. Interhemispheric climate links revealed by a late-glacial cooling episode in southern Chile. *Nature* **409**: 804–808.

Nishiizumi K, Imamura M, Caffee M, Southon J, Finkel R, McAnich J. 2007. Absolute calibration of ^{10}Be AMS standards. *Nuclear Instruments and Methods in Physics Research B* **258**: 403–413.

Nordenskjöld O. 1899. *Geologie, Geographie und Anthropologie: Scwedischen Expedition nach den Magellansländern, 1895–1897*. Norstedt & Söner: Stockholm.

Petit JR, Jouzel J, Raynaud D, Barkov NI, Barnola JM, Basile I, Bender M, Chappellaz J, Davis M, Delay G, *et al*. 1998. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature* **399**: 429–436.

Porter SC, Clapperton CM, Sudgen DE. 1992. Chronology and dynamics of deglaciation along and near the Strait of Magellan, southernmost South America. *Sveriges Geologiska Undersökning, Ser. Ca.* **81**: 233–239.

Rabassa J, Clapperton CM. 1990. Quaternary glaciations in the southern Andes. *Quaternary Science Reviews* **9**: 153–174.

Rabassa J, Coronato A, Bujalesky G, Salemme M, Roig C, Meglioti A, Heusser C, Gordillo S, Roig F, Borromei A, Quattrocchio M. 2000. Quaternary of Tierra del Fuego, Southernmost South America: an updated review. *Quaternary International* **68**: 217–240.

Rabassa J, Coronato AM, Salemme M. 2005. Chronology of the Late Cenozoic Patagonian glaciations and their correlation with biostratigraphic units of the Pampean region (Argentina). *Journal of South American Earth Sciences* **20**: 81–103.

Reimer PJ, Baillie MGL, Bard E, Bayliss A, Beck JW, Bertrand CJH, Blackwell PG, Buck CE, Burr GS, Cutler KB, Damon PE, Edwards RL, Fairbanks RG, Friedrich M, Guilderson TP, Hogg AG, Hughen KA, Kromer B, McCormac FG, Manning SW, Ramsey CB, Reimer RW, Remmele S, Southon JR, Stuiver M, Talamo S, Taylor FW, van der Plicht J, Weyhenmeyer CE. 2004. IntCal04 Terrestrial radiocarbon age calibration,26-0 ka BP. *Radiocarbon* **46**: 1029–1058.

Rojas M, Moreno PI, Kageyama M, Crucifix M, Hewitt C, Abe-Ouchi A, Ohgaito R, Brady E, Hope P. 2008. The Southern Westerlies during the Last Glacial Maximum in PMIP2 simulations. *Climate Dynamics*. doi: 10.1007/s00382-008-0421-7.

Shackleton NJ, Berger A, Peltier WR. 1990. An alternative astronomical calibration of the lower Pleistocene timescale based on ODP site 677. *Transactions of the Royal Society of Edinburgh, Earth Sciences* **81**: 251–261.

Schaefer JM. CRONUS Steering Committee. 2005. *The CRONUS-Earth (Cosmic-Ray prOduced NUclide Systematics on Earth) initiative: The 15th Annual Goldschmidt Conference*, Moscow, ID; 70.

Schaefer JM, Denton GH, Barrell DJA, Ivy-Ochs S, Kubik PW, Andersen BG, Phillips FM, Lowell TV, Schlüchter C. 2006. Near-synchronous interhemispheric termination of the last glacial maximum in mid-latitudes. *Science* **312**: 1510–1513.

Singer B, Hildreth W, Vincze Y. 2000. ^{40}Ar/^{39}Ar evidence for early deglaciation of the central Chilean Andes. *Geophysical Research Letters* **27**: 1663–1666.

Singer BS, Ackert RP, Guillou H. 2004. ^{40}Ar/^{39}Ar and K-Ar chronology of Pleistocene glaciations in Patagonia. *Geological Society of America Bulletin* **116**: 434–450.

Stone JO. 2000. Air pressure and cosmogenic isotope production. *Journal of Geophysical Research* **105**: 23753–23759.

Strelin J, Malagnino E. 2000. The Late-glacial history of Lago Argentino, Argentina, and age of the Puerto Bandera Moraines. *Quaternary Research* **54**: 339–347.

Strelin J, Denton G. 2005. Las morenas de Puerto Bandera, Lago Argentino. *Proceedings of the XVI Congreso Geológico Argentino*, CD-ROM, Article 269; 6 pp.

Sugden DE. 2005. Late-glacial glacier events in southern South America and their wider significance. *Geografiska Annaler* **87**; 408 pp.

Sugden DE, Hulton NRJ, Purves RS. 2002. Modelling the inception of the Patagonian icesheet. *Quaternary International* **95–96**: 55–64.

Sugden DE, Bentley MJ, Fogwill CJ, Hulton NRJ, McCulloch RD, Purves RS. 2005. Late-glacial glacier events in southernmost South America: a blend of 'northern' and 'southern' hemispheric climatic signals? *Geografiska Annnaler* **87A**: 273–288.

Turner KJ, Fogwill CJ, McCulloch RD, Sugden DE. 2005. Deglaciation of the eastern flank of the North Patagonian Icefield and associated continental-scale lake diversions. *Geografiska Annaler* **82A**: 363–374.

Vimeux F, Cuffey KM, Jouzel J. 2002. New insights into Southern Hemisphere temperature changes from Vostok ice cores using deuterium excess correction. *Earth and Planetary Science Letter* **203**: 829–843.

Wenzens G. 2005. Glacier advances east of the Southern Andes between the Last Glacial Maximum and 5,000 BP compared with lake terraces of the endorrheic Lago Cardiel (49°S, Patagonia, Argentina). *Zeitschrift für Geomorphologie* **49**: 433–454.

Wenzens G. 2006. Comment on: Cosmogenic nuclide chronology of pre-last glacial maximum moraines at Lago Buenos Aires, 46°S, Argentina (letter to the editor). *Quaternary Research* **66**: 364–366.