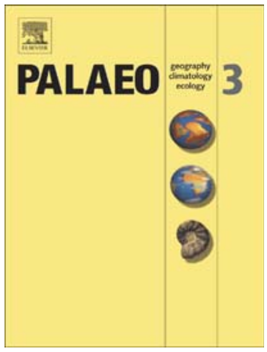

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Geomorphological response to the Lateglacial-Holocene palaeoenvironmental changes in the NE piedmont of the Sierra de Aconquija (Tafí Valley, NW Argentina)

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Abstract

Fluvial basins located on the NE side of the Sierra de Aconquija and facing the Tafí valley (NW Argentina) enable a study of the sedimentary records of valleys and alluvial fans that have been subject to glacial and periglacial dynamics since the Fini-Pleistocene to Upper Holocene. i) The oldest morphosedimentary unit (H1A) encompasses the Late Glacial and Early Holocene. A relationship was established linking fluvioglacial terraces to records from El Rincón profile (Younger Dryas) belonging to the most important glacial phase (G1) in the cirques found in the NE of Aconquija; ii) similarly, there is a G2 glacial phase (Neoglacial) that could be connected with the H1B records of the Muñoz River and dated to Early-Middle Holocene; iii) the final units (H2 and H3 from Upper Holocene) form a stepped terrace in the valleys and were interpreted as corresponding to the rock glacier phases from the high mountains and highlighting those that were active during the LIA.

Key words: glacial, periglacial, alluvial fans, coupled systems, Quaternary.

1. Introduction

Glacial and Periglacial geomorphological studies from the tropical Andes and N Argentina and Chile have acquired increasing importance in recent years, especially when considering improvements in our understanding of the chronological and regional paleoenvironment (Payne, 1998, Rodbell et al., 2009; Ahumada et al., 2017; Azócar and Brenning, 2010; Martini et al., 2013, 2017; Zech et al., 2009, 2017; Jomelli et al., 2014, 2017; Janke et al., 2015; Solomina et al., 2015; Ward et al., 2015, 2017; Mark et al. 2017). The main importance of the mountainous area is the isolated character of the glacial and periglacial testimonies due to its arid conditions. These remains were preserved due to the adequate altitude and orientation. The Sierra de Aconquija, NW Argentina, is one of the mountainous massifs whose physical testimonies regarding the cold environment are little known despite articles being published nearly a century ago (Tapia, 1925; Rohmeder, 1941, 1942) and including studies by Stingl and Garleff (1985), Fox and Strecker (1991), Haselton et al. (2002) and Ahumada et al. (2010, 2013).

The objective of this paper is to present the evolution of the NE side of the Sierra de Aconquija during the Lateglacial and Holocene periods. Sedimentary records from the piedmont area of the Las Carreras depression (Tafí valley) were taken together with the glacial and periglacial morphologies of the head basins. The Fini-Pleistocene and Holocene morphosedimentary information was introduced into the Tafí valley morphosedimentary context and completed by other proxies showing connectivity relationships between glacial-periglacial features and fluvial processes inside a coupled system (Brunsden and Thornes, 1979; Brunsden, 1993). This perspective may be applied in other intramountainous depressions from NW Argentina where these types of proxies are also confluent and important for paleoenvironmental reconstructions.

1.1. Regional settings and study area

The Tafí valley is an intramountain depression located in the Sierras Pampeanas in the Tucumán Province, NW Argentina. The valley has an elongated shape and is N-S oriented with its lower part located at between 1800-2500 m asl. The east and west borders are the high reliefs of the Cumbres Calchaquíes and the Sierra de Aconquija respectively, surpassing the 4600 m asl, while the southern limit is marked by the Cerro Ñuñorco Grande (3320 m asl). Inside the valley, an intermediate relief (Loma Pelada, 2680 m asl) divides the depression in two areas; the eastern side is drained by Tafí River, while the western side is drained by its two main tributaries, the Muñoz and Mollar Rivers (Fig. 1).The Mollar and Tafí Rivers converge at La Angostura reservoir (built in 1977) and flow down to the Tucumán plain through a narrow gorge named La Angostura and the river's name then changes to Los Sosa River.

The surrounding mountains exert an important role as a climatic barrier for the wet easterly winds, and so the climate is semiarid with average rainfalls of between 450-550 mm (Tafí del Valle, 476 mm) (Peña-Monné et al., 2018). Most of the rain falls in the summer (around 82%) when wet air masses arrive from the SE. The average annual temperature is 13.1ºC. Snow is scarce in the valley but more frequent in the summits during the winter, even during the dry season. The vegetation is adapted to these environmental conditions. Alder (*Alnus acuminata*) and queñoa (*Polylepis australis*) woodlands are widespread on the slopes and within the ravines, while most areas are grassland. It is necessary to consider that the area has been strongly deforested by human activities since Prehispanic times and has never recovered (Sampietro-Vattuone et al., 2018).

From the geological and structural point of view, the Tafí depression has a tectonic origin. The main fault is N-S oriented (Tafí del Valle fault) and located on the NE border. This fault is accompanied by other parallel faults located on the margins of Aconquija and Loma Pelada (Gutiérrez and Mon, 2004). The dominant lithologies in the mountains are granite, granodiorite, and metamorphic rocks (banded schists, biotitic and moscovite schists, and phyllites) (Ruíz Huidobro, 1972) of Precambrian to Lower Paleozoic ages. Some small Quaternary deposits are dominant at the bottom of the depression with small Tertiary outcrops. These include Pleistocene loess (Zinck and Sayago, 1999; Kemp et al., 2003; Schellenberger et al, 2003; Schellenberger and Veit, 2006) and large Holocene slope, terrace, and alluvial fan accumulations (Sampietro-Vattuone and Peña-Monné, 2016; Peña-Monné and Sampietro-Vattuone, 2019).

Previous studies established the geomorphological evolution of the eastern side of Tafí Valley analyzing the Holocene deposits on the eastern slope of Loma Pelada (Sampietro-Vattuone and Peña-Monné, 2016; Peña-Monné and Sampietro-Vattuone, 2016). The geomorphological and paleoenvironmental evolutionary model was also applied to the Cumbres Calchaquíes piedmont, the Tafí valley (Peña-Monné and Sampietro-Vattuone, 2019a), as well as to the evolution of the accumulations at the Sierra de Quilmes and El Paso, both in the Santa María valley (Peña-Monné and

Sampietro-Vattuone, 2016; Peña-Monné and Sampietro-Vattuone, 2018; Sampietro-Vattuone et al., 2019a) showing its regional relevance. The model settles the existence of four aggradative units separated by incision phases named H1 to H4, from the oldest to the younghes. The earliest stage (H1) covers the Early and Middle Holocene (until *ca*. 4200 cal BP). During its formation the environmental conditions changed from wet in the early times (H1A) to drier by the end of the period (H1B). After an incision phase, another three aggradational phases (H2, H3, H4) were defined, also separated by degradational stages, with H2 being the most represented in the landscape. Unit H3 was related to LIA times and H4 to sub-actual and present environmental conditions.

The study area covers the SW sector of the Tafí valley, on its limit with the Sierra de Aconquija (Fig.1). This mountainous unit is located in the Catamarca and Tucumán provinces and reaches a maximum height of 5552 m asl. Its northern section closes the western side of Tafí valley in a continuous line until the Abra del Infiernillo (3052 m asl) at the northern tip of the valley and the headwaters of the Blanco River (3845 m asl), and reaches its maximum height in the southern corner of the valley at Alto de Muñoz (4461-4572 m asl). Precambrian and Paleozoic granitic and metamorphic rocks dominate, while pegmatite and quartz dykes are abundant. Together with summit planation there are also castle rock and tor reliefs on the highest slopes that result from ancient weathering processes, as well as glacial cirques reflecting a Quaternary glacial presence. The Los Alisos and Muñoz rivers collect most of the NE Aconquija hillside waters and generate a wide piedmont formed by alluvial fans. The Los Alisos and Las Carreras alluvial fans are especially extensive (Fig. 1).

2. Methodology

A geomorphological map was made to understand the spatial distribution of the landscape units, as well as their spatial and temporal connectivity. Aerial photographs in several scales (from 1970, 1987, 2000) and images from GoogleMaps (2013-2016) were used. This cartography was complemented with field work during 2016-2018 when drones (DJI Phantom 4 and Mavic Pro) were used to gain access to inaccessible areas. Field data positions were taken with a GPS Garmin Montana 650 and the information was used to construct a GIS (QGIS v. 2.18).

Many stratigraphic profiles were recorded (25), although just five were selected due to their morphosedimentary representativeness. They belong to the Muñoz River upper valley (acronym CA), and the Mollar River El Rincón area (acronym RI). Samples for radiocarbon datings were taken and analyzed at the Laboratorio de Radiocarbono (Universidad de La Plata, Argentina) and DirectAMS Laboratory (USA). All radiocarbon datings were calibrated with OxCal 4.2 (2014) software, using the Southern Hemisphere calibration curve. Datings were expressed in cal years BP, expressed with 2 sigma. Tephra samples were analyzed at INENCO (CONICET-UNSA) to establish their geochemical characteristics for use as geochronological markers (as their ages are already known) (Sampietro-Vattuone et al., 2017).

For the paleo-ELA (paleo-Equilibrium Line Altitude) estimation of the Sierra de Aconquija glacial cirque, the Brückner-Richter AAR (Accumulation Area Ratio) method was applied (Serrano and González Trueba, 2004) at an AAR = 0.65 $\pm$ 0.05.

3. Results

The results obtained on this research allow to improve the previously established evolutionary model. We enlarge the coupled system connection among slopes, terraces, and alluvial fans and include a new correlation component: the morphologies produced under high mountain cold environments in the basins located in the NE of the Sierra de Aconquija. These basins produce data about the adjustments of the fluvial courses during the Holocene and the changes in the fluvial dynamics recorded in the Holocene accumulations.

3.1. Glacial headwaters

The NE sector of Sierra de Aconquija is highly mountainous with peaks around 2000-2200 m higher than the valley bottom (located around 2200 m asl). The area of the summit, where the water divide is located, is formed by an extended erosive surface (Fig. 1). Only more resistant pegmatite dykes are in relief. This morphology is probably inherited from old pre-Quaternary flattening. It also shows erosive features of glacial origin with soft depressions and abrasion forms corresponding with a Quaternary ice cap development.

In the S and E margins of this surface, glacial activity modelled the fluvial headwaters of the rivers flowing to the lower valleys. These headwaters face east (Figs. 1, 2) and show a steep scarp and a flat bottom with average heights of 4200 m asl. Highland swamps (*vegas*) that flood in summer due to snow melt and seasonal rains are found at the bottoms. Ice tongues descended through the valley during the cold phases and their limits may be deduced from the preserved lateral and front-lateral moraines.

Of the two main glacial cirques, the southern one forms the headwaters of Los Alisos River 2 (Fig. 2). The crests reach 4560 m asl (the gradient is about 300 m from top to bottom), and 650 m wide. Two moraine sets were identified at different altitudes (Fig. 2) and this indicates the existence of two successive glacial stages. The older (G1) is the most important. Its tongue almost reaches 3 km in length and descends to 3600 m asl – with a width of 360 m and an ice average thickness of between 120 and 170 m. The paleo-ELA (Equilibrium Line Altitude) for the G1 glacial stage was around 4230 $\pm$ 30 m asl. Its terminal section descends with a higher gradient, and so the till dispersion area is wider (Figs. 2). A large fluvioglacial terrace was formed downstream following glacial fusion (Figs. 2, 3). The second phase (G2) was smaller and generated two front-lateral moraine arcs with the largest inside the ridge of the older. At the same time, another ice tongue made a difluence through the Los Alisos River 3a. A small threshold separates both rivers, and the narrowness produced by the G2 moraine in the main channel must have favored the process. The terminal moraines are located at 3900 and 3965 m asl respectively. The glacial tongue did not reach more than 2450 m in length or 130 m in width, with an average ice thickness of 100 m. The ELA was located around 4890-4860 $\pm$ 30 m asl. The difluence opened the valley for the capture of the Los Alisos River 3a headwaters, although drainage is currently confusing. The old channel is still functioning and the new channel is in use only during floods. There are minimal obstacles between both river basins.

The northern glacial cirque, i.e. the headwaters of the Los Alisos River 3b, is composed of two stepped amphitheaters (Fig. 2). The upper one has features derived from glacial activity because the ice did not pass the external cirque threshold. It is wider than the southern cirque, and its scarps are located 100 m lower (4460 m asl). These characteristics enabled the development of a 700 m wide ice body during the G1 stage with a reduced length (1460 m) and an ice thickness of about 130-150 m. This data was deduced from the limits imposed by the most external lateral and frontal moraines and the presence of several retreat moraine ridges. These ridges extend up to a threshold of 4200 m where they are abruptly crossed by descending stream water (Fig. 2). The palaeo-ELA of the G1 phase was in 4300 $\pm$ 30 m asl in the northern cirque. An isolated moraine arc in an inner position (Fig. 2) was interpreted as a G2 terminal moraine, although it almost reached the same limits as the previous phase – but the ice was wider and thinner.

Lacking absolute datings, the moraines of both stages show sharp ridges, and no plant colonization or signs of erosive processes. We therefore believe that they must belong to two very recent glacial stages. Moreover, once the ice in both cirques had melted, rock glaciers developed in dryer periglacial conditions, fed by screes produced from surrounding scarps or previous glacial moraines. Rock glaciers indicate the limit of discontinuous permafrost, so its lower limit marks the altitudinal limit. Those rock glaciers that filled the Los Alisos River 3b cirque are the largest, with several tongues and lobulations (tongue-shaped and lobate rock glaciers, according to Wahrahfting and Cox (1959), and Barsch (1996) classifications).

These rock glaciers currently occupy the inner sector of both cirques (Los Alisos River 3a and 3b) and even the lower amphitheater of the Los Alisos River 3b. They are mostly pointing east (Fig. 2) and are relicts, although three could be classified as inactive (Fig. 2). Their lower limits are between 4200 and 4400 m (and even lower in some cases).

3.2. Fluvial morphosedimentary sequences

The fluvial course suffered one important capture process before reaching the Las Carreras depression. This process led to a general reorganization of the fluvial network (Fig. 3). The Muñoz River lost a large headwater extension, while the Los Alisos River notably enlarged its basin. This capture process was produced, according to available evidence, during the Upper Holocene (Peña-Monné and Sampietro-Vattuone, 2019b).

Downstream from this large capture area it is possible to find fluvial accumulations in which the dynamics and evolution match the set of Holocene units indicated by Sampietro-Vattuone and Peña-Monné (2016) for the Tafí valley.

From the 25 profiles recorded, five constitute a good sample of all the processes involved and are highly representative of the sedimentary sequence with good chronological information (Fig. 4). In the Mollar River, in a wide section before the canyon that flows to the El Mollar locality (Figs. 1, 3, 5a) the RI-01 profile is located – while RI-03 is further upstream at the confluence with the El Rincón River. The other three profiles are in the middle course of the Muñoz River (CA-0 1, CA-02, CA-03) (Figs. 1, 3, 5d).

The H1 unit covers an extensive area in the geomorphological map (Fig. 1) where it is represented mostly by slopes, while in terraces and alluvial fans this unit (H1) use to be covered by H2 accumulation. The H1 unit could be divided into two sub-units: H1A and H1B. The oldest one (H1A) lays in the basal section of RI-01 outcrop and reaches 5 m in depth, and also possibly forms the base of CA-01 (Figs. 4a, 4c, 5e). According to the evidence provided by the RI-01 outcrop, the H1A unit was initially formed by an accumulation of gravel and blocks – and following a 2 m sand layer there is another 2 m of silts and fine sand interbedded with peat. Five 3-10 cm thick peat layers were identified on top of the H1A accumulation at RI-01, and four of them were dated (Table 1). Ages correspond well with the stratigraphic position, extending from 13034-12571 cal BP in the first peat layer (RI-01-T1) to 11802-11192 cal BP in the youngest (RI-01-T5) (Figs. 4a, 5b).

The almost base age of CA-01 (10158-9539 cal BP, sample CA1-1) must be included in the H1A set. These datings are important for two reasons: firstly, because the sedimentation of the peat levels are implying an important dynamic change in the fluvial system that reflects what is happening in the glacial headwater in relation with the glacial and periglacial evolution; secondly, these datings enable the minimum age of the V0 ashes to be established. In general terms, the ashes are less than 11,000 or even 10,000 years old according to CA-01 dating. When considering other data from Santa María and Tafí valleys the later date seems to be more adequate, meaning they fell at approximately 10 000 BP (Sampietro-Vattuone et al., 2016, 2019b). This volcanic event was coincident with the limit between H1A and H1B units (Sampietro-Vattuone and Peña-Monné, 2016). The ash thicknesses varies between 2 and 20 cm, and sometimes has a coarse texture, with high biotite content. It uses to be very affected by bioturbation and its presence on a regional scale is scarce.

The H1B unit is present in the five profiles and, except in CA-01, is composed of detritic materials (mainly grus and fine sand). Thicknesses vary up to 4 m in RI-01 (Fig. 4a). Sand layers in the CA-01 alternate with peats up to 7233-6674 cal BP (CA1-2) (Fig. 4c). The H1B upper limit is marked by a new volcanic event produced by the plinian eruption at Cerro Blanco (Fernández-Turiel et al., 2012). This ash fall was named V1 by Sampietro-Vattuone and Peña-Monné (2016) and presents diverse characteristics. Normally, the deposits are formed by a laminated base followed by a massive and very white colored deposit that can reach 8 m in thickness. In some areas it has greyish colors and includes sands or blocks. The RI-01 and CA-0 profiles show only one V1 ash layer although profiles sometimes show two very close eruptive events of equal composition (Sampietro-Vattuone et al., 2019b). In these cases, the two V1 ashes (named V1a and V1b) are separated by sand or peats. Radiocarbon datings (Table 1) show that V1a is later than CA1-2, CA3-T3, and RI3-C2 and whose closest dating to the ash is 4789-4289 cal BP in RI-03 (Figs. 4c, 5c). The V1b ashes (Figs. 4d, 4e) are later than 4425-3915 cal BP (CA3-T2) and 4566-3972 cal BP (CA2-T1) (Fig. 5f). In general terms, Sampietro-Vattuone and Peña-Monné (2016) and Sampietro-Vattuone et al. (2016, 2019b) use the date ca. 4200 cal BP to refer to this volcanic set.

In the general evolutionary model, Peña-Monné and Sampietro-Vattuone (2016) show that the V1 ash fall is coincident in time with the starting of an incision phase that marks a change in the sedimentation and enables the individualization of H1 as a level. The H2 deposit was over V1 ashes, as shown in four profiles of Fig. 4. However, in other cases, new floodplain materials were deposited inside the H1 incision. As the first case is most common, H2 surfaces occupy large extensions in the present landscape (Fig. 1) and usually cover V1 ashes as well as H1 deposits. Fine sediments are dominant during the H2 phase. Most parts of the material come from the erosion of the earlier stages with higher granulometric selection. Thicknesses extend between 3 and 4 m, and in some cases there are new peats above (Figs. 4d, 4e, 5f). Finally, it is necessary to indicate that another ash fall occurred later, as shown in RI-03, CA-02 and CA-03 (Figs. 4b, 4d, 4e). This stage was named V2 (Sampietro-Vattuone and Peña-Monné, 2016; Sampietro-Vattuone et al., 2017, 2018). Peats located below V2 ash in CA-03 were dated to 1300-1065 cal BP (CA3-T1) and 961-774 cal BP in CA2-T2, and earlier than 655-524 cal BP (CA2-T3) and this enabled an estimation of the age of this volcanic event (Figs. 4d, 4e, 5f; Table 1) (Sampietro-Vattuone et al., 2019b).

4. Discussion

The sedimentary records of the Muñoz River and El Rincón show a deep change in the fluvial dynamics in a very specific temporal framework in the H1A unit. This is reflected by the alternation of peat levels corresponding to the development of swamps and detrictic layers of coarse sand. These alternations started at 13034-12571 (RI-01-T1, Fig. 4a), but were most frequently produced between 13064-12451 and 11802-11192 (RI-01-T3, RI-01-T4, RI-01-T5, Fig. 4a).

There are some disperse radiocarbon datings made on peats from El Rincón (13325-11846 cal BP) extracted by Garralla et al. (2001) and Fink

(2001, in Hermanns et al., 2006) and dated to 13325-11846 cal BP. Both are inside the ages obtained in this paper. This peat sequence encompasses a deposit about 65 cm thick for a stage of about 600 years. This sedimentary process was produced in a fluvial environment that was swamped during a long period of time and may be similar to current peat areas that are formed by abundant spring water in the highlands (*vegas*). The sedimentary records of El Rincón have been interpreted as lacustrine deposits in previous papers (Collantes and Sayago, 1987; Garralla et al., 2001; Collantes, 2001). In the same way, the peat deposits from the Muñoz River were described by Sayago et al. (1991) as “glaciolacustrine”. The references made in these papers to an area described as ‘Lake El Rincon’ are unfounded.

The pollen analyses made by Garralla et al. (2001) in profiles from El Rincón (more or less the same as in Fig. 4a, 4b) show the presence of vegetation from wet environments for this sequence. This information is normal for a swamped area, but it does not necessaryly mean that the global environment was wet. Fernández et al. (1991) show a chronologically similar peat sequence in a valley from the highlands of Jujuy Province. This sequence was dated to between 12530 ± 160 and 10200 ± 170 BP and a multiproxy examination concluded that the climate during this period was wet and cold with winter rains. The continuous flow of water into the valleys can be interpreted as the result of the permanent ice and snow melt coming from the summits. This means that during these dates (with maximum margins of error of between *ca.* 13000 and 11200 cal yrs BP) the G1 glacial phase (whose moraines were identified in Fig. 3) was functioning, with glacial tongues descending to 3628-4043 m asl. This data supports that the main glacial phase of the whole last glacial for the NE side of Sierra de Aconquija must be located during the Younger Dryas between 12.9 and 11.7 cal ky BP (Fig. 6). The younger dating, corresponding to the CA1-1 sample (Fig. 4c) belongs to the cold Preboreal Oscillation defined by Rasmussen et al. (2007) from the ice core NGRIP (Fig. 6). Hajdas et al. (2003) in southern Chile and Argentina (Huelmo and Mascardi lakes). This established the interhemispheric globality of the cooling phase of the Younger Dryas, starting *ca.* 550 years later than in the Northern Hemisphere and spanning between 13401-13041 cal BP and 12015-11321 cal BP.

These dates for glacial advances are frequent in the tropical Andes (11.8-10.9 ka BP) (Jomelli et al., 2014; Solomina, et al., 2015) and also in the southern Andes (Wenzens, 1999; Solomina et al., 2015). In the Río Salado Valley (Central Andes), Espizúa (1999) showed a glacial readvance dated to 10560 ± 140 (12708-11995 cal BP). In the Bolivian Andes, Ward et al. (2017) show a Holocene glacial phase at 11000 ± 40 cal BP. However, these events are less frequent in mountains closer to our study area – such as the Sierra de Quilmes (Zech et al., 2017). In the Sierra de Aconquija, although its glacialism has been known since ancient times (Tapia, 1925; Rohmeder, 1941, 1942), data about glacial stages and ages is confused. The same occurs in the Cumbres Calchaquíes. There is only limited and imprecise chronological data about moraine ridges that are thought to be from the Finipleistocene age in the Huaca Huasi area (Sayago et al., 1991; Arcuri, 1998). The lack of older glacial phases was explained by Strecker (1987) as a result of mountain uplift.

In the frame of the general units established by Sampietro-Vattuone and Peña-Monné (2016) the G2 glacial phase corresponds to the H1B stage, encompassing part of the Early Holocene and the entire Middle Holocene. It is in concordance with the records of two profiles from the Muñoz River (CA-02 and CA-03) dated to 7233-6674 cal BP (CA-01) and 6181-5585 cal BP (CA3-T3) (Table 1, Fig. 4c, e), inside the Neoglacial Cold Phase. Even CA3-T3 is coincident with the cold phase of the 5.9 Bond event (Bond et al., 1997). In the same way, Sayago et al. (1991) show a radicoarbon dating made over peat from the Muñoz River with a similar age (5950 ± 290 cal BP: 6957-6493 cal BP). In the Argentinean Central Andes, Espizúa (2005) and Espizúa and Pitte (2009) point to three Neoglacial readvance phases, the oldest being between 5700 and 4300 BP, and also coinciding with part of the dates obtained by Mercer (1976) between 4500-4000 BP – and so possibly matching the set determined for the NE Sierra de Aconquija.

During the Upper Holocene, coinciding with H2 and H3 sedimentary phases, there were rock glaciers in the NE of the Sierra de Aconquija. They developed when the cirque was ice free, with lower limits of between 4400-4200 m asl (Fig. 2). Ahumada et al. (2010, 2013, 2017) established the limit for inactive glaciers around 4000 ± 200 m asl (depending on the orientation). To the north, Martini et al. (2013) and Fox and Strecker (1991) show similar limits. According to its external appearance, the rock glaciers in NE Aconquija may belong to two different Upper Holocene phases. At least three inactive rock glaciers can be distinguished, with recent morphologies, probably of LIA age. Perhaps those of an older appearance can be considered rock glacier relicts belonging to the Upper Holocene cold phases – such as the 2.8 Bond event (Bond et al., 1997). In the Northern Hemisphere this event corresponds to the Iron Age Cold Epoch and its locally wetter and colder characteristics favored the development of soils during such periods – as were defined in the Tafí valley by Sampietro-Vattuone and Peña-Monné (2016) (Fig. 5, s1 soil).

5. Conclusions

The Tafí valley, surrounded by the Sierra de Aconquija, Cumbres Calchaquíes, and Ñuñorco Grande high mountains, received large quantities of sediments from the mountains during the Late Glacial and Holocene.

The H1A stage, between *ca.* 13 ka cal BP and *ca.*10 ka cal BP (Late Glacial and Early Holocene) is the most important. In the NE piedmont of the Sierra de Aconquija it is possible to identify major changes in the geomorphological dynamics. The sedimentary records of El Rincón show that during the Younger Dryas, together with the intense dynamics necessary for the alluvial fan formation (as is the case of the Las Carreras and Los Alisos alluvial fans), distal areas were dominated by swamps with peat formation and interbedded sand sedimentation during the entire period.

This dynamic is related with the existence of glaciers in the headwaters of both rivers that provided melt water from ice and snow. These glaciers (G1) left erosive and accumulative formations, and their ice tongues reached between 1.5 and 3 km in length and descended up to 3600-4000 m asl and with and an ELA of between 4200-4300 m asl.

In a second stage (H1B), between Early and Middle Holocene (*ca.* 10 ka cal BP to *ca*. 4.2 ka cal BP), similar but smaller new sedimentary events were recorded. Between *ca.* 7000 and 5000 years (Neoglacial cold phases) glacier readvances were produced (G2 phase) in the cirques with less magnitude than previously. Cone and floodplain sedimentation continued developing new peat levels during this period.

After the fluvial network general incision that occurred ca. 4200 BP, H2 and H3 stages developed during the Upper Holocene. In the headwaters, mainly during the LIA, rock glaciers developed in the old cirques.

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Figure captions

Fig. 1. Location and geomorphological maps of the study area.

Fig. 2. Geomorphological scheme of glacial, periglacial, and fluvioglacial morphologies of the headwaters of Los Alisos and Muñoz rivers. Oblique image from Google Earth Pro (2016).

Fig. 3. Geomorphological scheme of the NE side of the Sierra de Aconquija and Las Carreras valley showing the main components of the study area.

Fig. 4. Stratigraphic profiles showing the main morphosedimentary units, peat and tephra layers, and radiometric datings: a) and b) El Rincón profiles; c), d), and e) profiles from the upper section of the Muñoz River.

Fig. 5. a) General view of the Sierra de Aconquija and El Rincón fluvial sector, RI-01 profile is located to the east; b) RI-01 profile; c) RI-03 profile; d) view of the Sierra de Aconquija and the location of CA-03 and CA-01 profiles along the Muñoz River; e) CA-01 profile; f) CA-02 profile.

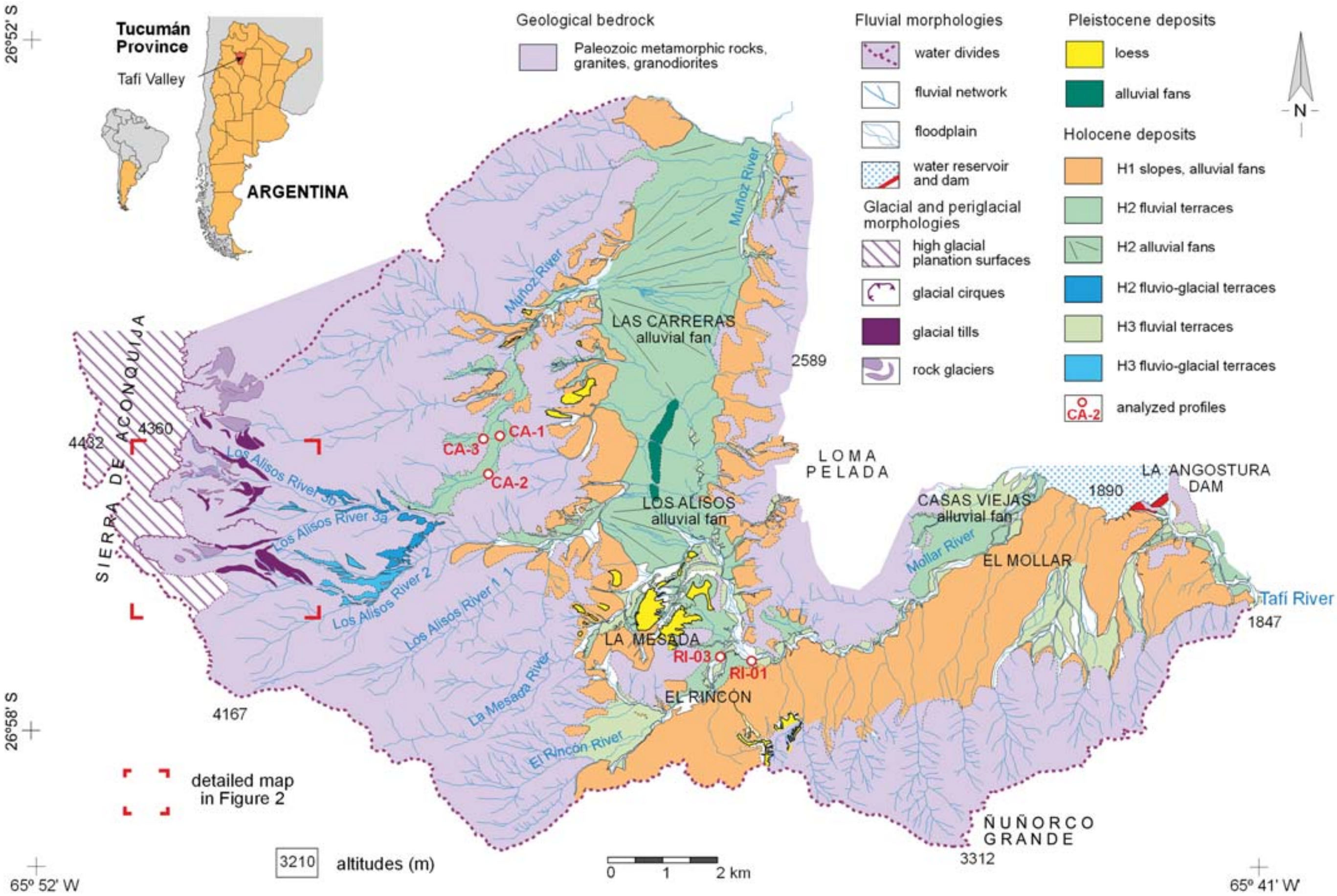
Fig. 6. Graphical representation of the Late Glacial and Holocene paleoclimatic markers. The accumulation and incision evolutionary curve of the morphosedimentary units (H1-H4) is overlapped with the location of tepras and radicoarbon datings obtained for this study.

Profile	Sample	14C BP	Cal BP 2 σ	Laboratory code	Dated material
RI01	RI01-T5	9980 ± 100	11802-11192	LP-3427	Peat
	RI01-T4	10130 ± 140	12367-11225	LP-3371	Peat
	RI01-T3	10890 ± 140	13064-12451	LP-3357	Peat
	RI01-T1	10910 ± 110	13034-12451	LP-3412	Peat
RI03	RI03-C2	4043 ± 50	4789-4289	D-AMS019331	Charcoal
CA01	CA1-2	6110 ± 100	7233-6674	LP-3345	Peat
	CA1-1	8790 ± 120	10158-9539	LP-3362	Peat
CA02	CA2-T3	630 ± 50	655-524	LP-3377	Peat
	CA2-T2	1020 ± 50	961-774	LP-3373	Peat
	CA2-T1	3900 ± 100	4566-3972	LP-3375	Peat
CA03	CA3-T1	1320 ± 60	1300-1065	LP-3342	Peat
	CA3-T2	3840 ± 90	4425-3915	LP-3352	Peat
	CA3-T3	5110 ± 130	6181-5585	LP-3380	Peat

Table 1. ^{14}C dated samples.

Highlights

- Fluvial records and geomorphological maps allowed to identify the existence of glacial stages.
- Glacial advances from Younger Dryas and Neoglacial periods were detected.
- Glacial landforms were coupled with contemporary slopes, terraces, and alluvial fans.
- Rock glaciers from LIA were identified and related with the younger fluvial stages.



26°52' S
26°58' S
65° 52' W
65° 41' W
Tucumán Province
Tafí Valley
ARGENTINA
Geological bedrock
Paleozoic metamorphic rocks, granites, granodiorites
Fluvial morphologies
water divides
fluvial network
floodplain
water reservoir and dam
Glacial and periglacial morphologies
high glacial planation surfaces
glacial cirques
glacial tills
rock glaciers
Pleistocene deposits
loess
alluvial fans
Holocene deposits
H1 slopes, alluvial fans
H2 fluvial terraces
H2 alluvial fans
H2 fluvio-glacial terraces
H3 fluvial terraces
H3 fluvio-glacial terraces
CA-2 analyzed profiles
N
SIERRA DE ACONQUIJA
4432
4360
4167
2589
1890
1847
3312
LAS CARRERAS alluvial fan
LOS ALISOS alluvial fan
CASAS VIEJAS alluvial fan
LOMA PELADA
LA ANGOSTURA DAM
EL MOLLAR
LA MESADA
EL RINCÓN
ÑUÑORCO GRANDE
Muñoz River
Los Alisos River 3b
Los Alisos River 3a
Los Alisos River 2
Los Alisos River 1
La Mesada River
El Rincón River
Mollar River
Tafí River
CA-1
CA-2
CA-3
RI-01
RI-03
detailed map in Figure 2
3210 altitudes (m)
0 1 2 km

Figure 1

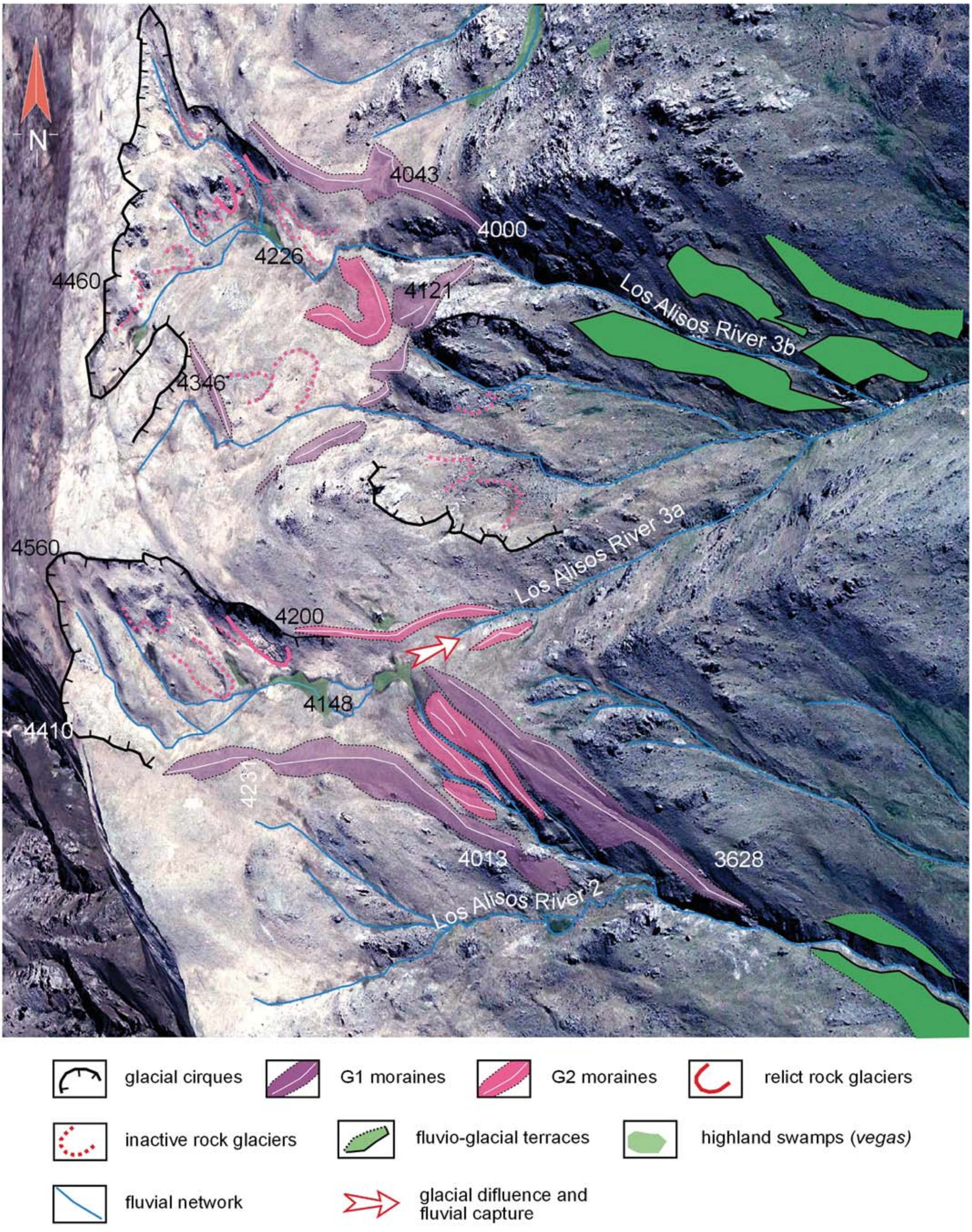

N
4043
4000
4226
4460
4121
Los Alisos River 3b
4346
Los Alisos River 3a
4560
4200
4148
4410
4231
4013
3628
Los Alisos River 2
glacial cirques
G1 moraines
G2 moraines
relict rock glaciers
inactive rock glaciers
fluvio-glacial terraces
highland swamps (vegas)
fluvial network
glacial difluence and fluvial capture

Figure 2

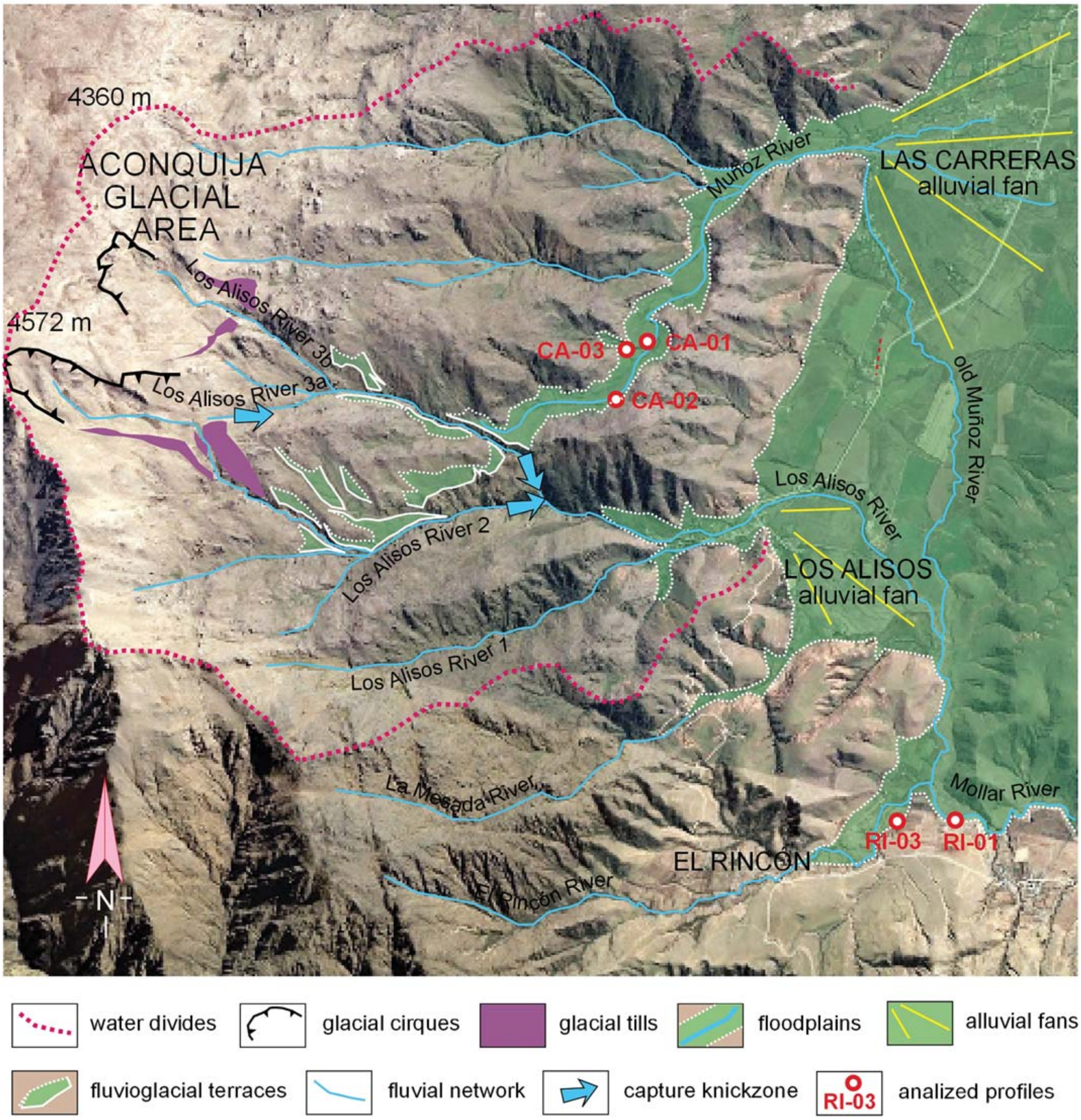

4360 m
ACONQUIJA GLACIAL AREA
4572 m
Los Alisos River 3b
Los Alisos River 3a
Los Alisos River 2
Los Alisos River 1
Muñoz River
LAS CARRERAS alluvial fan
CA-03
CA-01
CA-02
old Muñoz River
Los Alisos River
LOS ALISOS alluvial fan
La Mesada River
Mollar River
RI-03
RI-01
EL RINCON
El Rincon River
N
water divides
glacial cirques
glacial tills
floodplains
alluvial fans
fluvioglacial terraces
fluvial network
capture knickzone
RI-03
analized profiles

Figure 3

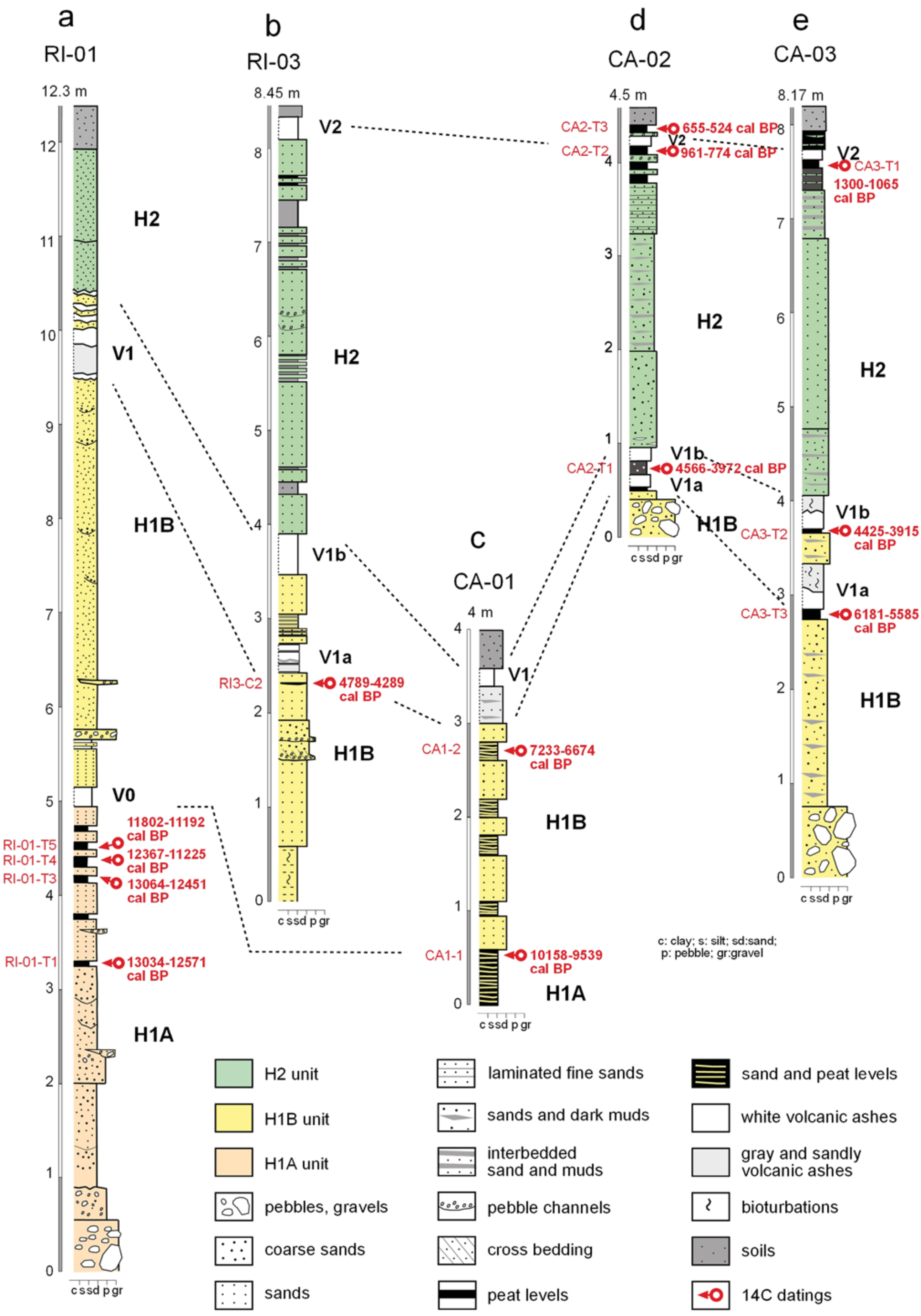

a
RI-01
12.3 m
b
RI-03
8.45 m
C
CA-01
4 m
d
CA-02
4.5 m
e
CA-03
8.17 m
H2
V1
H1B
V0
H1A
V2
V1b
V1a
RI-01-T5
RI-01-T4
RI-01-T3
RI-01-T1
11802-11192 cal BP
12367-11225 cal BP
13064-12451 cal BP
13034-12571 cal BP
RI3-C2
4789-4289 cal BP
CA1-2
7233-6674 cal BP
CA1-1
10158-9539 cal BP
CA2-T3
655-524 cal BP
CA2-T2
961-774 cal BP
CA2-T1
4566-3972 cal BP
CA3-T1
1300-1065 cal BP
CA3-T2
4425-3915 cal BP
CA3-T3
6181-5585 cal BP
c ssd p gr
c: clay; s: silt; sd:sand;
p: pebble; gr:gravel
H2 unit
H1B unit
H1A unit
pebbles, gravels
coarse sands
sands
laminated fine sands
sands and dark muds
interbedded sand and muds
pebble channels
cross bedding
peat levels
sand and peat levels
white volcanic ashes
gray and sandly volcanic ashes
bioturbations
soils
14C datings

Figure 4

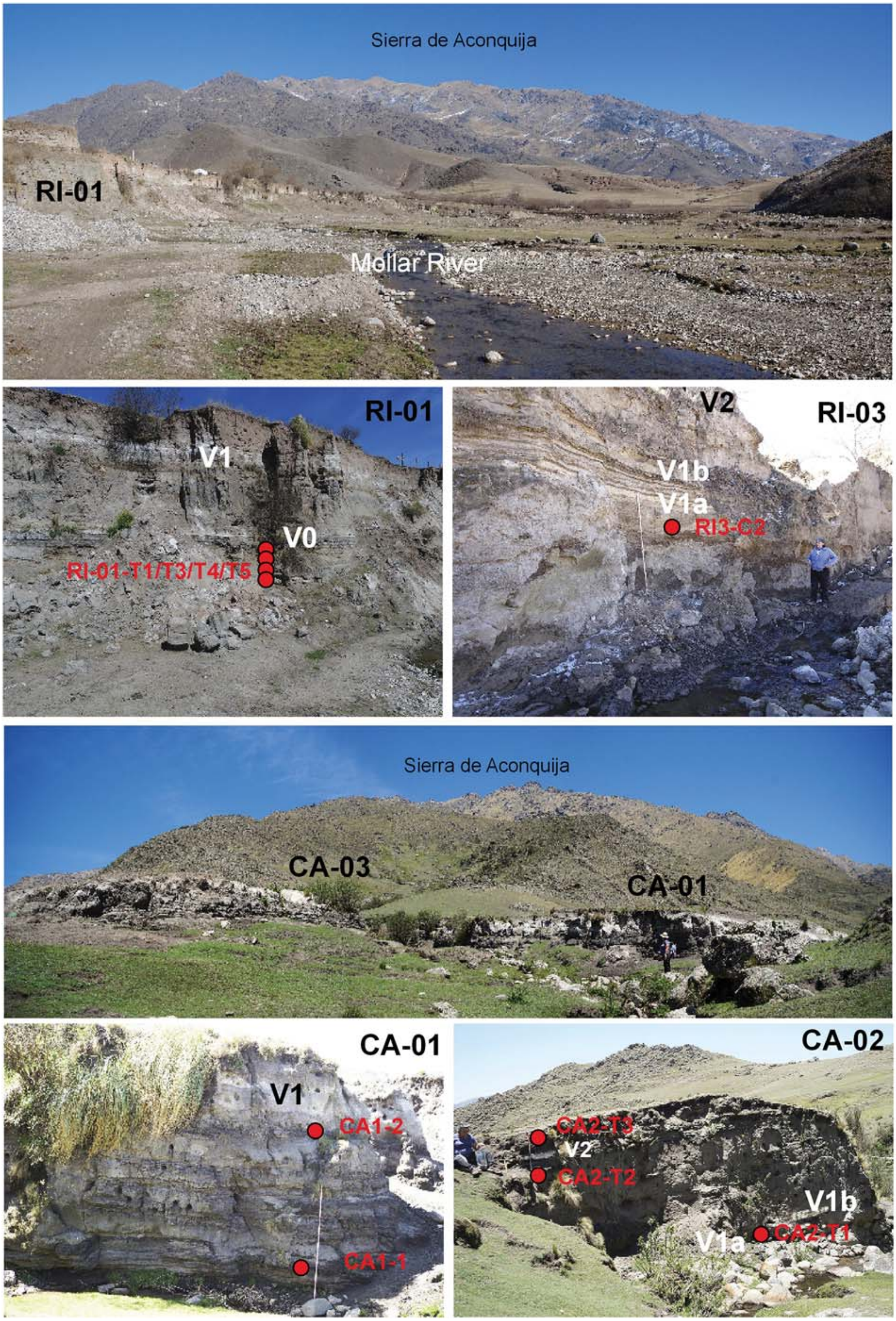
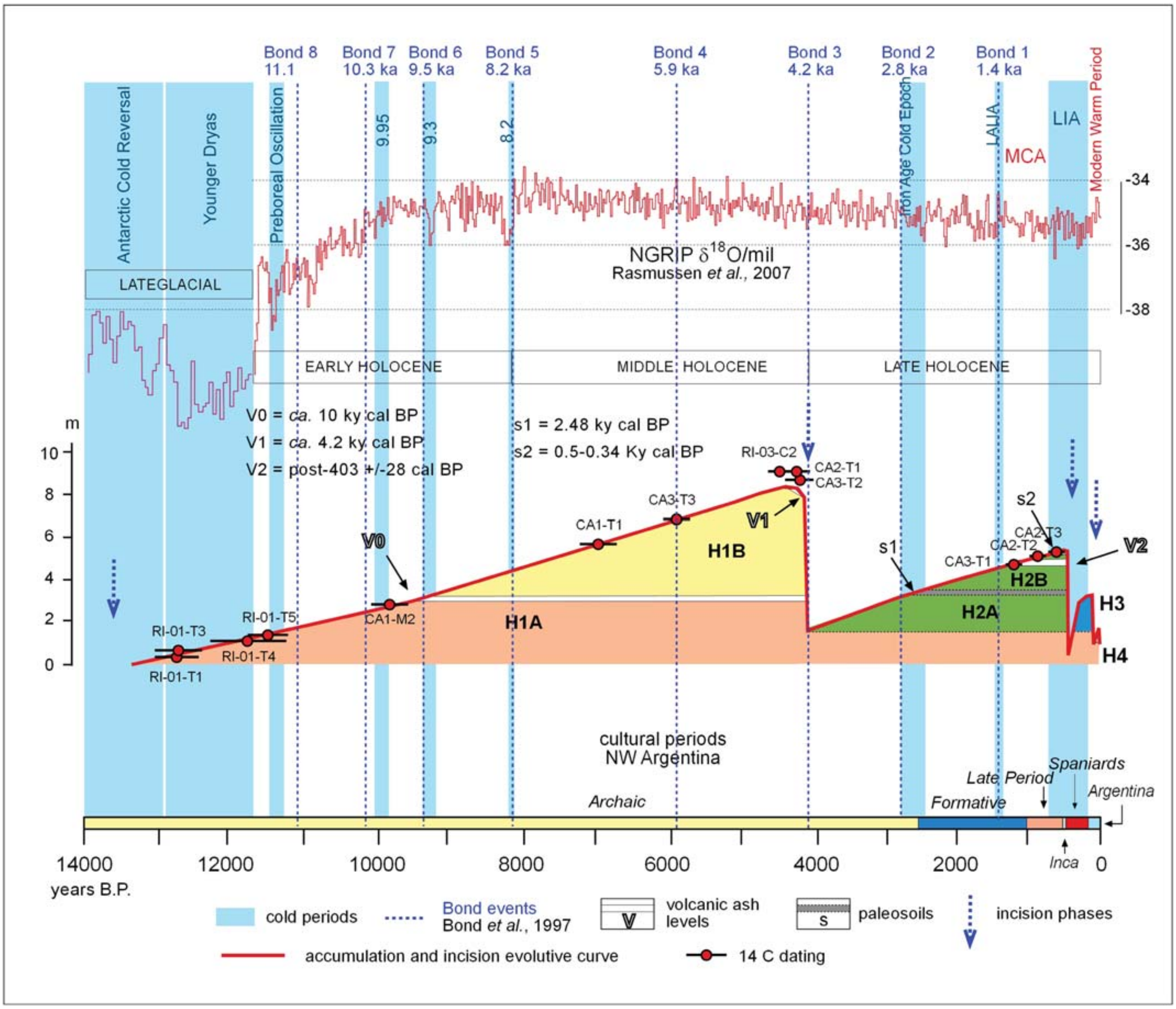

Sierra de Aconquija
RI-01
Mollar River
RI-01
V1
V0
RI-01-T1/T3/T4/T5
V2
RI-03
V1b
V1a
RI3-C2
Sierra de Aconquija
CA-03
CA-01
CA-01
V1
CA1-2
CA1-1
CA-02
CA2-T3
V2
CA2-T2
V1b
V1a
CA2-T1

Figure 5



Bond 8
11.1
Bond 7
10.3 ka
Bond 6
9.5 ka
Bond 5
8.2 ka
Bond 4
5.9 ka
Bond 3
4.2 ka
Bond 2
2.8 ka
Bond 1
1.4 ka
Antarctic Cold Reversal
Younger Dryas
Preboreal Oscillation
9.95
9.3
8.2
Iron Age Cold Epoch
LALIA
MCA
LIA
Modern Warm Period
-34
-36
-38
NGRIP δ18O/mil
Rasmussen et al., 2007
LATEGLACIAL
EARLY HOLOCENE
MIDDLE HOLOCENE
LATE HOLOCENE
V0 = ca. 10 ky cal BP
V1 = ca. 4.2 ky cal BP
V2 = post-403 +/-28 cal BP
s1 = 2.48 ky cal BP
s2 = 0.5-0.34 Ky cal BP
m
10
8
6
4
2
0
RI-01-T3
RI-01-T1
RI-01-T4
RI-01-T5
CA1-M2
V0
H1A
CA1-T1
CA3-T3
H1B
RI-03-C2
CA2-T1
CA3-T2
V1
s1
CA3-T1
CA2-T2
CA2-T3
s2
H2B
H2A
V2
H3
H4
cultural periods
NW Argentina
Archaic
Formative
Late Period
Spaniards
Argentina
Inca
14000
years B.P.
12000
10000
8000
6000
4000
2000
0
cold periods
Bond events
Bond et al., 1997
volcanic ash levels
V
paleosoils
s
incision phases
accumulation and incision evolutive curve
14 C dating

Figure 6