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[36]Cl terrestrial cosmogenic nuclide dating suggests Late Pleistocene to Early Holocene mass movements on the south face of Aconcagua mountain and in the Las Cuevas–Horcones valleys, Central Andes, Argentina

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Abstract: The morphology, sedimentology and mineralogy of deposits that previously had been associated with glacial advances (the Penitentes, Horcones and Almacenes drifts) were reinvestigated and dated using the terrestrial cosmogenic nuclide (TCN) [36]Cl. These results indicate that the deposits previously associated with the Horcones and Almacenes drifts are actually deposits of a rock slope failure from the southern face of Aconcagua mountain forming a debris–ice avalanche that were deposited 10 490 ± 1120 years ago, while the deposits previously associated with the Penitentes drift is a rock avalanche from the Mario Ardito valley that deposited in the Las Cuevas valley 11 220 ± 2020 years ago. Earlier in the Late Pleistocene a further rock–ice avalanche sourced from Aconcagua mountain and deposited in the Las Cuevas valley, predating related lake sediments with a calibrated ^{14}C age of 14 798–13 886 years and travertine deposits with a U-series age of 24 200 ± 2000 years. In addition, three further rock-avalanche deposits were dated that sourced from Tolosa mountain, having [36]Cl mean ages of 14 740 ± 1950 years, 12 090 ± 1550 years and 9030 ± 1410 years. No deposits of massive rock slope failures were found in those parts of the valleys that date younger, suggesting that climatic conditions at the transition from the Late Pleistocene to the Holocene, that were different from today's, caused the slopes to fail. Alternatively, the rock slope failures could have been seismically triggered. We suggest that the slope failures at the southern face of Aconcagua mountain have caused or contributed to a reorganization of glacial ice flow from Aconcagua mountain that might ultimately be the cause of the surging behaviour of the Horcones Inferior glacier today. Our results indicate that the glacial stratigraphy of this part of the Central Andes is still poorly understood and requires detailed mapping and dating.

Supplementary material: Sample coordinates, sample porosity and density, Cl nuclide composition and geochemical composition are available at http://www.geolsoc.org.uk/SUP18753.

The impact of climate warming on slope stability, mainly through thaw of alpine permafrost and debuttressing of glacially oversteepened, unstable rock slopes due to glacier retreat, has been the subject of much discussion (Abele 1974; Evans & Clague 1994; Noetzli *et al.* 2007; Huggel *et al.* 2010; Clague *et al.* 2012; Fischer *et al.* 2012). Except for the historic period, however, this causative relationship can only be demonstrated by dating large numbers of rock slope failures, although care has to be taken as both climate-related conditioning and seismic activity can result in multiple rock slope failures in a given region. In general multiple rock slope failures that occurred at the same time in the past are interpreted as indicators for palaeoseismic events, especially if additional independent indicators for such events exist (e.g. Adams 1981; Schuster *et al.* 1992; Moreiras 2006; Hermanns & Niedermann 2011). On the other

hand, temporal clustering of rock slope failures coinciding or following climatic changes are commonly interpreted as an indication that stability conditions of rock slopes are primarily linked to climate change. Statistically representative examples have been published from Norway, the European Alps and Scotland (e.g. Prager *et al.* 2008; Soldati *et al.* 2004; Hermanns & Longva 2012; Ostermann & Sanders 2012; Ballantyne & Stone 2013, respectively).

In the Andes the first systematic regional inventory of ages of rock slope failures was presented by Hermanns *et al.* (2000) for NW Argentina. Previously 25 of 55 mapped deposits had been dated; this dataset was extended by Hermanns & Schellenberger (2008) to 33 dated deposits. None of the mapped rock slope failures had a source on glaciated slopes, even though alpine glaciers reached down to 4300 m above sea-level (asl) in the easternmost

ranges during the Late Pleistocene (Haselton *et al.* 2002). Landslides occurred in the incised valleys mainly during periods of wetter climate; it is likely that enhanced runoff and lateral erosion of valley floors were the main causes of rock slope failures (Trauth *et al.* 2000; Hermanns & Schellenberger 2008). However, some large landslides apparently occurred during what are thought to have been dry phases of the Holocene. These exceptions occur near active faults and are interpreted to have been seismically triggered (Hermanns & Schellenberger 2008; Hermanns & Niedermann 2011).

At the transition between the Central and Patagonian Andes rock slope failures have occurred on a Plio-Pleistocene volcanic plateau incised by fluvial and glacial erosion by 200–1200 m deep valleys (Penna *et al.* 2011). About 80 percent of the landslide deposits occur in sections of the valleys that were eroded by glaciers and have higher local relief, indicating that glacial-toe erosion and debuttressing were important factors in conditioning the slopes for failure (Penna *et al.* 2011). However, because all of the rock slope failures predate the time of maximal glaciation in the area by more than 10 000 years, glacial erosion and debuttressing were conditioning, and not triggering, factors.

Due to similar landforms, large volumes, large aerial distribution, strong erosion and hence discontinuous deposits, deposits of rock slope failure are often misinterpreted as glacial landforms (e.g. Hewitt 1999; González Díaz 2003; Hewitt 2006). To recognize rock slope failures that fall onto glaciers is even more difficult, as the rock mass interacts with the glacial ice resulting in both run-out distances that are far beyond those of rock slope failures onto solid ground, and secondary processes once the ice melts within the sliding mass (Hauser 2002; Huggel *et al.* 2005; Evans *et al.* 2009). This has led to the misinterpretation of glacial advances and mountain valley evolution in the Himalaya and the Andes (e.g. Hewitt *et al.* 2011; González Díaz 2003, respectively). In the Central Andes the glacial advances were predominantly defined based on deposits in the Horcones, Las Cuevas and Mendoza valleys below Aconcagua mountain. With an altitude of 6959 m Aconcagua is the highest mountain in the Andes; due to their relatively easy access, the glacial deposits in Horcones, Las Cuevas and Mendoza valleys (Fig. 1) have been well studied (Espizúa 1993; Espizúa & Bigazzi 1998; Espizúa 1999). However, the origin of the supposed glacial deposits has been under dispute for a long time

Fig. 1. The study area lies in Argentina at the border with Chile and includes the Horcones and Las Cuevas river catchments down to the confluence with the Tupungato river where both rivers form the Mendoza river. The box indicates the area shown in Figure 2.

(Pereyra & González Díaz 1993). New sedimentological and geochronological data on those deposits suggest that a glacial origin is indeed an incorrect interpretation (Fauqué *et al.* 2009).

The glacial deposits of the Horcones, Las Cuevas and Mendoza valleys, although poorly constrained in age, are the reference section for glacial chronology in the Andes at *c.* 35°S (e.g. Heusser 2003; Zech *et al.* 2008). Zech *et al.* (2008) show that glacial advances in this area are asynchronous with glacial advances towards the north and south and suggest that this indicates that glaciations in the Aconcagua region are sensitive to precipitation while those further north and south are sensitive to temperature. We combine here data published in Spanish (Fauqué *et al.* 2009) with unpublished data to show that multiple deposits previously interpreted as glacial end moraines are massive landslide deposits and that therefore interpretation of the sensitivity of these deposits to various driving forces for glaciation must be made with care. Our data rather suggest that the timing of glacial advances in the area is not understood today and that an extensive effort needs to be made to establish a well-constrained glacial history of the Central Andes at 35°S. In turn this would also allow the driving forces of rock slope failures in this part of the Andes to be better constrained.

Geological setting

The study area lies along the Las Cuevas and Horcones valleys that lie at an elevation between 2500 m asl at the confluence of the Las Cuevas and the Tupungato rivers and the summit of Aconcagua mountain at 6959 m asl (Figs 1 & 2a). The study area does not include other valleys draining the Aconcagua massif that also contain deposits of large rock slope failures (e.g. Moreiras *et al.* 2008). The climate zones stretch from Tundra between 2700 and 4100 m altitude to Polar at altitudes above 4100 m, where mean monthly temperatures are below 0 °C (Minetti 1985); precipitation falls between May and October, mostly in the form of snow (Minetti 1986). The Las Cuevas and Horcones rivers are fed mainly by snowmelt and meltdown of glacial ice in the summer months. Glaciers exist in the study area on the south face of Aconcagua mountain and the lower Horcones valley.

This area lies at the transition from the Main Cordillera, characterized by Jurassic–Tertiary rocks, to the Frontal Cordillera, characterized by Permo-Triassic rocks (Giambiagi *et al.* 2003; Fig. 2b). The Main Cordillera is a thin-skinned thrust belt that exposes Jurassic–Tertiary clastic and volcaniclastic sediments and carbonates as well as Tertiary volcanic rocks (Ramos *et al.* 1996). The Frontal

Cordillera is composed of Permo-Triassic volcanic rocks and Jurassic intrusive rocks (Ramos *et al.* 1996). Within the Main Cordillera is the Aconcagua massif, built up of dacitic to andesitic volcanic rocks of Tertiary age. The remaining units are volcanic, volcaniclastic, clastic and carbonate rocks of Jurassic–Cretaceous age. These lithological differences are an important tool for determining the source area of landslides in the area that have travelled a long distance. Quaternary deposits are fluvial and glacial valley-fill deposits, moraines of previous glaciations, rock glaciers and deposits of various types of mass movements.

In this study, most of the glacial and mass-movement deposits were mapped out in the Horcones and the upper and lower Las Cuevas valleys (Fig. 3). All large landslide deposits have been sampled for age determination. Our earlier detailed mapping and dating (Fauqué *et al.* 2009) have shown that various deposits that had previously been interpreted as being of glacial origin based on relatively scarce chronological data with huge uncertainties (Espizúa 1993), are instead deposits of large mass movements while others indeed have a typical glacial morphology and are therefore of glacial age. This is suggested at least at two localities where lateral moraines were dated with single samples (Fauqué *et al.* 2009). Although this is not a statistically representative number of samples, these results give a first indication that the ages of these lateral moraines are *c.* 14 000 and 16 500 years old.

Methods

In this section, we first describe the morphology in connection with the lithology/mineralogy of the deposits. We then present multiple terrestrial cosmogenic nuclide (TCN) ages obtained with ^{36}Cl and accelerating mass spectrometry (AMS) ^{14}C ages of stratigraphically related deposits (Fauqué *et al.* 2009), as well as ^{36}Cl ages of multiple other large landslide deposits originated from massive rock slope failures in these valleys.

Mineralogical analyses

Mineral compositions (excepting clays) were determined by the analysis of 2–3 g (taken from 80 g of sample material, sieved to <35 μm) by X-ray powder diffraction using a D5000 diffractometer (Bruker AXS) at the Geological Survey of Canada Laboratory in Ottawa. Cu radiation and a secondary graphite monochromator were used. The diffraction data were collected from 4 to 70° 2θ with a step width of 0.02° and a counting time of 2 s per step. The generator settings were 40 kV and 30 mA. Quantitative phase analysis was determined
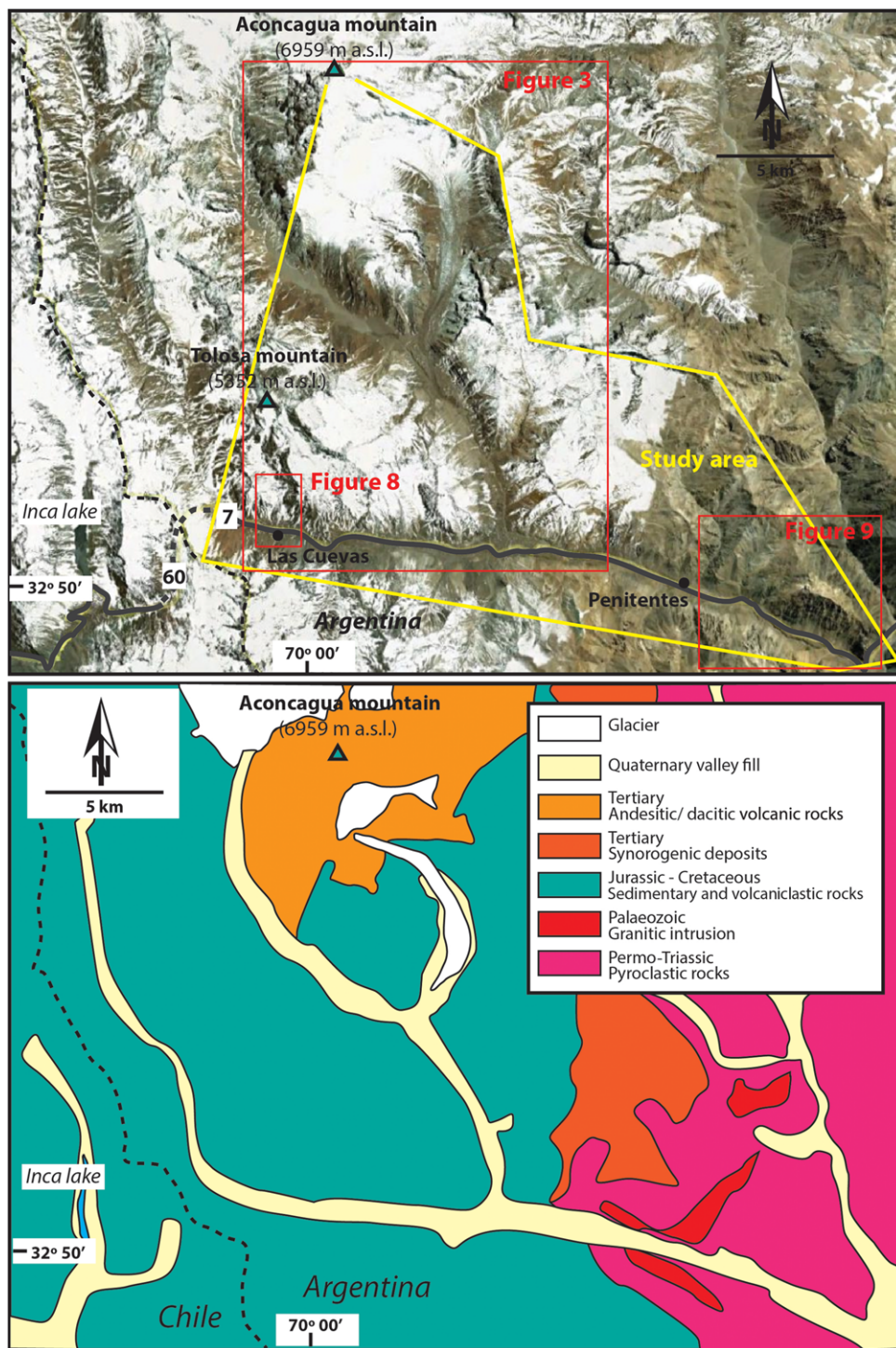
Fig. 2. (**a**) Satellite image of Aconcagua mountain and the Horcones and Las Cuevas valleys and outline of the study area. The boxes indicate the areas shown in Figures 3, 8 and 9. (**b**) Greatly simplified geological map of the study area showing main lithological differences between Aconcagua mountain and the Horcones and Las Cuevas valleys.
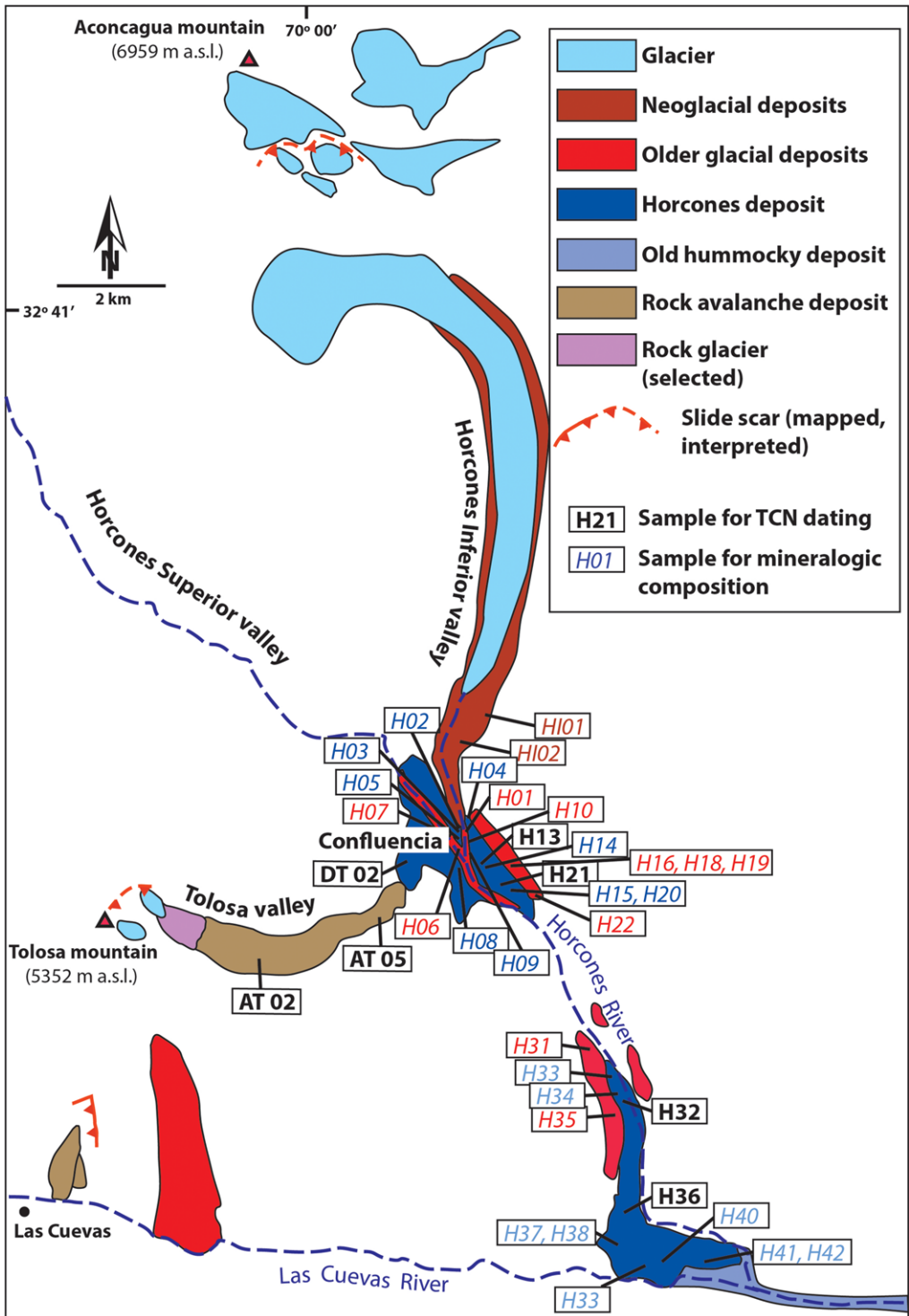
Fig. 3. Simplified and extended quaternary geological map after Fauqué *et al.* (2009) showing the distribution of selected quaternary deposits and sample sites for TCN dating and determination of mineralogical composition.

(a)

	HI 01	HI 02	H 01	H 02	H 03	H 04	H 05	H 06	H 07	H 08	H 09	H 10	H 14	H 15	H 16	H 18	H 19	H 20	H 22
Calcite	8.6	5.8	8.1					8.4	8.3	2.9		7.6			4.4	7.7	6.5		33.3
Dolomite																	3.3		5.2
Quartz	12.3	10.4	14.8	6.3	10.2	8.5	11.8	21.5	14.7	8.5	15.6	15.7	13.8	16.9	11.5	18.2	22.9	8.4	17.5
Plagioclase	58.7	59.4	43.2	70.6	79.4	70.9	77.2	58.6	49.9	77.4	72.6	46.9	61.2	68.8	50.9	44.3	40.0	78.3	32.7
Orthoclase			5.8																
Tremolite	6.6	4.6		8.2	9.2	6.5	4.4			6.9	6.7	1.4			1.6	1.0		9.1	
Clinochlore	12.0	2.9	6.7	13.7		12.6	4.1		17.8	2.8	1.7	6.1	11.8	9.0	7.2	6.0	7.0	3.1	7.0
Muscovite		4.2	7.1					6.7				17.8			15.4	17.9	16.3		2.9
Hastingsite			0.5																
Gypsum		1.2							3.8										
Hemetite	1.8	2.7	3.8	1.2	1.3	1.5	2.6	4.7	5.5	1.5		3.3	2.5	3.2	2.1	3.4	3.9	1.1	2.4
Ilmenite																			
Alunite											1.6		2.1	2.1	1.2	1.4			
Laumontite		9.0	10.0									1.2			5.5				

Fig. 4. Mineralogic composition in percent of sedimentological samples of supraglacial deposits (orange), basal and marginal moraine deposits (red), of the Horcones rockslide deposit in Confluencia (blue, see Fig. 4b), as well as of grey domains of the Horcones deposit in the confluence of the Horcones and Las Cuevas valleys (light blue, see Fig. 4b) and red domains in the same deposit (light red).

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(b)

	HI 31	HI 33	H 34	H 35	H 37	H 38	H 39	H 40	H 41	H 42
Calcite	10.5	4.1		14.6		14.2			3.5	5.1
Dolomite	4.3			2.2						
Quartz	37.9	7.1	14.6	20.0	15.1	14.2	12.5	9.5	9.1	5.1
Plagioclase	36.7	60.7	72.1	49.9	68.1	58.8	72.9	74.6	76.5	55.9
Orthoclase										
Tremolite		6.0	7.0	1.9	9.1		8.2	11.3	8.4	5.5
Clinochlore	3.5	11.0	2.0		3.6		5.7	3.9	1.5	5.8
Muscovite	4.2	3.2		4.1		4.5				9.0
Hastingsite						4.4				
Gypsum						1.4				
Hemetite	2.9	2.2	2.0	2.2	1.7	2.1	0.7	0.7	1.1	3.8
Ilmenite						0.4				
Alunite		1.6								0.7
Laumontite		4.3	2.4		2.3					9.0

Fig. 4. *Continued.*

using the Rietveld analysis technique contained in the BGMN/AUTOQUAN software package (Bergmann *et al.* 1998) and results are given in percent (Fig. 4).

Method of TCN dating using ^{36}Cl

As part of the Multinational Andean Project: Geosciences for Andean Communities feasibility study on reopening the trans Andean railroad connecting Mendoza with Santiago, we collected samples for ^{36}Cl dating in order to help estimate the rock-avalanche hazard in the area. Given good preservation of the deposits, surface exposure dating with cosmogenic nuclides is an excellent method for obtaining the age of a rock-avalanche deposit, and eliminates the need for stratigraphic interpretation. Excellent summaries of this method were published by Lal (1991), Cerling & Craig (1994), Kurz & Brooke (1994) and Gosse & Phillips (2001) and the method has been repeatedly used for dating mass movements (e.g. Ballantyne *et al.* 1998; Hermanns *et al.* 2001, 2004; Bigot Comier *et al.* 2005; Dortch *et al.* 2009; Antinao & Gosse 2009; Welkner *et al.* 2010; Blais-Stevens *et al.*

2011, and references therein). Here, we briefly review only the methods of sampling, principles of the method and correction factors, as they require some special considerations.

In selecting the boulders to be sampled, the geomorphological environment and surface characteristics were examined with great care. We selected boulders ranging from 1 to 30 m in diameter located in the central part of the deposit, away from any steps in the valley relief as well as from the failure surfaces of the Las Cuevas rock avalanches. We sampled when possible the uppermost 3–5 cm from central, horizontal surfaces of the boulders with a hammer and chisel to minimize any effects of boulder morphology on the resulting age (Masarik *et al.* 2000). We measured the shielding of the topography in steps of 30°. The local elevation was taken with a GPS and altimeter calibration in the morning. We therefore believe that the accuracy is within a margin of error of 20 m.

Sample density was measured in the Geological Survey of Canada Laboratory. Samples were prepared for isotopic concentration measurements at the PRIME Laboratory (Purdue University). Geochemical composition of rocks was analysed in

Table 1. *Results of ^{36}Cl cosmogenic nuclide ages of deposits in the Horcones and lower Las Cuevas valleys with different erosion rates*

	Erosion rate (mm thousand years^{-1})									
	0.00	0.56	1.11	1.67	2.22*	2.78	3.33	3.89	4.44	5.00
AT02										
Statistical mean	8890	8760	8650	8540	**8450**	8360	8270	8190	8120	8050
$\pm \sigma_2$	550	540	520	510	**500**	490	480	480	470	460
$\pm$ Snow cover	1400	1400	1300	1300	**1300**	1200	1200	1200	1200	1200
AT05										
Statistical mean	10 050	9920	9810	9700	**9600**	9510	9430	9350	9280	9210
$\pm \sigma_2$	560	540	530	520	**510**	500	500	490	480	480
$\pm$ Snow cover	600	600	500	500	**500**	500	500	500	500	500
DT02										
Statistical mean	9960	9930	9900	9870	**9850**	9820	9800	9780	9760	9740
$\pm \sigma_2$	830	830	820	820	**820**	810	810	810	800	800
$\pm$ Snow cover	600	600	600	600	**600**	600	600	600	600	600
H13[†]										
Statistical mean	8300	8260	8230	8200	**8170**	8140	8120	8100	8070	8050
$\pm \sigma_2$	750	740	730	730	**720**	720	720	710	710	710
$\pm$ Snow cover	500	500	500	500	**500**	500	500	500	500	500
H21										
Statistical mean	10 710	10 660	10 600	10 550	**10 510**	10 470	10 430	10 390	10 360	10 320
$\pm \sigma_2$	660	650	640	640	**630**	630	630	620	620	620
$\pm$ Snow cover	600	600	600	600	**600**	600	600	600	600	600
H32										
Statistical mean	11 390	11 310	11 240	11 170	**11 110**	11 050	11 000	10 950	10 910	10 870
$\pm \sigma_2$	160	160	160	160	**160**	150	150	150	150	150
$\pm$ Snow cover	700	700	600	600	**600**	600	600	600	600	600
H36[†]										
Statistical mean	8930	8850	8780	8710	**8640**	8580	8520	8470	8420	8370
$\pm \sigma_2$	710	700	690	680	**670**	660	650	650	640	630
$\pm$ Snow cover	500	500	500	500	**500**	500	500	500	500	500
PE01										
Statistical mean	15 200	14 800	14 450	14 150	**13 890**	13 650	13 430	13 240	13 070	12 910
$\pm \sigma_2$	1540	1460	1400	1350	**1300**	1270	1240	1210	1190	1170
$\pm$ Snow cover	1100	1000	1000	1000	**900**	900	900	900	800	800
PE02										
Statistical mean	11 020	10 900	10 800	10 710	**10 620**	10 540	10 470	10 400	10 330	10 270
$\pm \sigma_2$	1200	1180	1160	1140	**1120**	1110	1090	1080	1070	1060
$\pm$ Snow cover	800	800	800	700	**700**	700	700	700	700	700
PE03										
Statistical mean	12 720	12 460	12 220	12 010	**11 820**	11 650	11 500	11 360	11 230	11 110
$\pm \sigma_2$	1610	1540	1490	1450	**1410**	1370	1340	1320	1300	1280
$\pm$ Snow cover	900	900	800	800	**800**	800	800	700	700	700

*We assume that an erosion rate of 2.2 mm thousand years^{-1} is most representative. Ages are given with 2 sigma analytical uncertainty and an additional uncertainty based on snow cover of boulders.
[†]Not considered in calculation of the ages as interpreted too young due to boulder rotation (see text).

XRAL Laboratories (SGS Canada Inc.). Following these results, ^{36}Cl ages were calculated using a Microsoft Excel spreadsheet, CHLOE31, published by Phillips & Plummer (1996). One of the major uncertainties on the ages in this region is the estimation of snow cover. We used oral reports from park rangers of the Aconcagua Provincial Park, army employees from the Puente del Inca post, and the Argentine road authorities who also frequently transit the area in wintertime. Besides, this is an area of snow drift so that we can consider that the snow cover on large boulders is greater than that on top of smaller boulders. Taking into account these differences, we estimate an additional

Table 2. *Results of ^{36}Cl cosmogenic nuclide ages of deposits in the upper Las Cuevas valley with different erosion rates*

	Erosion rate (mm thousand years^{-1})									
	0.00	0.56	1.11	1.67	2.22*	2.78	3.33	3.89	4.44	5.00
CU0101										
Statistical mean	13 160	12 970	12 810	12 660	**12 530**	12 400	12 290	12 190	12 100	12 020
$\pm \sigma_2$	730	710	690	680	**670**	660	650	640	630	630
$\pm$ Snow cover	800	700	700	700	**700**	700	700	700	600	600
CU0102										
Statistical mean	12 630	12 420	12 240	12 070	**11 920**	11 780	11 650	11 540	11 430	11 330
$\pm \sigma_2$	670	650	630	610	**600**	590	580	570	560	560
$\pm$ Snow cover	600	600	500	500	**500**	500	500	500	500	500
CU0201										
Statistical mean	14 880	14 660	14 470	14 300	**14 140**	14 000	13 880	13 770	13 660	13 570
$\pm \sigma_2$	930	900	880	860	**850**	830	820	810	810	800
$\pm$ Snow cover	400	300	300	300	**300**	300	300	300	300	300
CU0202†										
Statistical mean	12 130	11 870	11 650	11 450	**11 270**	11 110	10 960	10 820	10 700	10 580
$\pm \sigma_2$	750	720	690	670	**650**	640	620	610	600	590
$\pm$ Snow cover	500	500	500	400	**400**	400	400	400	400	400
CUA01										
Statistical mean	12 400	12 240	12 090	11 960	**11 840**	11 730	11 630	11 540	11 460	11 380
$\pm \sigma_2$	1220	1190	1160	1140	**1120**	1100	1090	1080	1070	1060
$\pm$ Snow cover	1200	1100	1100	1100	**1100**	1000	1000	1000	1000	1000
CUA02										
Statistical mean	16 260	15 980	15 730	15 520	**15 330**	15 160	15 010	14 870	14 750	14 650
$\pm \sigma_2$	1500	1450	1410	1370	**1350**	1320	1300	1290	1280	1260
$\pm$ Snow cover	1500	1500	1400	1400	**1400**	1300	1300	1300	1300	1300
CU3										
Statistical mean	17 180	16 750	16 390	16 080	**15 810**	15 570	15 360	15 170	15 000	14 850
$\pm \sigma_2$	1730	1640	1580	1530	**1490**	1450	1420	1400	1380	1360
$\pm$ Snow cover	1700	1600	1600	1500	**1500**	1400	1400	1400	1400	1400
CU401										
Statistical mean	15 340	14 990	14 680	14 420	**14 190**	13 980	13 790	13 620	13 470	13 330
$\pm \sigma_2$	2160	2070	1990	1930	**1880**	1840	1800	1770	1740	1720
$\pm$ Snow cover	1400	1300	1300	1200	**1200**	1200	1200	1100	1100	1100
CU402										
Statistical mean	9700	9530	9380	9240	**9120**	9000	8890	8790	8700	8610
$\pm \sigma_2$	1460	1410	1370	1330	**1300**	1270	1240	1220	1200	1180
$\pm$ Snow cover	1200	1100	1100	1100	**1000**	1000	1000	1000	900	900

*We assume that an erosion rate of 2.2 mm thousand years^{-1} is most representative. Ages are given with 2 sigma analytical uncertainty and an additional uncertainty based on snow cover of boulders.
†Not considered in calculation of the ages as interpreted too young due to boulder rotation (see text).

uncertainty factor to the statistical uncertainty of analytical results. This uncertainty reflects the variation of snow cover as an estimate of the uncertainty resulting from the size of boulders in relation to the average snow cover in the area and the effect of wind on large boulders. This is necessary because we cannot know if a boulder of 5–10 m length and 10–15 m width is indeed snow-free if it overtops the surrounding area by the snow depth. Thus, we estimate an uncertainty due to snowdrifts by calculating the age without snow cover and a maximum estimated snow cover (Tables 1 & 2)

following the principle outlined in Blais-Stevens *et al.* (2011). The resulting difference is significant and amounts to as much as 15 percent of the age. However, if snow cover had been more pronounced in the past than today or vice versa this would apply to all samples, hence the relative age difference is mainly expressed by the analytical uncertainty.

In the summary of the results in Tables 1 and 2 we present different ages corresponding to an assumption that there was no erosion of the boulders, and that there were different erosion rates up to 5 mm ka^{-1}. We interpret the ages marked in bold

(erosion rate of 2.22 mm ka^{-1}) to be those closest to the true age of exposure. These erosion rates are similar to erosion rates used by Kaplan *et al.* (2004) and Costa & González Díaz (2007) in TCN studies, further south in the Argentinean Andes.

Results

Deposits at Confluencia, the confluence of the Horcones Superior and Inferior valleys

The Horcones Inferior glacier is a glacier which has had multiple surges in the past decades (e.g. Milana 2007; Fauqué *et al.* 2009; Pitte *et al.* 2009). At present the glacial terminus is *c.* 1.5 km NE of the Confluencia area (Fig. 3). However, several well-preserved interleaved lateral and frontal moraines up to 15 m in thickness indicate that the Horcones Inferior glacier has reached down to Confluencia in the recent past (Espizúa 1993, Fig. 5). The mineralogical composition of supraglacial deposits of the Horcones glacier and the neoglacial deposits (samples HI 01, HI 02, and H 06 respectively, Fig. 4) were taken as representative samples for glacial deposits. These have a composition of 58 percent plagioclase, 10–20 percent quartz, 6–8.5 percent calcite as well as various amounts of tremolite, clinochlore, muscovite, gypsum, laumontite and 1.8–4.7 percent hematite, the latter giving the reddish colour to those deposits.

On the east side of the Horcones valley occurs a lateral moraine that is several tens of metres high and stretches over 2 km (Fig. 3). Espizúa (1993) and Fauqué *et al.* (2009) agree upon the glacial origin of the deposit and Espizúa (1999) maps this deposit as the Almacenes lateral moraine. She assigns a maximum age of 15 000 ± 2100 years of underlying fluvial sediments to this unit that is in agreement with a single ^{36}Cl age obtained from a boulder, (which suggests that this moraine is 13 900 ± 2200 years old; see Fauqué *et al.* (2009)). The mineralogical composition and the colour of the lateral moraine (samples H 16, H 18, and H 19 in Fig. 4) are similar to the neoglacial deposits but on average 10 percent lower in plagioclase, 5 percent higher in quartz and higher in muscovite.

In vertical cuts it is visible that the valley floor of Confluencia is furthermore covered by deposits of the same reddish colour (Figs 5 & 6). These deposits are a polymict, matrix-supported conglomerate, with grain sizes rarely exceeding a few tens of centimetres in diameter (lower part of photo in Fig. 5). The mineralogical composition of this basal deposit (samples H 01, H 07 and H10 in Fig. 4) is identical with the lateral moraine deposit. The deposit is interpreted by Espizúa (1993) and Fauqué *et al.* (2009) as basal moraine. However, Espizua (1999) dates the deposit by thermoluminescence (TL) of quartz grains extracted from overlying fluvial deposits, up to 30 cm thick (photo in Fig. 5). These grains are older than 31 000 ± 3100 years.
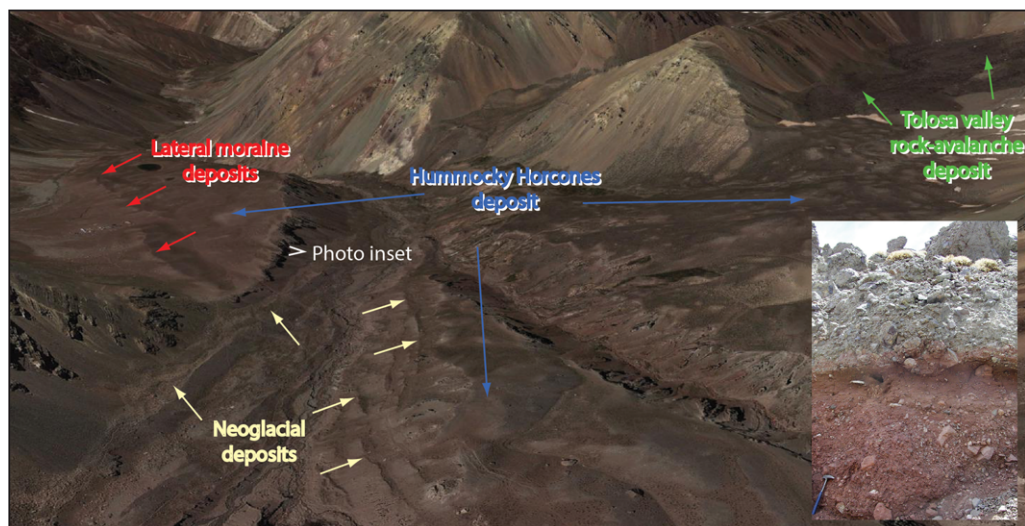
Fig. 5. Oblique satellite view towards SSW showing the Confluencia area (see Fig. 3 for location) with distribution and character of various deposits. Note the lower Aconcagua base camp east of the lateral moraine for scale. The location of the photo in the lower right corner is given by the open triangle and shows a lower reddish matrix-supported conglomerate covered by 30 cm fine-grained fluvial deposits in turn covered by a grey breccia that is matrix-supported in the lower part and clast-supported in the upper part (the hammer for scale is 29 cm high).

Fig. 6. Photo of site for sample AT02 over Quebrada del Tolosa rock avalanche towards hummocky deposit. Note that in the gorge eroded by Horcones Superior river it is visible that the greyish deposit is underlain by a reddish basal deposit.

Fauqué *et al.* (2009) AMS ^{14}C dated the same fluvial deposits with a whole organic content sample to a calibrated age of 13 543–12 098 years BP. It is unlikely that this fluvial deposit spans an interval of *c.* 18 kyr. However, based on missing additional ages for the underlying basal moraine it is not possible to determine whether (1) the TL age is too old and the quartz was not entirely bleached during transport or (2) the organic content of the fluvial deposit got contaminated by modern root penetration of the several-metre-thick overlying deposit. Alternatively, the deposit might have been formed at 31 000 $\pm$ 3100 years and has been on the surface until 13 543–12 098 years BP when covered by the overlying deposits.

Between the lateral moraine and the opposite valley side, the valley is entirely filled by a hummocky deposit. Hummocks are up to 20 m high with a high concentration of large boulders on their surfaces. The hummocky deposit also intrudes the Quebrada del Tolosa valley for a length of 1000 m stretching along the valley up to an altitude of 3570 m, which is 150 m above the elevation of the Confluencia area. In vertical cuts it is visible that this deposit is composed of grey breccias of several metres to several tens of metres thickness that are matrix-supported in its lower part and clast-supported in its upper part. The mineralogical composition (H 02, H 03, H 04, H05, H 08, H 09, H 14, H 15 in Fig. 4) is characterized by 60–80 percent plagioclase, 6–17 percent quartz, as well as tremolite, clinochlore and hematite. Calcite and muscovite are nearly absent from the deposit.

Espizua (1993, 1999) maps this deposit as the Almacenes moraine, and describes it as indistinguishable from the lateral moraine in Confluencia. We took three samples for TCN dating of the deposit using [36]Cl (samples H 13, H 21, DT 02 in Table 1). Ages obtained vary between 8170 $\pm$ 1220 and 10 510 $\pm$ 1230 years.

Further inside the Quebrada del Tolosa there is a massive deposit with a lobate form composed entirely of a volcanic conglomerate rock. The entire deposit is covered by a carapace of large boulders that vary in size between a few metres to tens of metres (Figs 3 & 6). The deposit spans two-thirds up the Tolosa valley, has lateral and frontal rims, and is thus mapped as a rock-avalanche deposit. The upper third of the Tolosa valley is covered by a rock glacier with typical concentric rings covering most of the deposit. It has ice close to the surface and is therefore interpreted as being active. The rock glacier connects to a niche in Tolosa mountain situated NE from the top that is today occupied by a glacier. This niche is interpreted as representing the scar area of the rock avalanche (Fig. 3).

These deposits have not been described previously. We dated two samples of selected boulders AT 02 and AT 05 that resulted in ages of 8450 $\pm$ 1850 and 9600 $\pm$ 1010 years, respectively.

Fig. 7. Oblique satellite view towards the NW of the confluence of the Horcones and Las Cuevas valleys showing the hummocky deposit dominating the area. On the west side of the Horcones valley a lateral moraine deposit has an elevation 100 m higher than the Horcones valley. In the foreground there is a more subdued hummocky deposit, mainly covered by scree deposits. Note for scale that the lake at the foot of the moraine is 200 m long. Photo A shows breccias with greyish and reddish domains overlain by lacustrine deposits (person for scale is 175 cm tall). Photo B shows breccias of the hummocky deposit that have reddish domains with polymict clasts that are more rounded and a greyish

Deposits at the confluence of the Horcones and Las Cuevas valleys

In the area of the confluence of the Horcones and Las Cuevas valleys, a prominent lateral moraine exists on the NW slope of the Horcones valley (Fig. 3). The top of the moraine is c. 100 m higher than the valley infill. On the opposite valley side only patches of this moraine are preserved (Figs 3 & 7). This lateral moraine in the Horcones valley had not been dated but was associated by Espizúa (1999) with a glacial advance called the Punta de Vacas moraine that has its frontal moraine further downstream in the Mendoza valley. There the deposits overlie alluvial fan sediments that contain a tephra layer dated by fission-track on glass shards to 134 000 $\pm$ 32 000 years. Fauqué *et al.* (2009) obtained a ^{36}Cl age on one boulder from that deposit of 16 510 $\pm$ 2110 years. The deposit has a reddish colour and is composed of 36–50 percent plagioclase, 20–38 percent quartz, 15–17 percent carbonates, 4 percent muscovite, 2–3 percent hematite as well as tremolite and clinochlore (samples H31 and H35 in Fig. 4). Although otherwise indicated on an overview map (Espizúa 1993) no lateral moraines exist at this confluence inside the Las Cuevas valley (Rosas *et al.* 2007).

Similar to the valley fill at Confluencia, the valley floor here is also filled by a hummocky deposit (Figs 3 & 7). The deposit spans the entire Las Cuevas valley and thus caused the damming of the valley as indicated by lacustrine sediments directly overlying the rim of the hummocky deposit (Espizúa 1993; Fauqué *et al.* 2009). Furthermore the deposit forms a lobe downriver within the Las Cuevas valley that is 2 km long and ends in an abrupt 20 m high front. Downriver more subdued hummocks continue that are strongly covered by rock-fall cones from the side of the valley. This surface is cemented by a travertine layer.

This hummocky deposit was previously interpreted as a frontal moraine (Espizua 1993, 1999) of a separate glacial advance (the Horcones moraine) but was reinterpreted as the deposit of a mass movement (Fauqué *et al.* 2009). The deposit has large boulders up to several metres in diameter on the surface. In erosional cuts along the Horcones and Las Cuevas rivers as well as along the road it is visible that the deposit is patchy with greyish and reddish domains. While the reddish domains are in general polymict, the greyish domains are rather monomict. The deposit is a matrix-supported breccia. The transition between the domains is often

sharp (Fig. 7b) and the deposit was sampled for its mineralogy in both the greyish and reddish domains (light blue and light red respectively in Fig. 4, H 37–H 42). While the greyish domains have a higher concentration of plagioclase, tremolite and clinochlore, with carbonates and muscovite being nearly absent, the reddish domains in contrast contain both carbonates and muscovite as well as a higher concentration of hematite. Also, the deposit below the travertine layer is a breccia containing boulders more than 10 m in diameter and has the same greyish and reddish domains. Separated outcrops of the deposit can be found along the gorge of the Las Cuevas river down to its confluence with the Tupungato river, where the Mendoza river forms. Similar deposits can also be found locally in patches several hundred metres long along the Mendoza river (Fig. 2); however, the end of this older deposit is difficult to determine as side valleys have not been investigated and the deposits within Mendoza river could easily also have sourced from any other side valleys. To map out the lower limit of this lower deposit, detailed mapping of valley-fill deposits in all side valleys of the Mendoza river valley has to be carried out.

Espizua (1999) dated the travertine layer underlying the hummocky deposit in the Las Cuevas valley with U-series ages to 24 200 $\pm$ 2000 years and 22 800 $\pm$ 3100 years. A further travertine layer overlying the hummocky deposit was dated to 9700 $\pm$ 5000 years (Bengochea *et al.* 1987). This is congruent with AMS ^{14}C ages on whole organic carbon of the lake sediments that were deposited in the Las Cuevas valley that were dated to whole organic carbon to calibrated ages of 14 798–13 886 years BP obtained from sediments close to the bottom of the lacustrine sequence and of 8620–8254 years BP close to the top of this unit (Fauqué *et al.* 2009). Two samples were taken for ^{36}Cl dating of boulders from the top of the younger pristine hummocky deposit (H 32 and H 36 in Table 1). Ages obtained are 11 110 $\pm$ 760 years and 8640 $\pm$ 1170 years and therefore do not coincide within uncertainties.
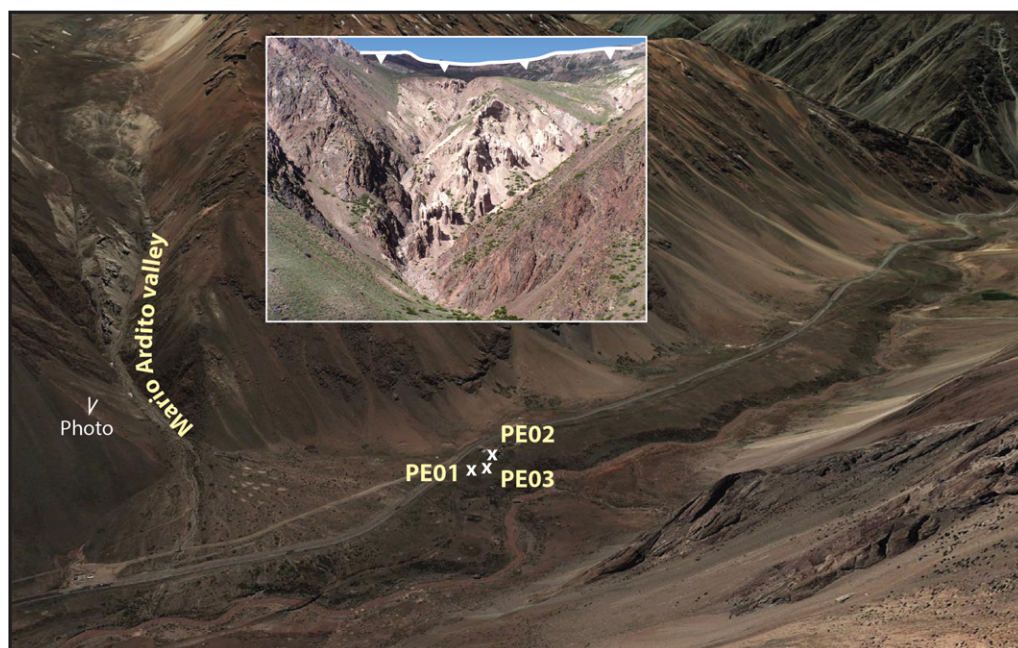
Rock-avalanche deposits within the Las Cuevas valley

Rock-avalanche deposits at Las Cuevas. Ten kilometres upriver from the confluence of the Horcones and the Las Cuevas valleys massive deposits of mass movements exist at the Las Cuevas locality

Fig. 7. (*Continued*) domain that is mainly composed of the same lithology (hammer for scale is 29 cm high). Photo C shows the lower more subdued hummocky deposit. The top of that deposit is sealed by travertine. Also this breccias is patchy with greyish and reddish domains. The height of the travertine layer above the river is 18 m.
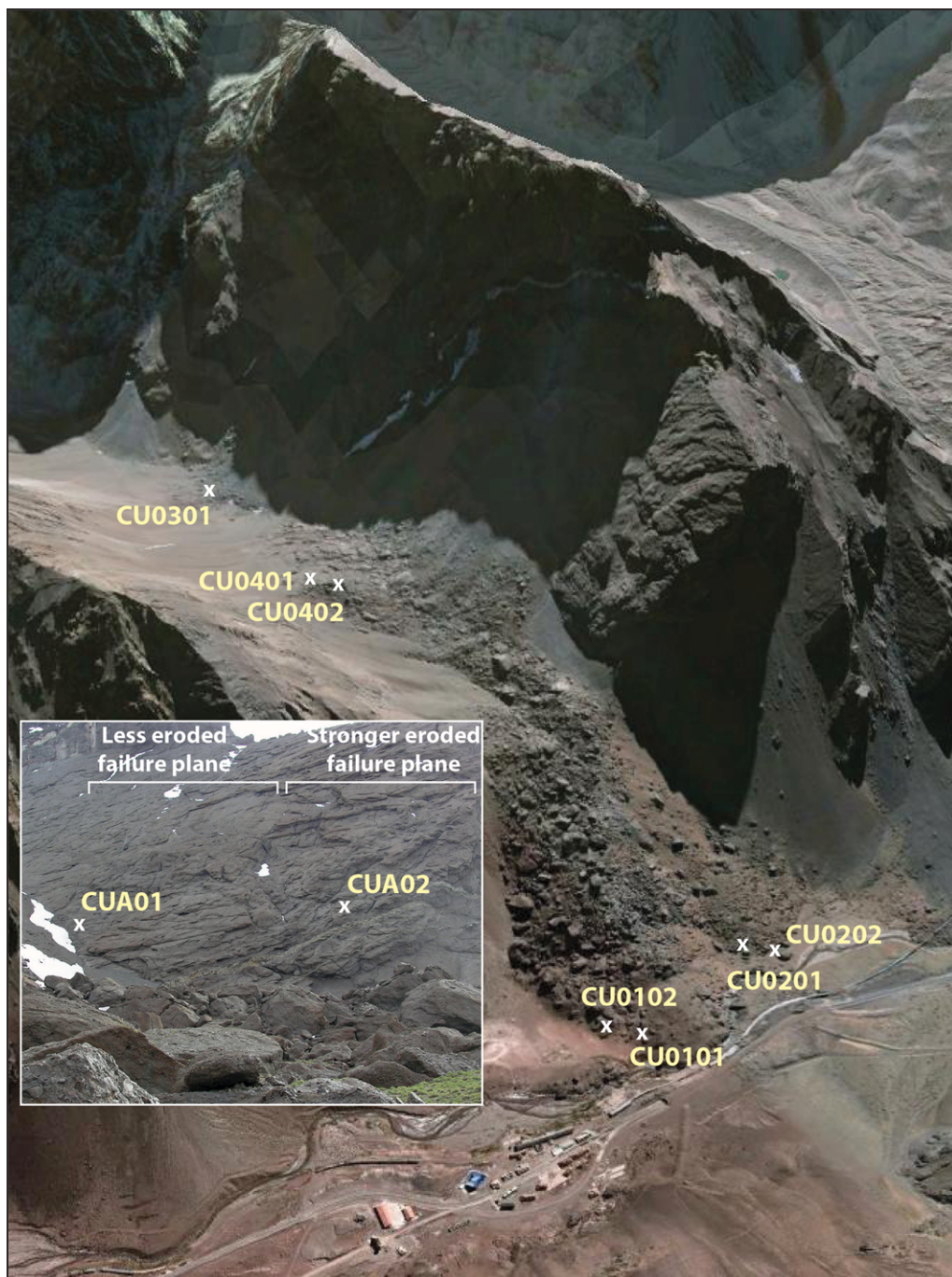
Fig. 8. Oblique satellite view towards NE showing the locality of Las Cuevas, lobate deposits of mass movements, rock-fall deposits within hanging side valley, west-facing failure surface, and sample locations (note for scale that the elongated building with a red roof in the foreground is 57 m long). The photo highlights the difference between the northern and southern parts of the failure surface.

Fig. 9. Oblique satellite view towards NE showing a massive deposit filling the Las Cuevas valley over a distance of 3 km and Mario Ardito side valley with landslide scar and filled with rock-avalanche deposits. The photo shows landslide deposits several tens of metres thick filling the Mario Ardito valley.

(Rosas *et al.* 2008) that were sourced from the southern side of Tolosa mountain (Fig. 3). Two lobate rock-avalanche deposits covered with boulders several metres to tens of metres in diameter partially overlie each other (Fig. 8). While the eastern deposit has a more subdued morphology, the western deposit is more pristine. The deposits lie directly below an important niche in the mountain that has a pronounced failure surface dipping *c.* 40° west towards a hanging side valley. Along the failure surface two distinctive domains can be discriminated based upon the development of erosional features (Rosas *et al.* 2008; Fig. 8). The northern part of the sliding plane is smooth and continuous while the southern part is partially eroded by channels and slabs that are missing. We sampled both domains of the sliding plane, and both lobate deposits within the valley as well as rock-fall deposits within the hanging side valley for ^{36}Cl TCN dating. While sampling the more eroded failure surface we took care over the most outstanding spurs to avoid sampling surfaces that were eroded post-failure. The sample from the more eroded and hence older failure surface resulted in an age of 15 330 ± 1350 years; this is slightly older than the age of the partially covered, more subdued and therefore older deposit that resulted in ages of 11 910 ± 1100 and 14 100 ± 1150 years (CUA02,

CU0201, and CU0202 in Table 2 and Fig. 7, respectively). The sample from the less eroded and therefore younger failure plane resulted in an age of 11 810 ± 1120 years that coincides well with the ages obtained for the samples taken from the overlying more pristine and therefore younger lobe that yield ages of 12 530 ± 1330 years and 11 920 ± 1100 years (CUA01, CU0101, and CU0102 in Table 2 and Fig. 7, respectively).

The samples CU3, CU401 and CU402 that were taken from rock-fall deposits from two distinct deposits (Table 2; Fig. 8) resulted in ages of 15 810 ± 2990 years, 14 190 ± 3080 years and 9120 ± 2300 years, respectively; these ages overlap within uncertainties. Hence, two rock avalanches sourced from that side of Tolosa mountain in the Late Pleistocene, and rock-fall activity has also been more active than in the Holocene.

Rock-avalanche deposit east of Penitentes. Eleven kilometres east of the confluence of the Horcones and Las Cuevas valleys and 1.5 km east of the locality of Penitentes, a massive deposit fills the Las Cuevas valley floor for a distance of 3 km (Figs 2 & 9). This deposit was previously interpreted as the end moraine of a glacial advance sourcing from the Horcones valleys and mapped as the Penitentes moraine (Espizúa 1993). Travertine

that lies between two deposits interpreted as tills was dated with a $^{230}Th/^{232}Th$ age to 38 300 ± 5300 years (Espizúa 1999). The deposit is a breccia composed of material that is exposed within the Frontal Cordillera. No material sourcing from the Main Cordillera was recognized (Fauqué *et al.* 2009). In addition the texture and composition of the deposit is identical to a rock-avalanche deposit that fills the Mario Ardito side valley that enters the Las Cuevas valley at the upper end of the deposit and was therefore reinterpreted as belonging to the same rock-avalanche event. Although the boulder carapace of this deposit is much less developed than at the rock-avalanche deposits originating from Tolosa mountain, this landslide is interpreted, due to the run-out distance, to be a rock avalanche and is defined here as the Penitentes rock-avalanche deposit. As would be expected, boulder size is smaller as the source area coincides with a important thrust fault (Ramos *et al.* 1996) that caused a significant break-down of the source rock prior to its failure.

Three samples (PE01, PE02 and PE03) were taken for TCN dating (Table 1; Fig. 9) using ^{36}Cl, resulting in ages of 13 890 ± 2200, 10 620 ± 1820 and 11 820 ± 2.210 years, respectively. Ages coincide within uncertainty limits and the mean age of the three ages is 12 110 ± 2100 years.

Discussion

The source and genesis of the hummocky Horcones deposit

Neoglacial deposits in the lower Horcones valley have a mineralogical composition corresponding to a mixture of the lithologies cropping out in the Horcones valley that include both the andesitic south face of Aconcagua mountain and the sedimentological rocks that crop out in the valley. Besides the relative quartz/plagioclase/tremolite content showing the andesitic composition of the Aconcagua source, the carbonates are also ideal for determining the source of the sediment as they do not occur within the south face of Aconcagua mountain. The neoglacial deposits are closer to an andesitic composition than the lateral moraines preserved from earlier glaciations (Fig. 4). This is likely to be because the lower Horcones glacier does not erode the valley walls along the part where it overlies the sedimentary sequence (Fig. 3), thus fresh bedrock originates from the south face of Aconcagua mountain only; all other materials transported by the glacier are remobilized Quaternary sediments. The older glacial deposits are more enriched in carbonates and more distinct due to their andesitic composition and are interpreted to represent a

more balanced average composition of the Horcones valley. These deposits have polymict clasts and are well homogenized as no spatial variation is visible. The lateral moraine deposits are also identical in colour and composition to the lower unit in Confluencia that fills the valley. Hence these deposits are interpreted as being of the same glacial origin and that they are basal moraines.

Beside the lateral moraines and on top of the basal moraine, hummocky deposit fills the entire valley over a distance of 2 km at Confluencia (Figs 3 & 5). This deposit has only andesitic boulders and its mineral composition is predominantly andesitic. Carbonate minerals as tracers for sedimentary rocks are nearly absent. Such hummocky deposits do not occur within the Horcones Superior and Horcones Inferior valleys; the only possible source for these andesitic rocks is Aconcagua mountain. The Horcones Superior valley is today ice-free and if this deposit had sourced out of that valley, any deposits should be preserved also inside the Horcones Superior valley. In contrast, the Horcones Inferior valley today is covered by the Horcones glacier and neoglacial deposits; a connection of the Horcones deposit to the southern face of Aconcagua mountain would therefore be masked. Indeed the southern face of Aconcagua mountain is represented by bedrock, glaciers and snow fields only and several large niches within the face exist from which large volumes could source (Fig. 10). We tentatively marked a niche that is today filled by two hanging glaciers as the potential source area (Figs 3 & 10). Most striking of the morphology of the south face of Aconcagua mountain is the missing catchment of the valley hosting the Ventisquero de Relinchos glacier (Fig. 10). This valley is *c.* 1.2 km wide in its lower parts but only a tiny glacier *c.* 10 m wide fills its upper part. While the northern slope of that valley is represented by the south face of Aconcagua mountain, a southern limiting slope is missing. Furthermore this hanging valley connects directly to a niche filled by the Superior glacier of the south face of Aconcagua mountain. This is a hanging glacier that is disconnected from the lower Horcones glacier but feeds that glacier by calving. The missing southern slope of the Ventisquero de Relinchos valley thus represents a missing andesitic rock mass on the south face of Aconcagua mountain that was eroded in the past from the south face. We postulate here that the andesitic deposit in Confluencia is at least part of that mass that had failed in one or more massive landslides into the Horcones Inferior valley.

A rockslide origin of the hummocky Horcones deposit is suggested not only by its morphology and purely andesitic origin but also by the position of this deposit within the Quebrada del Tolosa, being 150 m higher than its position in Confluencia
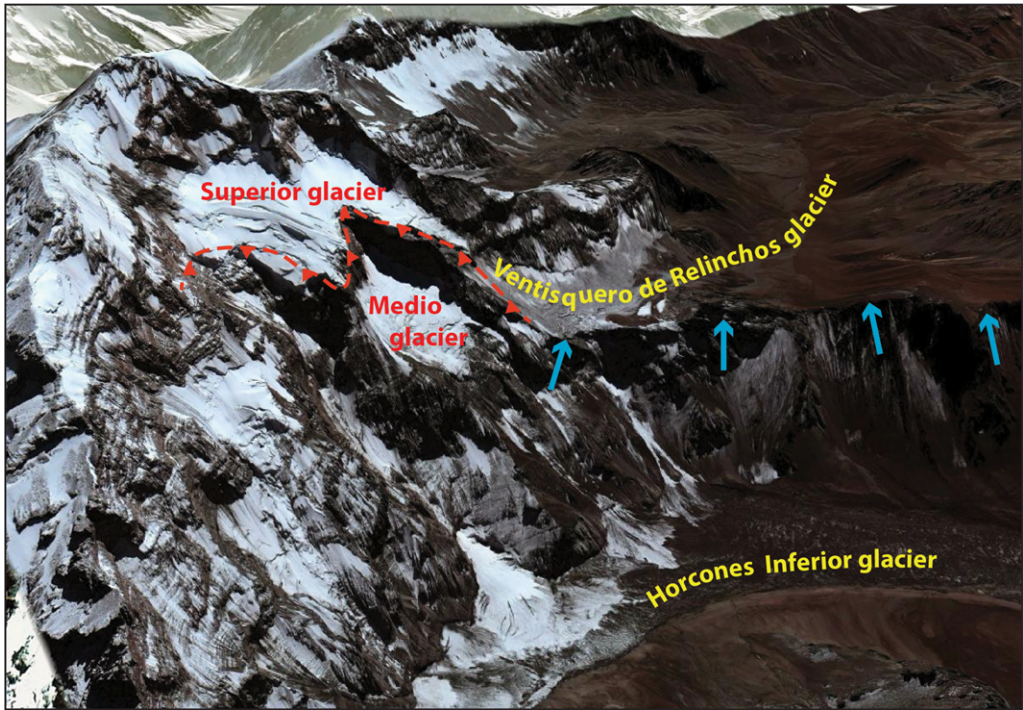
Fig. 10. Oblique satellite view of the south face of Aconcagua mountain showing the distribution of today's glaciers. Blue arrows mark abrupt termination of the Ventisquero de Relinchos valley floor that has no upper catchment matching the lower part of the valley. Note that the altitude difference between the Horcones Inferior glacier and the top of Aconcagua mountain is 2500 m.

and thus representing a run-up (Figs 3 & 5). In order for a glacier that sedimented in the Tolosa valley up to that altitude to have deposits sourced from the southern face of Aconcagua mountain, the glacier would need to have been at least 150 m thick at Confluencia; however, the lateral moraine at Confluencia is only a few tens of metres above the base of the valley. This further supports the landslide origin.

The hummocky deposit has the same morphology and texture at the confluence of the Horcones and Las Cuevas valleys (Figs 3 & 7). However, the composition has changed slightly, as expressed by a patchy distribution of reddish breccias with polymict clasts and greyish breccias with monomict clasts (Fig. 7b). The greyish domains have an andesitic composition nearly identical to the deposit at Confluencia while the reddish domains have a composition that is a mixture of the andesitic breccias and the glacial moraine deposits. Thus those reddish domains are interpreted to be glacial deposits entrained into the landslide.

The terminus of the pristine hummocky deposit lies within the Las Cuevas valley 21 km away from the foot of the southern face of Aconcagua

mountain. However, downriver from that and cemented by travertine there is an identical deposit with more subdued hummocky morphology. The terminus of this is not mapped out yet but deposits have been found at least further 10 km downriver. This deposit is interpreted to be of the same source and type as the stratigraphically higher and more pristine hummocky deposit. It is not possible to locate a second niche in the south face of Aconcagua mountain as hanging glaciers occupy the massif and are likely to have reshaped its face. The travel distances of both hummocky deposits are very long. This is especially true as the velocity of the landslides was 54 m s^{-1} at Confluencia (calculated on the basis of the run-up height at Confluencia of 150 m following the principles of Crandell & Fahnestock (1965)) but not significant at the confluence of the Horcones and Las Cuevas valleys (no deposits showing run-up could be found). Therefore these deposits do not represent typical rock-avalanche deposits. This is not surprising as a failure on the south face of Aconcagua mountain would have fallen on the Horcones Inferior glacier. Such rock-slope failures onto glaciers in other parts of the Andes and the world have entrained large amounts

of glacial ice (Hauser 2002; Huggel *et al.* 2005; Evans *et al.* 2009) that have always resulted in an excessive travel distance of the landslides and a change of landslide behaviour as ice started melting out. It can also be expected that a failure at the southern face of Aconcagua mountain would have entrained glacial ice into the flow. This ice would have melted not only during sliding but also out of the deposit after deposition (thermocast). Thermocast also explains the strong hummocky morphology of the Horcones deposit. Such a deposit is not as compact as a typical rock avalanche and erosion of hummocks and deposition into depressions left by melted glacial ice can be expected. Such mass redeposition on the surface would also affect the position of large boulders, causing rotation and toppling. This strongly influences cosmogenic nuclide production in boulders, as boulder surfaces that are horizontal today have not necessarily been horizontal in the geological past, and this would have resulted in lower irradiation and a lower age determination. For this reason, a large spread of ages of boulders on the deposit is to be expected (see below). We argue therefore, following Fauqué *et al.* (2009), that the pristine hummocky deposit at Confluencia and at the confluence of the Horcones and Las Cuevas valleys represents the deposit of the same landslide deposit (hereafter called the Horcones deposit, Fig. 3) that originated from the south face of Aconcagua mountain. Hence the deposit represents that of a debris-ice avalanche. The underlying deposit in the Las Cuevas valley that has a surface with more subdued hummocks, is interpreted similarly to be the deposit of a similar but much older debris-ice avalanche originating from the same source. The origin is therefore distinct from previous interpretations (Espizúa 1993, 1999) in which these deposits were defined as frontal moraines of various glacial advances (Almacenes, Horcones). In the same way the Penitentes rock-avalanche deposit does not represent a glacial end moraine but rather the deposits of a rock avalanche from a side valley (Fauqué *et al.* 2009). Therefore the situation in the high Andes of Argentina is similar to the Himalaya where deposits of rock slope failures have been misinterpreted as glacial deposits (Hewitt 1999).

It is not possible to establish the failed volume that caused the younger and older debris-ice avalanche based on the deposits, as deposits are strongly eroded along several kilometre-long stretches of the valley, for example, the younger deposit is entirely eroded for more than 3 km in the narrowest part of the Horcones valley (Fig. 3). In addition we showed that significant entrainment of moraine material had occurred before the debris-ice avalanche arrived in the Las Cuevas valley. The volume also cannot be established based

on the source area as we do not have information on the prefailure topography, and the niche in the south face of Aconcagua mountain is today almost entirely filled with a hanging glacier making a reconstruction of the failure surface very difficult. Furthermore, the travel distance of 21 km between the foot of Aconcagua mountain and the lower limit of the Horcones deposit is considerable. This is in line with run-out behaviour of rock slope failures on to ice in other parts of the Andes and the world (Hauser 2002; Huggel *et al.* 2005; Evans *et al.* 2009; Delaney & Evans 2014).

Quality of TCN ages

TCN is an ideal tool to date the age of rock-avalanche deposits as no further material than the deposit itself is needed and no stratigraphic interpretations with under- or overlying deposits have to be taken into account (e.g. Ballantyne *et al.* 1998; Hermanns *et al.* 2001; Hermanns *et al.* 2004; Dortch *et al.* 2009). However, Ivy-Ochs *et al.* (2009) were able to show a very wide range of ages by dating a large number of boulders on the same surface of a rock-avalanche deposit that was deposited in a single event. This is interpreted as being due to pre-exposure on the rock slope prior to failure in the case of older ages, or block rotation of the boulders following rock-avalanche deposition in the case of younger ages. Therefore, TCN ages that do not coincide with the average of multiple ages are not considered further when calculating the mean age of all samples for a given surface (Ballantyne & Stone 2013; Martin *et al.* 2014). Our multiple TCN ages from the various sampled deposits presented in this paper coincide in general within analytical uncertainty limits (Fig. 11). However, there are a few exceptions. Two boulders sampled from the Horcones deposit date as too young in comparison to three other samples. As discussed above, rotation of blocks is typical for surfaces that undergo thermocast and the younger ages are therefore excluded from data for calculating the age of the event. One of the boulders sampled from the Penitentes rock-avalanche deposit is dated as older than the other two. This sample is of a different litholology and is therefore interpreted as having been exposed before becoming entrained into the landslide. Also, one of the samples from the older lobe at Las Cuevas has a younger date and is again interpreted as representing a boulder that rotated after rock-avalanche deposition.

The Las Cuevas river upstream from the confluence of the Horcones and Las Cuevas valleys had been temporarily blocked in the Late Pleistocene into the Holocene (Figs 3 & 7); sedimentation rate was probably low in this lake basin in the Late Pleistocene as two additional blockages of
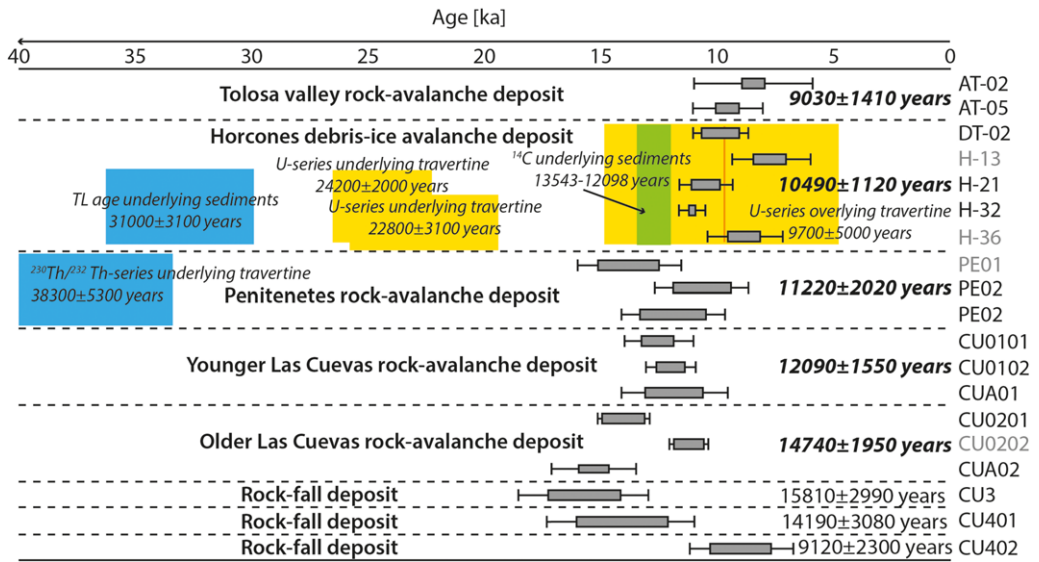
Fig. 11. Overview of ^{36}Cl ages of samples given in this study and average age for the deposit as well as previously published ages for each deposit: U-series, ^{230}Th/^{232}Th and TL ages from Bengochea *et al.* (1987) and Espizúa (1999); ^{14}C age from Fauqué *et al.* (2009). The boxes represent the ages including analytical 2 sigma uncertainties, while the error bars represent the uncertainty due to snow cover. The age of the deposit is based on the samples represented with a black label. Sample ages given with sample number in grey are not considered as these ages are interpreted as being too old or too young, due to pre-exposure of the sample prior to landsliding or due to boulder rotation after deposition, respectively.

the Las Cuevas river existed, one due to rock-avalanche deposits at Las Cuevas, the other due to glacial deposits. The related lake sediments were dated by AMS ^{14}C dating of organic material extracted from the lake deposit (Figs 3 & 7; Fauqué *et al.* 2009), resulting in calibrated ages of 14 798–13 886 and 8620–8254 years BP. The older ages predate the pristine Horcones deposit, also suggesting an older event of similar type (see discussion above). The younger ages postdate the Horcones deposit. Furthermore, ^{14}C ages of organic materials within fluvial deposits directly underlying the Horcones deposit in Confluencia fit both with a calibrated age of 13 543–12 098 years BP and the stratigaphic position (Fig. 11). In addition, all our ages fit within the stratigraphic position and with previously published ages obtained by TL dating, U-series dating and ^{230}Th/^{232}Th dating. However, often there are considerable time gaps between the ages of the underlying strata and the deposit itself.

Ages of large rock slope failures in the Horcones and Las Cuevas valleys

The age of the Horcones and underlying older hummocky deposits. The age of the deposit underlying the hummocky Horcones deposit has not yet

been directly determined. However multiple stratigraphic relationships give a minimum age. At Confluencia only one deposit exists that originated from the south face of Aconcagua mountain. A single TCN age of the lateral moraine at that locality suggests that the area was still covered by a glacier at 13 880 ± 830 years (Fauqué *et al.* 2009). At the same time the confluence of the Horcones and Las Cuevas valleys was dammed by a breccia that has reddish and greyish domains as suggested by overlying lacustrine sediments that yielded a calibrated ^{14}C age of 14 798–13 886 years BP. That this area was ice-free at that time is suggested by a single boulder from the lateral moraine in the Horcones valley dated to 16 510 ± 2110 years (Fauqué *et al.* 2009). The age of this deposit is further contrained by U-series dating of travertine that cements its surface, yielding two ages of 24 200 ± 2000 and 22 800 ± 3100 years (Espizúa 1999).

The Horcones deposit, in contrast, postdates a fluvial phase in Confluencia dated with a calibrated ^{14}C age to 13 543–12 098 years BP (Fauqué *et al.* 2009). This coincides with the multiple ^{36}Cl TCN ages presented here that assign a mean age of the deposit to 10 490 ± 1120 years (Fig. 11). These ages are further supported by the top of the lacustrine sediments in the Las Cuevas valley having a

calibrated ^{14}C age of 8620–8254 years BP (Fauqué *et al.* 2009), indicating that by that time this landslide barrier was still not eroded. Furthermore a U-series age of 9700 ± 5000 years of a travertine layer overlying the Horcones deposit is congruent with our age (Bengochea *et al.* 1987).

Ages of other rock avalanches from Tolosa mountain and from the Quebrada Mario Ardito. Similarly to the landslides sourced from the south face of Aconcagua mountain, all rock avalanches in the Las Cuevas and adjacent valleys that have been dated with ^{36}Cl TCN, date to the end of the Pleistocene. From Tolosa mountain two rock avalanches occurred on the south side; the failure planes could be differentiated by the degree of erosion and the deposits partially overlie each other. The older of the two events has an age of $14\,740 \pm 1950$ years while the younger has an age of $12\,090 \pm 1550$ years (Fig. 11). Hence the largest time interval of the exposure history of both sliding planes was common. The visible strong variation of erosional features of both planes might be explained by the three ages of rock-fall deposits sourcing from the same slope and dating between $15\,810 \pm 2990$ years and 9120 ± 2300 years suggesting that geomorphic processes were much more intensive at the transition from the Pleistocene to the Holocene than throughout the Holocene (Fig. 11). This is also suggested by the age of the rock avalanche that occurred on the east side of Tolosa mountain that dates to 9030 ± 1410 years. Also the rock avalanche that sourced from the Mario Ardito valley and entered the lower part of the Las Cuevas valley has, with an age of $11\,220 \pm 2020$ years, a Late Pleistocene age.

Possible causes for temporal distribution of slope failures in the Horcones and Las Cuevas valleys

It is not within the scope of this paper to redefine the glacial chronology of the Horcones and Las Cuevas valleys. However, we have shown that multiple deposits previously interpreted as representing frontal moraines are actually deposits of massive rock slope failures. Therefore the glacial chronology should be established on lateral moraines that exist in those valleys. So far only two of these moraines have been dated with single ^{36}Cl ages (Fauqué *et al.* 2009). One is the lateral moraine in the Horcones valley close to the confluence with the Las Cuevas valley (Figs 3 & 7) that has an age of $16\,510 \pm 830$ years and the other the lateral moraine at Confluencia (Figs 3 & 5) that has an age of $13\,880 \pm 830$ years (Fauqué *et al.* 2009).

The large rock slope failures dated in our paper have ages that follow the last glacial advance, while the Holocene was free of such events in the study area. This suggests that climatic changes towards warmer conditions might have conditioned the slopes to fail. Evans & Clague (1994) propose that (1) slope debuttressing by glacial erosion and glacial retreat, (2) permafrost melting, and (3) increased pore-water pressure within the slope might have conditioned slopes for failure in the Canadian Rockies. Special emphasis has been given in recent years to the effects of permafrost melting (Noetzli *et al.* 2007; Fischer *et al.* 2012; Huggel *et al.* 2010) that can condition large rock slopes to fail. The permafrost in the Central Andes lies today at an elevation of 4000 ± 200 m (Schrott 1991), and was not likely to have been lower at the end of the Pleistocene due to larger glacial extents. With elevations of the source areas of the rock avalanches on the south side of Tolosa mountain and in the the Mario Ardito valley lying at 3900 and 3500 m asl, respectively, this effect might have contributed to those failures. In contrast the interpreted source areas of the rock avalanche lie on the east side of Tolosa mountain and on the south face of Aconcagua mountain at elevations of 4300–5200 and 5200–5800 m asl, respectively. Hence neither permafrost melting nor enhanced pore-water pressure could have contributed to destabilizing rock slopes. However, both the uppermost Tolosa valley and the south face of Aconcagua mountain are occupied by glaciers today. Hence, increased glacial erosion at the foot of those mountains during the Late Pleistocene might have contributed to failure.

Rock-avalanche deposits overlying each other and failure surfaces with significant variation of erosional features clearly indicate two generations of events at Las Cuevas, although uncertainty margins are overlapping (Fig. 11). The younger event coincides in age within uncertainty margins with the age of the Horcones deposit and the age of the rock avalanche in the Tolosa valley, as well as the age of the Penitentes rock-avalanche deposit, and therefore they could have occurred simultaneously. The source area of all rock slope failures lies within a periphery of only 20 km. The older deposit at Las Cuevas coincides with the age of a rock-avalanche deposit damming the Inca lake in Chile (Welkner *et al.* 2010) in a distance of less than 10 km (Fig. 2). Applying the relationship of distance v. magnitude of triggering earthquakes given by Keefer (1984) all rock slope failures, except the older debris-ice avalanche deposit in the Las Cuevas valley, might have been triggered by two earthquakes within the study area that had a magnitude 6 or higher. Seismic triggering is also proposed as a possible cause for rock avalanches

at Laguna del Inca (Welkner *et al.* 2010) and elsewhere in Chile close to our study area (Sepúlveda *et al.* 2012).

This temporal distribution of large rock slope failures is different outside the Aconcagua region in the Central Andes of both Chile and Argentina. In Chile, Antinao & Gosse (2009) indicated that rock slope failures distribute more or less evenly over the Late Pleistocene and Holocene, yet the number of events in the Middle Pleistocene was reduced. In contrast, in the Cordon de Plata south of Uspallata in Argentina, all rock slopes failures are several tens to hundreds of thousands of years old (Moreiras 2006; Fauqué *et al.* 2008). The only exceptions in this part of Argentina are three rock avalanches along the Mendoza river that date into the Late Pleistocene and Early Holocene (Hermanns & Longva 2012). This river also drains the glaciated part of the Andes, and enhanced erosional undercutting of valley slopes due to glacial meltdown might also act here as a conditioning factor.

Therefore the situation in this part of the Andes is different from the transition from the Central Andes to the Patagonian Andes 600 km to the south or in the northern Central Andes 800 km to the NNW. In the south most rock slope failures occurred on glacial oversteepened slopes in the Middle Holocene but postdate deglaciation by *c.* 10 kyr (Penna *et al.* 2011). In the north most rock slope failure in valleys correlate with phases of higher precipitation and runoff in the Late Pleistocene and Holocene (Trauth *et al.* 2000; Hermanns & Schellenberger 2008).

Surges of the Lower Horcones glacier

The lower Horcones glacier had multiple historical surges (e.g. Habel 1897; Milana 2007; Fauqué *et al.* 2009; Pitte *et al.* 2009; Wilson 2010). The last surge occurred in 2004 and followed a summer characterized by enhanced snow and ice avalanches on the south face of Aconcagua mountain (personal communication of park rangers of Aconcagua provincial park). This glacier is fed only by snow and ice avalanches from Aconcagua mountain as the lower catchment is too small to form a glacier of that size and lies just above the modern permafrost line. If the Ventisquero de los Relinchos valley had not been captured on the south face of Aconcagua mountain, this ice – which today drops onto the Horcones Inferior glacier – would flow off to the east into the Ventisquero de los Relinchos valley (Fig. 10). Hence ice distribution on Aconcagua mountain might have significantly changed due to slope failures. Because of this, the glacial history of Aconcagua mountain cannot be assessed by studying moraine deposits in the Horcones valley alone. Also, valleys draining to the

east have to be analysed to understand past glacial dynamics on Aconcagua mountain.

Conclusions

We have studied the morphology, sedimentology and mineralogy of deposits previously interpreted as glacial deposits in the Horcones and Las Cuevas valleys as well as TCN-dated them using ^{36}Cl. Although some of these deposits contain moraine material, they are related to large rock slope failures that entrained moraine deposits and probably ice on their path. Our data suggest that two rock slope failures sourced from the south face of Aconcagua mountain. These failures might have rearranged glacial flow significantly. This is supported by a captured glacial valley that is missing its upper drainage on that side of Aconcagua mountain. These slope failures dropped into the Horcones Inferior valley and travelled over the glacier. They passed the glacial front and deposited a mixture of rock materials from the south face of Aconcagua mountain and entrained glacial deposits on their way further down-valley in the Horcones and Las Cuevas valleys. The first event had a higher mobility and predates $24\,200 \pm 2000$ years. The second event occurred at the transition from the Late Pleistocene to the Holocene. Four further rock slopes failures date to the time between 15 ka and the onset of the Holocene. No deposits of large younger rock slopes failures have been recognized in this section of the valleys suggesting that processes related to climatic changes in the Late Pleistocene caused the slopes to fail. Alternatively, all slope failures except the older debris-ice avalanche from the south face of Aconcagua mountain could have been triggered by two earthquakes with magnitudes higher than 6.

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