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Evidence from the Rio Bayo valley on the extent of the North Patagonian Icefield during the Late Pleistocene–Holocene transition

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Abstract

This paper presents data on the extent of the North Patagonian Icefield during the Late Pleistocene–Holocene transition using cosmogenic nuclide exposure age and optically stimulated luminescence dating. We describe geomorphological and geochronological evidence for glacier extent in one of the major valleys surrounding the North Patagonian Icefield, the Rio Bayo valley. Geomorphological mapping provides evidence for the existence of two types of former ice masses in this area: (i) a large outlet glacier of the North Patagonian Icefield, which occupied the main Rio Bayo valley, and (ii) a number of small glaciers that developed in cirques on the slopes of the mountains surrounding the valley. Cosmogenic nuclide exposure age dating of two erratic boulders on the floor of the Rio Bayo valley indicate that the outlet glacier of the icefield withdrew from the Rio Bayo valley after 10,900 ± 1000 yr (the mean of two boulders dated to 11,400 ± 900 yr and 10,500 ± 800 yr). Single-grain optically stimulated luminescence (OSL) dating of an ice-contact landform constructed against this glacier indicates that this ice mass remained in the valley until at least 9700 ± 700 yr. The agreement between the two independent dating techniques (OSL and cosmogenic nuclide exposure-age dating) increases our confidence in these age estimates. A date obtained from a boulder on a cirque moraine above the main valley indicates that glaciers advanced in cirques surrounding the icefield some time around 12,500 ± 900 yr. This evidence for an expanded North Patagonian Icefield between 10,900 ± 1000 yr and 9700 ± 700 yr implies cold climatic conditions dominated at this time.

Introduction

Understanding the pace and timing of Quaternary climatic changes is a key issue in southern South America for three main reasons. Firstly, these changes reflect variations in climatic gradients across the region, for example the latitudinal migration of the precipitation-bearing Southern Westerlies (Veit, 1996; Lamy et al., 2001, 2004). Secondly, the timing of glacier expansion and contraction in different parts of the region provides information on the forcing mechanisms of climate change (Van Geel et al., 2000; Markgraf and Seltzer, 2001). Thirdly, there is considerable uncertainty concerning interhemispheric timing of climatic changes during the Late Pleistocene–Holocene transition (e.g., Lowell et al., 1995; Denton et al., 1999). Some authors (e.g., Ivy-Ochs et al., 1999) have proposed that there was cooling in parts of the southern hemisphere (e.g., in New Zealand) during the Younger Dryas chronozone, whilst others (e.g., Bennett et al., 2000) have argued that such a cooling did not occur in southern South America. In this paper, we describe evidence for Late Pleistocene–Holocene glacier fluctuations in one of the major valleys surrounding the North Patagonian Icefield, the Rio Bayo valley, and provide a chronology for these glacier fluctuations.

Study site

The Rio Bayo Valley stretches from Exploradores Glacier in the west to Lago General Carrera in the east, a distance of approximately 40 km (Fig. 1). Around Lago Tranquilo, the valley floor comprises ice-scoured bedrock draped with low elongated drift ridges and hummocks. Ice-contact glaciofluvial landforms (kames and kame terraces) and alluvial fans and debris cones occur at the mouths of tributary valleys (Harrison et al., 2004) (Fig. 1). The drift ridges are broad belts of sediment comprising a thin layer of sandy boulder-gravel and diamicton (generally c. 0.5 to 2 m thickness, but locally thicker in places), draped onto a gently undulating bedrock surface. The surrounding mountain ranges host cirques, many of which contain well-developed but undated terminal and lateral moraines.

Methods

The extent of former glaciers in the study area was established through geomorphological mapping (using both remotely sensed data and field observations), together with descriptions of landforms and sediments in the field. Interpretation of ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) images with a ground resolution of 15 m in the visible and near-infrared bands was used to compile a geomorphological map, which was supplemented by field observations in March/April 2003. Samples for cosmogenic nuclide exposure-age dating were taken from the upper surfaces of three flat-topped erratic boulders following the sampling guidelines of Gosse and Phillips (2001). Each boulder was larger than 1.5 m (b axis) and care was taken to avoid boulders on uneven or unstable surfaces, which may have moved since deposition (Figs. 2A–C). Angles were measured to the horizon using an Abney level at 5° intervals to account for topographic shielding. Rock samples were crushed and sieved to a grain size less than 0.6 mm. Quartz was isolated by selective chemical dissolution with weak HF using a shaker table and hot ultrasonic bath (Kohl and Nishiizumi, 1992). The quartz mineral separates were further enriched using a Frantz magnetic separator. After addition of ^{9}Be carrier, the quartz was dissolved with concentrated HF. We used anion and cation exchange and selective pH controlled precipitations (Ochs and Ivy-Ochs, 1997) to separate and purify Be. The ^{10}Be/^{9}Be ratio along with appropriate standards and blanks were measured by accelerator mass spectrometry at the ETH/PSI tandem facility in Zurich (Synal et al., 1997). Chemistry blanks yielded ratios of 1–2 X 10^{-14}. Surface exposure ages were calculated using a sea-level, high-latitude ^{10}Be production rate of 5.1 $\pm$ 0.3 atoms per gram SiO_2 per year, with a contribution from muons of 2.6% (Stone, 2000). Scaling to the sample latitude (geographic) and altitude were also carried out following Stone (2000). To correct for the effect of erosion of the rock surface on the exposure age, we have used an erosion rate of 2 mm/10^3 yr. This rate is conservative and is based on down-wearing (weathering) rates of granitic rock surfaces in Alpine settings, which are generally 2 mm/103 yr or less (e.g., Small et al., 1997; Ivy-Ochs et al., 2004).

Optically stimulated luminescence (OSL) dating was used to obtain estimates of the ages of the ice-contact landforms in the Rio Bayo valley. Quartz grains in sediment accumulate trapped charge as a result of exposure to ionizing radiation from their environment, principally from radioactive decay of the uranium and thorium decay series and potassium, along with a small contribution from cosmic rays (Duller, 2004). Luminescence measurements can be used to estimate the radiation dose that the sample has been exposed to since deposition (the palaeodose), measured in Grays (Gy). Other laboratory measurements can be undertaken to assess the U, Th and K concentrations in the sediment, and thus calculate the radiation dose to which the sample is exposed. This is termed the dose rate (Gy/10^3 yr), and dividing the palaeodose by the dose rate yields an estimate of the date of last exposure of the sediment to daylight. The use of quartz OSL has been shown to produce accurate ages in the range from a few decades to over 100,000 yr (Murray and Olley, 2002). In conventional luminescence measurements, the OSL signal from many hundreds or thousands of grains are integrated together. Where a sample contains a proportion of grains that have not had their OSL reset at deposition, this will lead to an overestimate of the age. Recent technological developments have made it feasible to measure the luminescence signal from individual sand-sized (~200 Am diameter) grains of quartz (Duller and Murray, 2000). It is then possible to analyze the resulting data to discern which grains have had their signal reset at deposition and to use only these for age calculation. This single grain approach has been successfully applied to a number of sedimentary environments consisting of complex mixtures (e.g., Roberts et al., 1998; Jacobs et al., 2003; Olley et al., 2004).

Sediment samples for luminescence dating were obtained by inserting an opaque plastic tube into the section, avoiding obvious weathering horizons and other pedogenic features. Sample tubes were removed from the sections, the ends packed with plastic bags to ensure the sample did not crumble during transport, wrapped in opaque plastic bags and sealed with tape to protect from light. Samples for OSL dating were collected from two ice-contact landforms in the Rio Bayo valley, where material might be expected to be exposed to sunlight during transport and thus zeroed prior to deposition. Luminescence measurements were performed in the Aberystwyth Luminescence Laboratory.

Delimitation of former glaciers

Geomorphological mapping reveals evidence for two types of former ice masses in the Rio Bayo Valley. First is a large outlet glacier of the North Patagonian Icefield, which occupied the main valley, and second are a number of small glaciers that developed in cirques surrounding the valley. The presence of the former outlet glacier in the Rio Bayo valley is marked by a valley-floor sediment-landform assemblage comprising ice-scoured bedrock, kames and kame terraces and ice-contact glaciofluvial landforms (Fig. 1B). The presence of the former cirque glaciers on the higher land is indicated by the cirques and associated cirque moraines (Fig. 1C).

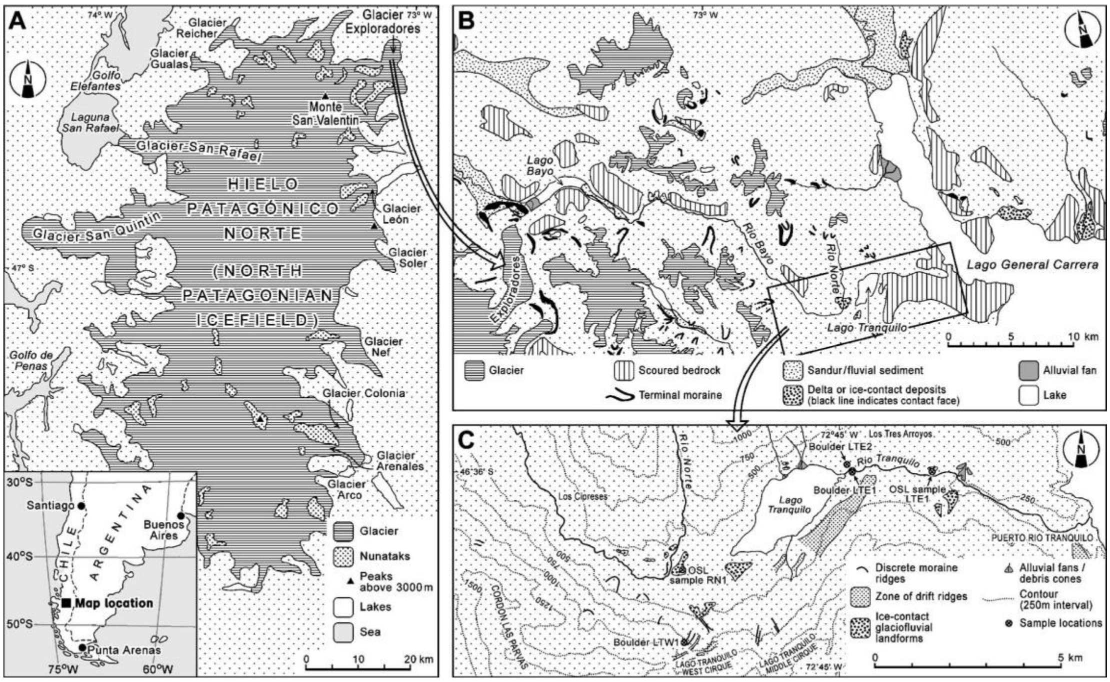

Figure 1. The study area in southern Chile, indicating place names and sample locations mentioned in the text. (A) The North Patagonian Icefield and its main outlet glaciers. (B) Outline geomorphological map of the Rio Bayo valley between Exploradores Glacier in the west and Lago General Carrera in the east. (C) Geomorphological map of the area around Lago Tranquilo. The location of boulders sampled for cosmogenic nuclide exposure age dating (Boulders LTW1, LTE1 and LTE2) and sample localities for OSL dating (OSL samples RN1 and LTE1) are indicated.

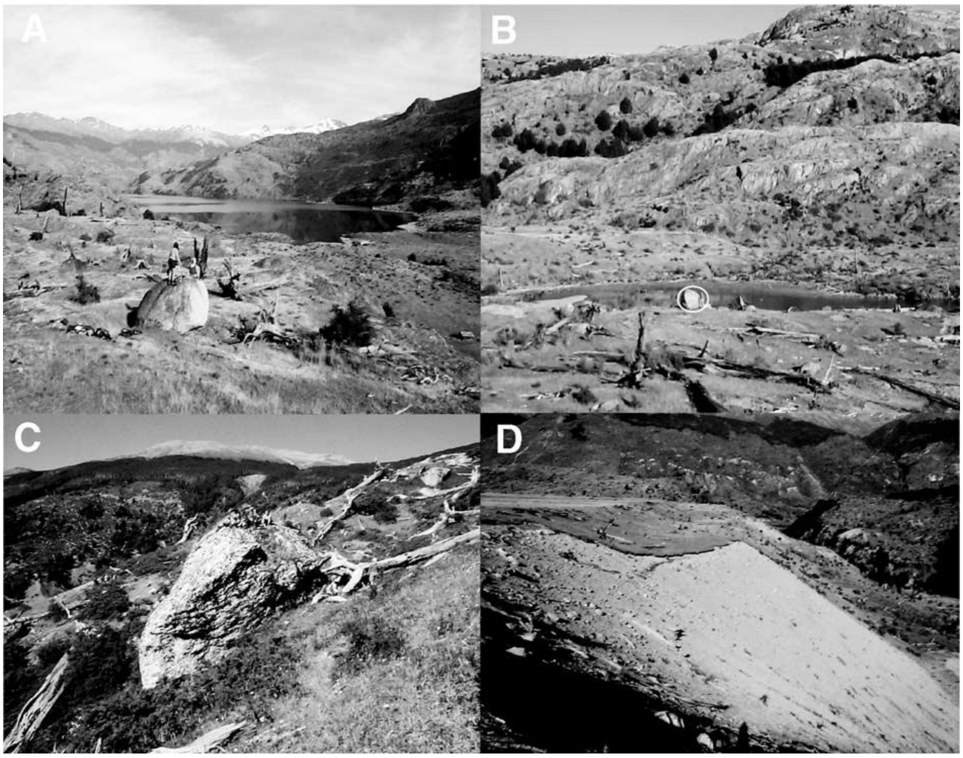

Figure 2. Cosmogenic nuclide exposure age and OSL dating sites. (A) Photograph of boulder LTE1 on the floor of the Rio Bayo valley. Note figures on boulder for scale. (B) Photograph of boulder LTE2 (ringed) on the floor of the Rio Bayo valley. Figure to right of boulder indicates scale. (C) Photograph of boulder LTW1 on large lateral moraine in cirque LTW above the main valley. Note figures on

boulder for scale. (D) Photograph of the ice-contact landform at Rio Norte. OSL sample RN1 was taken from the upper surface of the landform.

The outlet glacier of the North Patagonian Icefield in the Rio Bayo valley

Geomorphological evidence for a former extensive valley glaciation includes the extent and nature of ice-scoured bedrock, features of glacial and glaciofluvial deposition such as kames, large alluvial and ice-contact landforms built out from tributary valleys (such as at the mouth of Rio Norte), drift hummocks and subdued moraines (Fig. 1C). The moraines, drift hummocks and bedrock-cored ridges on the valley-floor comprise thin (c. 0.5–2 m, but locally thicker in places) layers of sandy gravel, sandy boulder-gravel or diamicton draped on a gently undulating bedrock surface (Figs. 2A and B). The sandy boulder-gravel, although texturally variable, is typically a massive boulder-gravel in a sand matrix. The alluvial and ice-contact landforms are large (c. 80 m high and 250 m wide) accumulations of sand and gravel located at the mouths of tributary valleys (Fig. 1C). The largest of these landforms, at the mouth of the Rio Norte Valley, is composed of a locally crudely-bedded to well-sorted sandy cobble-gravel (Fig. 2D). It is texturally variable but typical proportions are gravel (80%) and sand (20%). The kame features, located on the valley floor, are low (c. 7 m high), elongated (c. 15 m diameter) mounds of sand and gravel composed of variable amounts of fine to coarse sand, sandy gravel and cobble gravel (Fig. 3).

Two cosmogenic nuclide exposure age dates were obtained from two adjacent glacially transported boulders on the valley floor immediately east of Lago Tranquilo (boulders LTE1 and LTE2; Table 1 and Figs. 2A and B). These granitic boulders rest directly on an ice-scoured (striated and abraded) schist bedrock outcrop and yielded ages of 11,400 $\pm$ 900 yr and 10,500 $\pm$ 800 yr. Samples for OSL dating were obtained from an ice-contact glaciofluvial landform on the valley floor east of Lago Tranquilo (OSL sample Aber79/LTE1; Fig. 1C) and a large ice-contact glaciofluvial sediment accumulation at the confluence of the Rio Norte/Rio Bayo valleys (OSL sample RN1; Fig. 1C). Under subdued red lighting in the laboratory, quartz grains 180–211 Am in diameter were extracted using standard laboratory procedures. Over 1000 individual grains of each sample were then mounted in specially designed holders. Each sample holder consists of an array of 100 holes, each hole being 300 Am deep and 300 Am in diameter (Duller, 2004). The luminescence signal from each grain was then read individually using a focussed 532 nm laser mounted on a Risø automated TL/OSL reader (Bøtter-Jensen et al., 2003). The palaeodose for each grain was calculated using the single aliquot regenerative dose procedure, using five regeneration doses and associated test doses (Murray and Wintle, 2000). An important check on the validity of the data is to ensure that the grains being measured are pure quartz and do not contain other mineral components that may contribute to the OSL signal. For this purpose, the effect of illuminating the grains with infrared (880 nm) was measured. This has been shown to be an effective means of identifying the presence of other minerals, including feldspars (Duller, 2003).

Sample LTE1 yielded very little quartz, and less than 1% of the 1000 grains measured gave any measurable OSL signal. Of those grains that did give a measurable OSL, the majority showed evidence for the presence of feldspar inclusions based on the IR measurements.

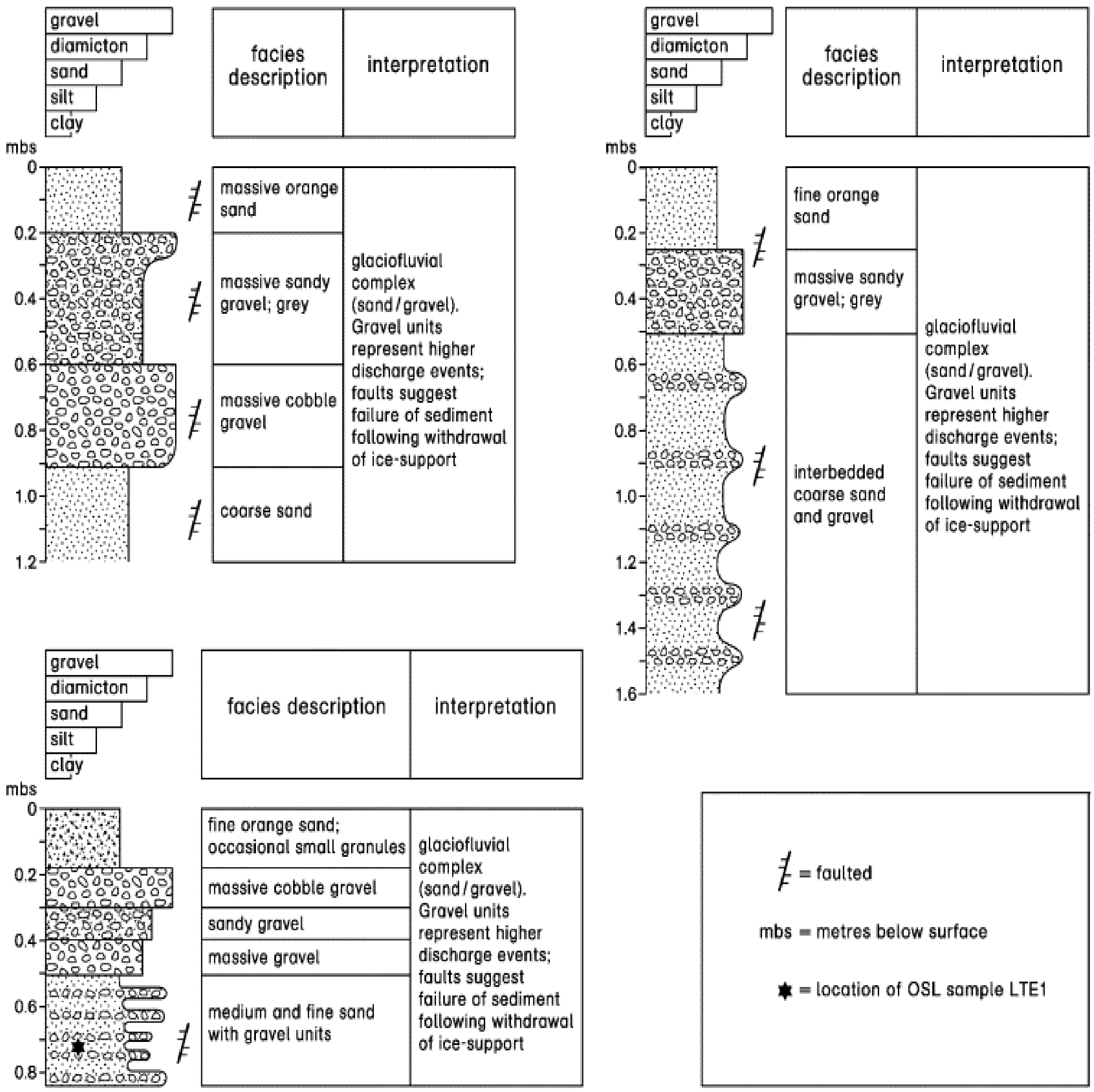

Figure 3. Sedimentary logs of the ice-contact glaciofluvial landform (kame) midway between Lago Tranquilo and Puerto Rio Tranquilo (see Fig. 1C for location), with summary facies description and interpretation of depositional process. Location of OSL sample LTE1 is indicated.

Thus, it was not possible to obtain an age for sample LTE1. For sample RN1, 1200 grains were measured. As with LTE1, many grains gave little or no luminescence signal. However, from the 1200 grains, 64 (5%) were shown not to have any evidence of contamination and to have a sufficiently bright OSL signal to enable a palaeodose to be calculated. Values range from 0.25 Gy to ~ 170 Gy. Analysis of these data is made complex by the large variation in the brightness of the OSL signal from different grains. The effect of this variation is that the precision with which palaeodoses can be calculated varies by over an order of magnitude.

Table 1

Cosmogenic nuclide exposure age estimates for three boulders in the Lago Tranquilo area

Boulder number	Altitude (m)	Latitude	Height (m)	Thick (cm)	Shielding Correction	^{10}Be 10^4 atoms/g	No-erosion exposure age (10^3 yr)	2 mm/ka erosion corrected exposure age (10^3 yr)
LTE1	336	46.612	2.3	3	0.991	7.71 ± 0.47	11.2 ± 0.9	11.4 ± 0.9
LTE2	317	46.611	1.8	4	0.980	6.86 ± 0.38	10.3 ± 0.8	10.5 ± 0.8
LTW1	773	46.652	3.0	3	0.982	12.00 ± 0.45	12.2 ± 0.9	12.5 ± 0.9

Note. AMS measurement errors are at the 1σ level, including the statistical (counting) error and the error due to the normalization to the standards and blanks. Exposure age errors include the production rate error but do not include errors due to latitude and altitude scaling. The overall uncertainty of a given exposure age should be less than 15% (see also Gosse and Phillips, 2001).

Plotting these data as a histogram is therefore inappropriate and Figure 4 shows the palaeodose values for 64 grains of sample RN1 on a radial plot (Galbraith et al., 1999; Duller,
2004). Each point represents the results from a single grain, and the more precisely known data are plotted to the right of the diagram.

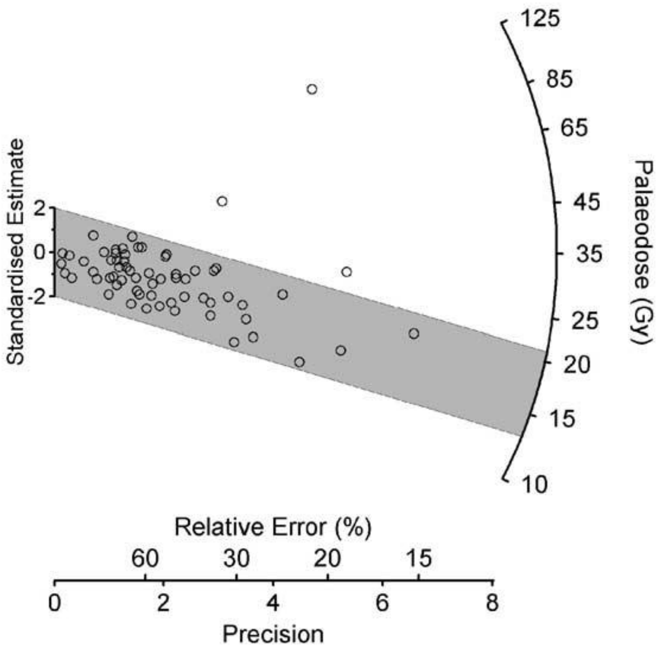

Figure 4. Radial plot showing the distribution of palaeodose values for 64 single grains of quartz from sample Aber79/RN1. See text for full explanation.

If one draws a line from the origin to the radial scale on the right of the diagram, any point along that line has the same palaeodose, but the precision with which it is known increases to the right. If all the grains had the same palaeodose value within their measurement uncertainties, they should all fall within a single band running from the origin to the radial axis. For this sample, it is clear that while many points are clustered along a single band with palaeodose values between 15 and 20 Gy, there are also some grains with much larger palaeodose values. To calculate the most appropriate value of palaeodose for age calculations, the minimum age model of Galbraith et al. (1999) was used. This gave a value of 16.8 $\pm$ 1.2 Gy, which is denoted by the shaded band on Figure 4. The dose rate for this sample was obtained by laboratory emission counting, and when combined with an estimate of the water content of 10 $\pm$ 5% this gives a dose rate of 1.73 $\pm$ 0.08 Gy/10^3 yr. Thus the age for sample RN1 is 9700 $\pm$ 700 yr.

Interpretation

Collectively, these landforms and sediments comprise a valley glaciation event when a large temperate valley glacier occupied the Rio Bayo valley. Ice-contact landforms were produced wherever meltwater from tributary valleys was impounded against the glacier. Evidence for this is their position relative to the main valley and their sedimentary composition (locally crudely-bedded to well-sorted sandy cobble gravel). The faulted and bedded sand and gravels exposed in the kames demonstrate that they were deposited by meltwater streams in an ice-contact environment. The alternation of sand and gravel units represents fluctuating discharge levels. These sediment associations are typical of those found in proglacial locations in other Patagonian valleys (e.g., Aniya, 1987; Harrison and Winchester, 1998).

The cosmogenic nuclide exposure ages for boulders on the valley floor indicate that the glacier withdrew from the Rio Bayo valley around 10,900 $\pm$ 1000 yr (mean of 11,400 $\pm$ 900 yr and 10,500 $\pm$ 800 yr). The Rio Norte ice-contact landform was built out against this body of glacier ice by meltwater draining from the Rio Norte valley up until 9700 $\pm$ 700 yr. The height of the ice-contact landform above the Rio Bayo Valley and its considerable size lend weight to this interpretation since sediment could not accumulate in this manner without such an ice mass in the Rio Bayo Valley below. The dates obtained for the ice-contact landform and the glacially transported boulders are thus consistent with the geomorphological setting.

Former cirque glaciers

Cirques and associated cirque moraines occur on the valley sides, with cirque floor altitudes rising generally from west to east. Natural exposures in the cirque moraines show that these are composed of sandy boulder-gravel and sandy gravel. The sandy boulder-gravel, although locally variable, consists of a massive boulder gravel in a sand matrix. The following proportions are typical: gravel 60%, sand 30% and mud <10%. The sandy gravel facies is a moderately well sorted unit, consisting of gravel (70%) and sand (30%). A boulder sampled on the moraine crest of the outer moraine of a cirque above Lago Tranquilo (sample LTW1 on Fig. 1; Table 1) yielded a cosmogenic nuclide exposure age date of 12,500 $\pm$ 900 yr.

Interpretation

The cirque moraines indicate a more restricted glacial advance. The sandy boulder-gravel and sandy gravel are interpreted as ice-marginal deposits, with a mixture of sediment types including those derived originally from basal glacial sediments (Glasser and Hambrey, 2002). We infer that the cirque glacier advanced to form this terminal moraine some time around 12,500 $\pm$ 900 yr.

Discussion

The cosmogenic nuclide exposure age and single-grain optically stimulated luminescence dates presented here indicate that an outlet glacier of the North Patagonian Icefield withdrew from the Rio Bayo valley around 10,900 $\pm$ 1000 yr and that an associated ice-contact landform developed against this ice mass up until 9700 $\pm$ 700 yr. The agreement between the two independent dating techniques provides confidence in these age estimates. An independent glacier in a high level cirque outside the main icefield advanced to form its terminal moraine around 12,500 $\pm$ 900 yr. Establishing the paleoclimatic significance of these data is difficult because of the temporal resolution of cosmogenic nuclide exposure age and OSL dating, and because previous studies have relied almost exclusively on radiocarbon. Calibrating radiocarbon results in this time interval is complex because of the existence of plateaux due to rapid changes in ^{14}C in the atmosphere.

These new data add to debates concerning Southern Hemisphere climate during the Late Pleistocene–Holocene transition (e.g., Denton and Hendy, 1994; Moreno et al., 2001; Markgraf et al., 2002; Rahmstorf, 2002; Andres et al., 2003). For example, there is considerable debate about the existence or otherwise of a cooling event in southern South America that may correlate with the northern hemisphere Younger Dryas chronozone (e.g., Bennett et al., 2000; Heusser, 2003; Glasser et al., 2004; Wenzens, 2001; McCulloch and Sugden, 2001).

Evidence for climate change during the Late Pleistocene–Holocene transition in the zone of the Southern Westerlies between 40° and 50° comes from a small number of sites where glacier advances have been dated and from sites where palaeoecological evidence is available. In the Chilean Lake District at 41° S, the age of a glacier advance at Lago Mascardi, originally dated to between 11,400 and 10,200 ^{14}C yr BP by Ariztegui et al. (1997), has recently been refined by precise radiocarbon dating (Hajdas et al., 2003). The dates presented by Hajdas et al. (2003) confirm that the final cooling phase in this locality began at ~11,400 14C yr BP, preceding the Younger Dryas by ~550 calendar years, and ended at 10,150 $\pm$ 90 ^{14}C yr BP. An advance of Grey Glacier on the southern edge of the South Patagonian Icefield at 50° S is dated on the basis of tephrochronology to between 12,010 ^{14}C years BP and 9180 $\pm$ 120 ^{14}C years BP (McCulloch et al., 2000).

Unfortunately, the palaeoecological evidence for climate change at this time is equivocal. At a site near Alerce in the Chilean Lake District (41° S), Heusser and Streeter (1980) used palynological evidence to show a reduction in temperature and increased precipitation at around 10,500 ^{14}C yr BP. Farther south at 43° S, analysis of chironimid remains from Taitao to the west of the North Patagonian Icefield indicates cooling during the Younger Dryas chronozone (Massaferro and Brooks, 2002). In southern Patagonia, White et al. (1994) showed evidence for strong warming at 10,000 and 12,800 ^{14}C yr BP, whilst in the vicinity of the North

Patagonian Icefield, Hoganson and Ashworth (1992) used beetle remains to suggest that no cooling occurred during the Younger Dryas chronozone in this region.

To summarize, the available evidence for cooling from palaeoecological studies around the Chilean Lake District and the North Patagonian Icefield is equivocal. Some studies show a climatic shift during the Pleistocene–Holocene transition (e.g., Heusser, 1993) whilst others (Markgraf, 1991, 1993; Ashworth et al., 1991; Lumley and Switsur, 1993; Bennett et al., 2000) do not. The data presented in this paper indicate that glaciers in the northeast sector of the North Patagonian Icefield were larger between 12,500 and 9700 yr than at the present day (cf Turner et al., 2005). Further work is required to elucidate the precise timing of this period of glacier expansion and to establish its palaeoclimatic significance.

Conclusions

This paper presents cosmogenic nuclide exposure age and single-grain optically stimulated luminescence dates from the vicinity of the North Patagonian Icefield during the Late Pleistocene–Holocene transition. These data are used to establish the extent of a large outlet glacier of the North Patagonian Icefield that withdrew from the Rio Bayo valley around 10,900 $\pm$ 1000 yr and the age of an ice-contact landform that developed against this ice mass up to 9700 $\pm$ 700 yr. Glaciers in cirques surrounding the icefield advanced to a maximum position at 12,500 $\pm$ 900 yr.

Acknowledgments

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