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Ivana Laura Ozán
National Scientific and Technical Research Council

César Méndez
Centro de Investigación en Ecosistemas de la Patagonia

Sebastián Oriolo
National Scientific and Technical Research Council

María Julia Orgeira
National Scientific and Technical Research Council

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Depositional and post-depositional processes in human-modified cave contexts of west-central Patagonia (Southernmost South America)

Ivana Laura Ozán[a,*], César Méndez[b], Sebastián Oriolo[a], María Julia Orgeira[a], Alfonsina Tripaldi[a], Carlos Alberto Vásquez[a]

[a] Instituto de Geociencias Básicas, Aplicadas y Ambientales de Buenos Aires, Universidad de Buenos Aires, Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Departamento de Ciencias Geológicas, Ciudad Universitaria C1428EGA, Buenos Aires, Argentina

[b] Centro de Investigación en Ecosistemas de la Patagonia, José de Moraleda 16, Coyhaique, Aisén, Chile

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ABSTRACT

This contribution aims to analyse depositional and post-depositional processes from two volcanic caves (Baño Nuevo 1 and Cueva de la Vieja) from west-central Patagonia, in order to evaluate if natural and anthropogenic processes recorded therein are representative of basin-scale processes. For this purpose, geomorphological, sedimentological, micromorphological, petrographic, magnetic, paleontological and archaeological data are integrated. Results allow correlating the Baño Nuevo 1 and Cueva de la Vieja sequences, comprising a record of ca. 19,000 years. In the first place, the distinction between endogenous and exogenous detritus input, mainly recorded by the mineralogy and lithotypes, provided environmental data related to landscape stability (i.e., vegetation cover). The latter, in turn, could be interpreted as part of a complex feedback associated with major climatic changes. On the other hand, cave weathering rates observed through vertical variations of the gravel fraction, along with bioactivity recorded by percentages of Total Organic Carbon and micromorphological analysis, provided constraints on temperature and/or humidity, being in agreement with available regional information. Main regional palaeoenvironmental changes observed in the sequences were the deglaciation processes, the Pleistocene-Holocene transition, the Holocene amelioration and the Anthropocene. Although no distinctive variations were observed within Holocene deposits, biological processes mainly resultant of the human occupations could have obliterated such finer scale distinctions.

1. Introduction

Caves are sheltered microenvironments, commonly developed in carbonatic or volcanic rocks, whose interaction with the external landscape depends on factors such as their lithology, geomorphological position, size, morphology, orientation, climate and biochemical conditions (e.g., Brook and Nickmann, 1996; Cucchi et al., 1998; Courty and Vallverdú, 2001; Karkanas, 2001; Woodward and Goldberg, 2001; Pickering et al., 2007). Due to their relatively well-preserved biological potential and their role as sediment traps, caves usually allow accurate palaeoenvironmental reconstructions (e.g., Courty and Vallverdú, 2001; Pirson et al., 2006; Ajas et al., 2013). Indeed, as these contexts are also ecological attractors, their study is a significant part of archaeological and palaeontological agendas (e.g., Wang and Martin, 1993; Farrand, 2001; Goldberg et al., 2001, 2009; Straus et al., 2001; Morwood et al., 2004; Karkanas, 2006; Goldberg and Sherwood, 2006; Mallol et al., 2010; Hubbe et al., 2011; Ajas et al., 2013; Nejman et al., 2018).

Particularly, this has been the case of Patagonian caves, which were frequently used as shelters by the Late Pleistocene megafauna (e.g., Martin et al., 2013; Villavicencio et al., 2016), as well as by highly-mobile human groups across the Holocene until the European arrival (e.g., Bird, 1993; Borrero, 2015; Borrero et al., 2019; Brook et al., 2015; Martin and Borrero, 2017; Méndez et al., 2018, 2019). Here, the high archaeological visibility of caves, resulting from their brief, but recurrent human use through time along with their relatively good preservation, has contributed to their archaeological attention (Borrero, 2008; Prates et al., 2013). Nevertheless, many taphonomic and geoarchaeological studies show that caves seldom provide intact pictures given the complex and often very intense formation processes and should be carefully assessed before deriving behavioural or ecological conclusions (e.g., Brain, 1983; De Ruiter and Berger, 2000; Kos, 2003; Karkanas et al., 2000; Borrero and Martin, 2012; Haddad-Martim et al., 2017).

* Corresponding author.
E-mail address: soriolo@gl.fcen.uba.ar (I.L. Ozán).

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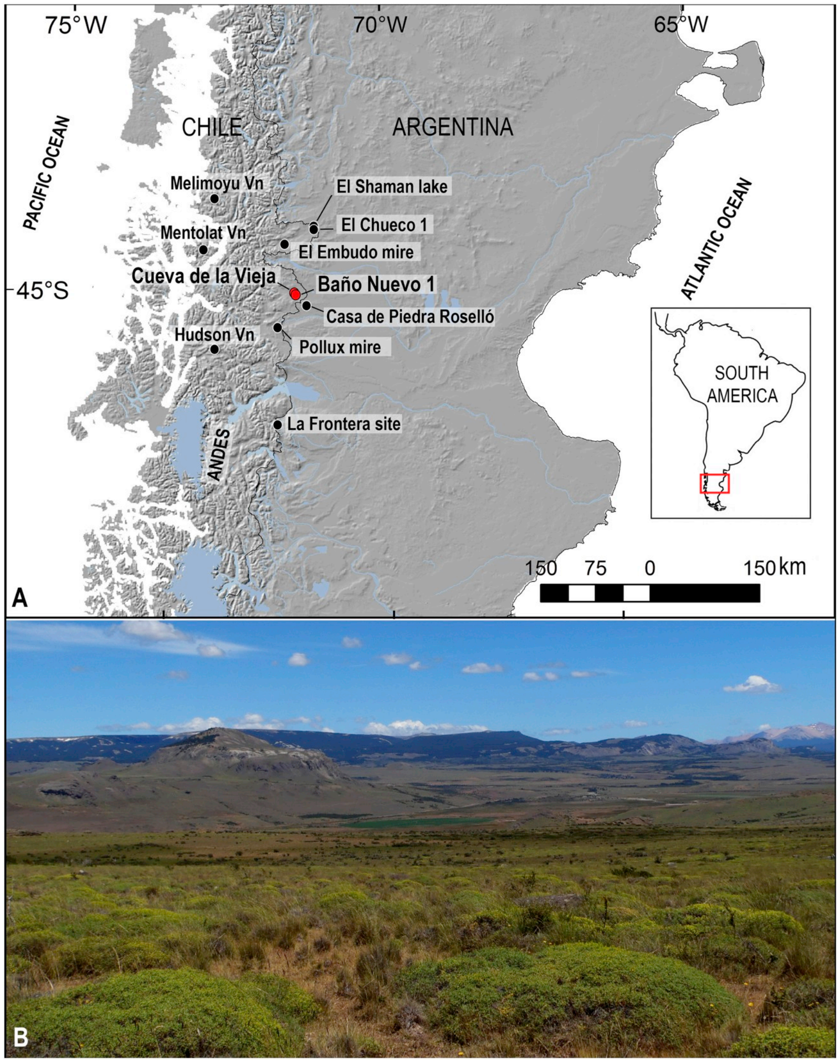

Fig. 1. A) West-central Patagonia with the studied caves location and other sites mentioned in the text. "Vn" = volcano. B) Landscape view of the steppe ecozone.

This contribution aims discussing depositional and post-depositional processes from two volcanic caves from west-central Patagonia; Baño Nuevo 1 and Cueva de la Vieja (Fig. 1), with deposits spanning over 19,000 years and which have been archaeological and paleontological sources of evidence (Méndez et al., 2018; Mena and Stafford, 2006; Table S1). How representative are these micro-environments from the surrounding landscape and to what degree their natural and anthropogenic processes suggest basin-scale representativeness are questions that are addressed. In order to achieve these aims, sedimentological, micromorphological, petrographic and magnetic data are integrated to serve the ultimate goals of understanding key issues of the local landscape evolution, as well as to calibrate the nature of anthropogenic deposition inside these sites. Since sedimentological studies focused on non-karst caves are relatively scarce (e.g., Howarth, 1996; Coello et al., 1999), this contribution also offers valuable methodological insights to the analysis of volcanic cave deposits.

2. Environmental setting

The Baño Nuevo 1 and Cueva de la Vieja sites are located in the Ñirehuao valley of the Aisén region (west-central Patagonia, Chile; Fig. 1A). The area is part of the Austral Patagonian Range geological province (Ramos, 1999), and caves under study are made up of rocks of the Baño Nuevo Volcanic Complex (~121 Ma) (Suárez et al., 2010; Fig. 2), composed by lavas ranging from basalts to andesites (Demant and González, 2010). Further volcanic (e.g., Casa de Piedra and Divisadero Formations) and siliciclastic (e.g., sandstones of the Apeleg Formation) units are found in the area as well (Bell and Suárez, 1997; Suárez et al., 2007; Fig. 2).

The Ñirehuao valley was mainly modified by Pleistocene glacio-lacustrine action, subsequently reworked by Holocene fluvial, aeolian and gravity-driven processes (Fig. 2). Several moraines arches related to the LGM show the ice lobe action flowing along the Ñirehuao and Cisnes valleys, where the presence of terraces evidence ice dams and large glacial lakes during the deglaciation (McCulloch et al., 2000; García et al., 2019).

A cold and semi-arid climate characterizes the study area, with an average annual temperature of ~6.5 °C and precipitations below 500 mm (DMC, 2018; Balmaceda and Baño Nuevo ranch stations). Intense summer winds mainly coming from the northwest-west quadrant, with annual averages above 30 km/h and gusts over 90 km/h (DMC, 2018) are important features of this region (Garreaud et al., 2009). In fact, main climatic shifts across the Holocene might be triggered by changes in the latitudinal movement and/or intensity of those westerly winds (e.g., Markgraf et al., 2007; Garreaud et al., 2009; De Porras et al., 2014; McCulloch et al., 2017), though recent studies suggest relatively moderate variations across the Holocene at centennial and millennial timescales (Moreno et al., 2019).

These climatic conditions define a steppe ecozone, close to the western deciduous and evergreen forest. The sharp west-east

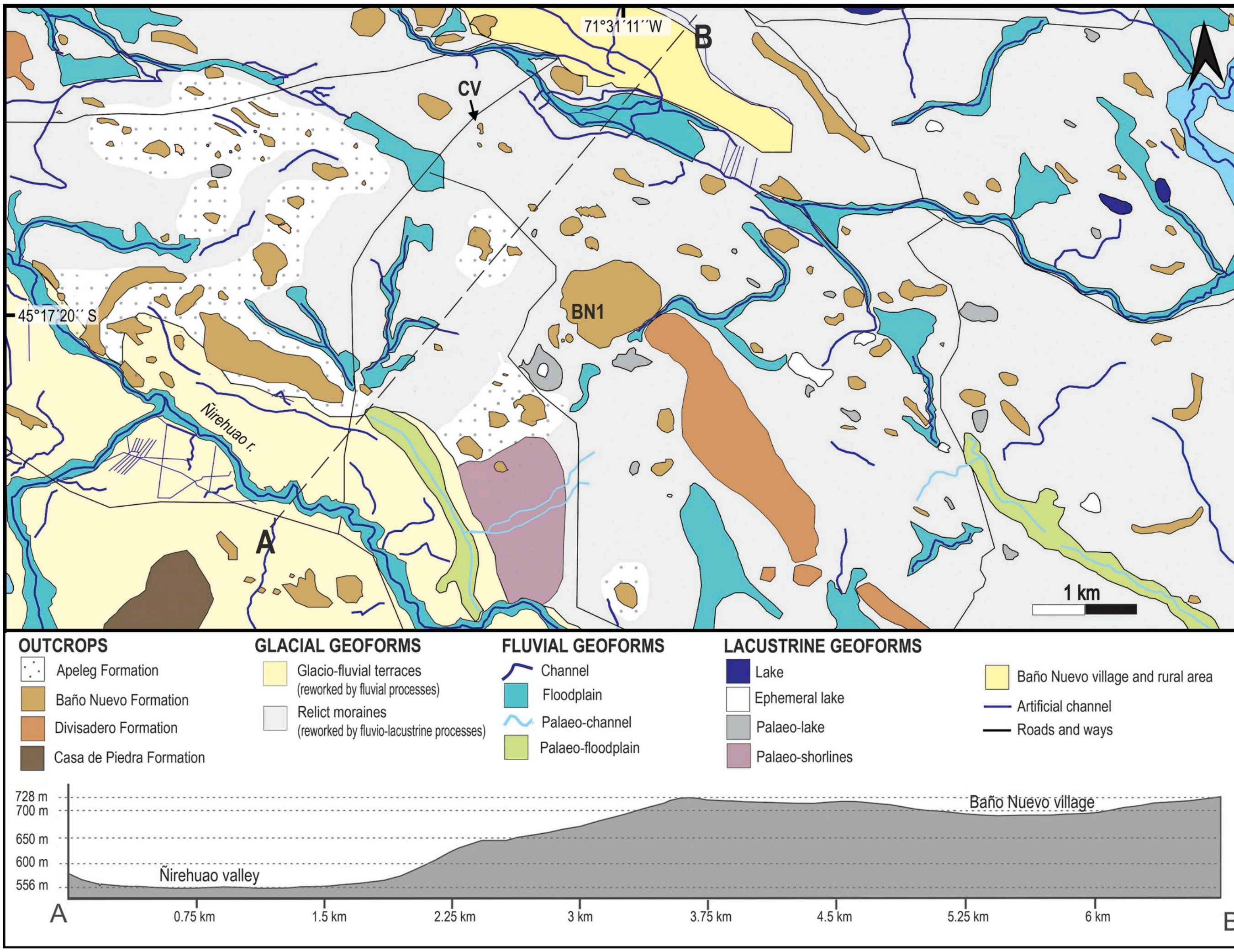

Fig. 2. Geomorphological and geological map, including a topographic profile (A–B).
Data are modified after Demant and González (2010) and García et al. (2019). CV = Cueva de la Vieja; BN = Baño Nuevo 1.

precipitation gradient (across ~100 km), defined by the presence of the Andes (Garreaud et al., 2009), conditioned such vegetation. The Patagonian steppe is dominated by grasses (*Festuca pallescens*), with a mosaic representation of *Nothofagus antartica* and *pumilio* trees (Luebert and Pliscoff, 2005). Soils present a poor development out of coarse parent materials and volcanic ash as a major element (Vandekerkhove et al., 2016).

2.1. Palaeoenvironmental background

Palaeoenvironmental reconstructions in the region were mainly based on the record of the El Shaman lake (forest-steppe ecotone; De Porras et al., 2012; Fig. 1A), El Embudo mire to the north (deciduous forest; De Porras et al., 2014) and the Pollux mire to the southwest (deciduous forest; Markgraf et al., 2007). Pollen and charcoal data indicate that relative cold and dry conditions characterized the period of glacier retreat between ca. 19,000 cal yr B.P. and ca. 14,800 cal yr B.P. (De Porras et al., 2012). Then, palaeoecological studies indicate high variability and a relative increase on the effective moisture (though below present values) between ca. 14,800–11,200 cal yr B.P. (De Porras et al., 2014), in a landscape characterized by profound hydrological changes (García et al., 2019). A sudden increase on the effective moisture and possibly summer temperature after ca. 11,200/11000 cal. yr B.P., accompanied by dry summers, are observed alongside high frequency of fires, possibly enhanced by a combination of greater fuel availability and human presence (De Porras et al., 2012, 2014; Méndez et al., 2016). Such amelioration tendency towards moister and warmer Middle Holocene conditions (Berman et al., 2018) continues until ca. 9500/8000 cal yr B.P., depending on records which vary in distance from the forests and altitude (De Porras et al., 2012, 2014; McCulloch et al., 2017). At the La Frontera site, further southeast, relatively cold conditions were also recorded between ca. 7420–6480 cal yr B.P. (McCulloch et al., 2017).

Under a moister regional trend established after ca. 5000 cal yr B.P. (Iglesias et al., 2014), modern seasonality conditions are inferred (De Porras et al., 2012). Under such a high climatic variability, slightly drier scenarios were, however, identified around 5700 cal yr B.P., ca. 4200 cal. yr B.P. and between ca. 3000–2000 cal yr B.P. (De Porras et al., 2012, 2014). After ca. 2000 cal. yr B.P. modern climatic conditions are established, whereas the last 100 years are characterized by an abrupt landscape shift due to the intentional clearance during the XX century herding colonization (Martinic, 2005; Markgraf et al., 2007; De Porras et al., 2014).

2.2. Study sites

Caves deposits were studied with a multidisciplinary approach. The Baño Nuevo 1 cave (45°17′35.8″S 71°32′48″W) is placed at 750 masl, being made up of exposures of the Baño Nuevo Volcanic Complex. The cave (20 m long, 4 m wide and 2.5 m high) presents low humidity and

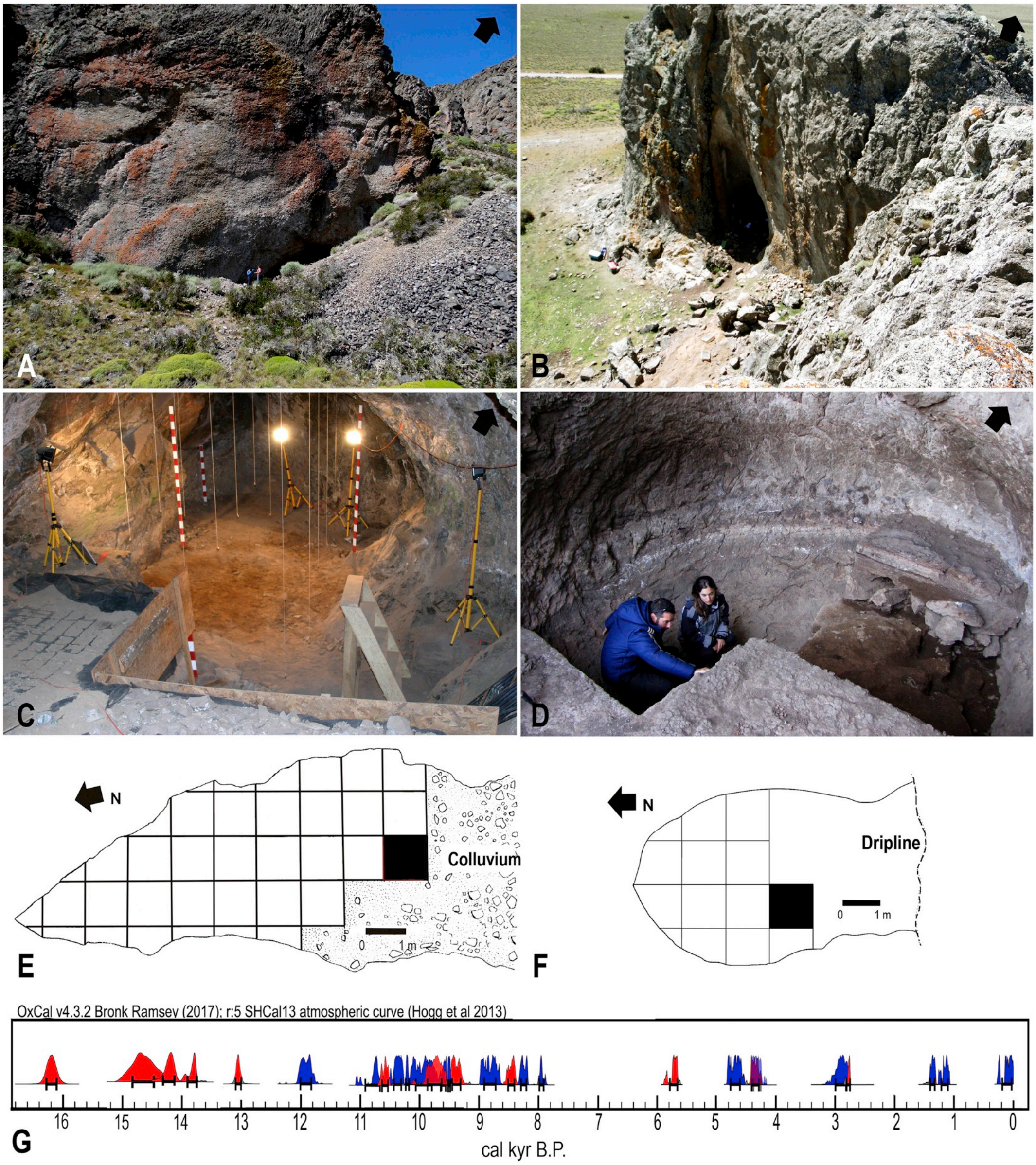

Fig. 3. A) The Baño Nuevo 1 and B) Cueva de la Vieja. C) View of the Baño Nuevo 1 (photo courtesy of T. Stafford) and D) Cueva de la Vieja excavations. E) Plan view and studied quadrant (black squares) of the Baño Nuevo 1 and F) Cueva de la Vieja. G) Archaeological and palaeontological calibrated dates (see ^{14}C dates in Mena and Stafford, 2006 and Méndez et al., 2018) obtained from the Baño Nuevo 1 (red) and Cueva de la Vieja (blue) (run in Oxcal v.4.3.2., ShCal 13 curve, 2σ confidence level; Bronk Ramsey, 2009; Hogg, 2013). See Table S1 for not calibrated dates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

stable temperature, with an entrance that faces south and has a restricted access due to colluvial debris coming from outside (Fig. 3A, C and E). Mena and Stafford (2006) defined six macroscopic layers (named as "stratigraphic units" –SU-herein) along a maximum depth of ~160 cm.

Late Pleistocene deposits include extinct fauna such as Equidae, *Macrauchenia* sp., Felidae, Camelidae, Mylodontidae, *Diabolotherium* and *Arctotherium* (López Mendoza et al., 2015; Westbury et al., 2017). Sediments containing anthropogenic materials (deposited between ca. 10,800–2900 cal. yr B.P.; Fig. 3G) seal that palaeontological component. Archaeological studies indicated that past human groups used the cave as brief but redundant campsites (i.e., manufacture, use and discard of tools, butchering and consumption of fauna) and for funerary purposes (e.g., Mena et al., 2003; Mena and Stafford, 2006; Reyes et al., 2012), probably during spring-summer, as suggested by the presence of certain plant taxa (Belmar et al., 2017). Artefacts, fauna bones, plant macro-remains and human remains show that occupants had a highly mobile system, a good knowledge of the local and regional landscape, and a broad spectrum terrestrial diet (mainly based on *Lama guanicoe*), with a supplementary consumption of local plants (e.g., Velásquez and Mena, 2006; Reyes et al., 2012; Méndez et al., 2014; Belmar et al., 2017). These human activities, which comprised burials, hearths and other activity areas within abandonments and re-occupations across several millennia, had created a complex stratigraphy, being particularly difficult to discriminate the limits between paleontological and archaeological layers across the cave surface (Mena et al., 2003; Velásquez and Mena, 2006).

The Cueva de la Vieja site (45°16′27″S 71°32′24″W) is placed at 718 masl in an outcrop also of the Baño Nuevo Volcanic Complex (Méndez et al., 2018). This cave is located 2.18 km to the northwest of the Baño Nuevo 1, it has a limited sheltered area (6 m long, 4 wide, 17 m high) and faces south (Fig. 3B, D and F). The Cueva de la Vieja site yielded the

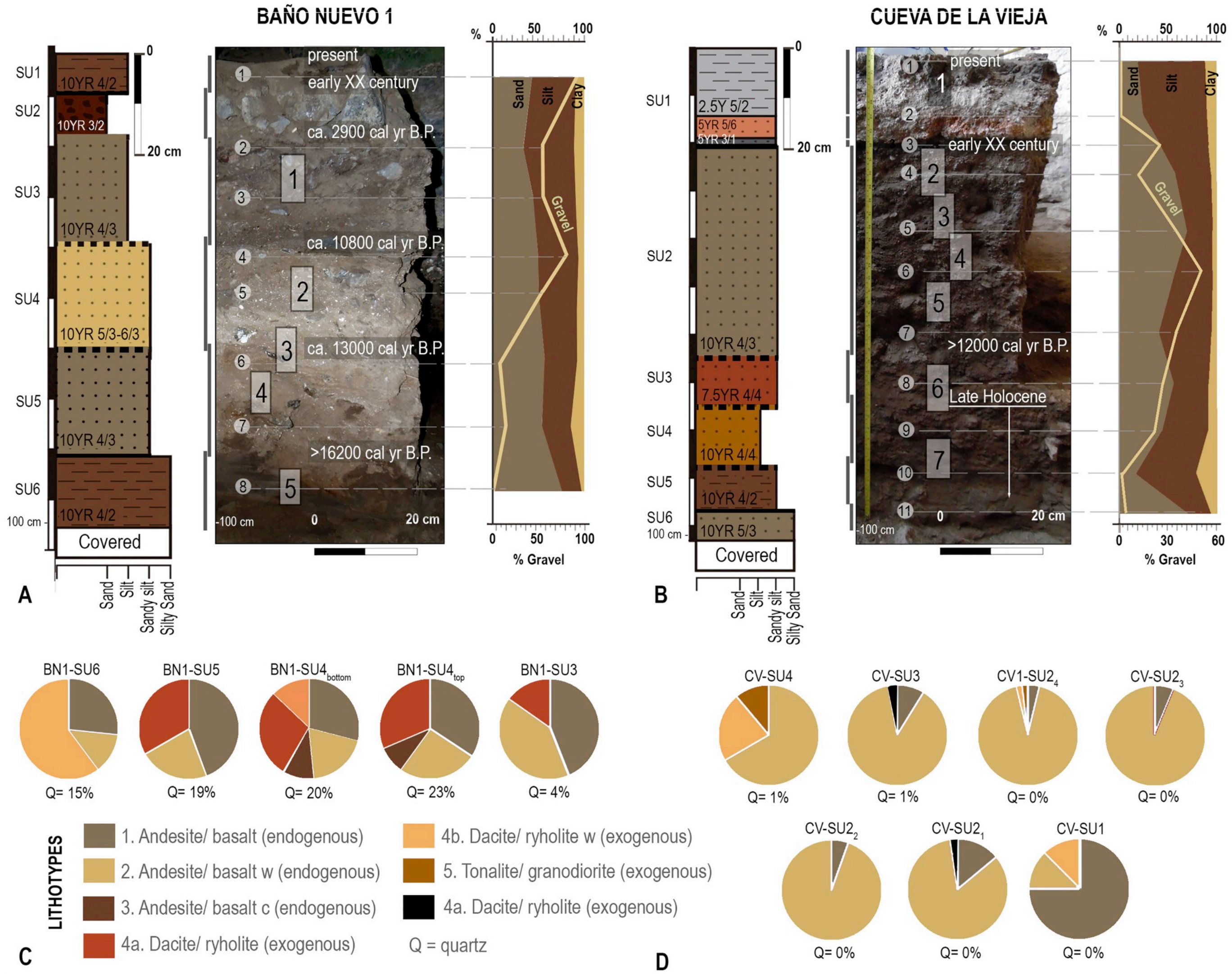

Fig. 4. Granulometric data of A) Baño Nuevo 1; and B) Cueva de la Vieja (modified after Méndez et al., 2018). Lithotype profiles of C) Baño Nuevo 1 and D) Cueva de la Vieja. "w." = weathered; "c" = carbonate veins (Table S5, Fig. S1). In the sections, numbers in rectangles correspond to micromorphological samples, also studied for lithotype definitions. Numbers in circles represent bulk samples for granulometric, magnetic and geochemical analyses.

earliest human context of west-central Patagonia (Méndez et al., 2018), with several brief occupational events spanning the last 12,000 years (Fig. 3G). These occupations took place during the end of the spring and summer season, as suggested by plant macro-remains and zooarchaeological analyses. Six SUs in a maximum ~120 cm depth section were recognized (Méndez et al., 2018). Based on the proximity between both sites, the fact that they share common lithic raw materials, and that occupational events and abandonment periods coincide, these two sites are regarded as part of the same settlement system throughout the Holocene (Méndez et al., 2018).

3. Methodology

Detailed analysis on the sedimentary record of the Baño Nuevo 1 was performed in the western section of square 9C (Fig. 3E), where a total of eight samples were taken at ~10 cm intervals to measure granulometry (Malvern Sedigraph, on-line USDA texture triangles), gravel frequency (by sieving), pH (SANXIN Instrument) and an indirect measurement of the total organic (%TOC) and inorganic (%TIC) carbon by loss-on-ignition (Heiri et al., 2001). Five undisturbed samples for micromorphological analysis were collected across the SUs (Fig. 4A). Samples were air-dried, impregnated with e-poxy resin, polished to ~30 μm and mounted on a glass slide for thin section analysis under a petrographical polarizing microscope, following standard protocols (Bullock et al., 1985; Stoops, 2003; Stoops et al., 2010). Porosity was quantified from thin sections, using the software *JMicroVision* 1.27. An optical mineralogical analysis, consisting of counting and averaging sand fraction grains at five equidistant spots (10×) along each slide, was carried out. Sand/gravel-size lithic fragments were classified in lithotypes to define sedimentary sources.

Magnetic analyses were performed on dried-grounded samples to identify types and grain-size of magnetic minerals, which in turn allow inferring depositional and post-depositional conditions of the deposits (Dalan and Banerjee, 1998; Liu et al., 2005; Hrouda, 2011). Magnetic properties have been extensively applied in paleoenvironmental reconstructions in South America to infer relative variations in humidity/temperature, pedogenetic processes and sediment source variations (e.g., Orgeira et al., 2011; Irurzun et al., 2014). On the other hand, magnetic analyses have been used to estimate anthropogenic combustion activities and post-depositional processes in archaeological sites (e.g., Evans and Heller, 2003; Dalan, 2008; Capriles et al., 2016).

Magnetic susceptibility (X) (Bartington Instrument) was normalized to mass. The magnetic susceptibility versus field (5-700 A/m) at a frequency of 1000 Hz was also performed (AGICO-Multifunction

Kappabridge Instrument, model MFK1-FA) in order to infer the presence of titanomagnetite. Additionally, hysteresis loops and magnetization with reverse field were measured in the vibrating sample magnetometer (VSM, Molspin Ltd.). Results allowed the calculation of the saturation remnant magnetization (Mrs), the saturated magnetization (Ms), the coercivity of remanence (Hcr) and the coercivity (Hc). Extensive parameters (X, Ms and Mrs) enable estimating mineralogy, concentration and size of magnetic minerals, whereas the calculation of rock-magnetic parameters such as X/Ms, Hcr/Hc and Mrs/Ms helps to identify variations in the particle size of the magnetic minerals.

In the case of the Cueva de la Vieja, analytical data include porosity quantification, petrography and magnetic properties, following the aforementioned methods and techniques. These results were integrated with published information (Méndez et al., 2018).

4. Results

4.1. Sedimentology, micromorphology and petrography

Macro- and microscopic analysis of the Baño Nuevo 1 section confirmed the presence of six SUs (Mena and Stafford, 2006), broadly comprising massive deposits (with the exception of the laminar sedimentary structure at SU6) of silt/sandy textures (Fig. 4A). Colours vary between brown and greyish brown, while layer contacts are mostly gradual, excepting for SU6/SU5 and SU3/SU2 sharp transitions. Gravels show their maximum frequencies at SU4 (upper half) and SU1. Endogenous lithotypes (1, 2, 3) mainly composed the lithic fraction along the section, with variable yet subordinated presence of exogenous lithotypes (4a, 4b, 5, 6) (Fig. 4C; Tables S2, S5; Fig. S1). Similarly, mineral percentages coming from the endogenous lithotypes weathering (i.e., plagioclases, opaques, pyroxenes, amphiboles, etc.) are more frequent than exogenous ones (i.e., quartz, microcline, K-feldspars, volcanic glass) (Fig. 5A; Table S4).

Micromorphology indicates an increase of bioactivity upwards (Fig. 5B, C), signals of clay translocation at SU5 (Fig. 5D) and sandy/clay inter-digitated microlayers at SU6 (Fig. 5E; Tables S2, S3). The %TOC increases upwards, %TIC shows a mode at SU4 and pH values vary between 6 and 7.7 (Fig. 7A; Table S2). The presence of anthropogenic activity is well-recorded at SU3, though some micro-bones and one charcoal particle were observed at SU4 (Fig. 5F).

New analytic data of the Cueva de la Vieja site support previous results (Méndez et al., 2018), while offer a more detailed evaluation of processes involved along the section, particularly on the levels predating the human occupation (SU6-SU3). Broadly, SUs comprise massive deposits (or slightly laminated at SU5) dominated by loamy silty/sand textures; with gradual contacts among layers (excepting SU6/SU5 and SU2/SU1 transitions) (Fig. 4B; Table S2). Sediments have brownish to greyish colours, with yellowish/reddish chroma at SU4 and SU3. The gravel fraction has its mode at the lower SU2 (Fig. 4B). As in Baño Nuevo 1, endogenous lithotypes (1, 2) dominate the lithic fraction, whereas exogenous lithotypes (4b, 5, 6) are marginally represented across the sequence, excepting at SU4 (Fig. 4D; Table S5, Fig. S1). With the exception of few quartz grains ($< 1\%$ across SUs) and some possible K-feldspar grains, the mineral assemblage is mainly composed of endogenous particles, namely, coming from the bedrock weathering (Tables S4, S5).

Broadly, micromorphological analysis shows bioactivity increasing upwards and properties associated with vertical movements of water and fine material (coatings, hypocoatings, striated/speckled b-fabrics, etc.; Fig. 6A, B, C) (Table S3). Both %TOC and %TIC increases upwards, and pH values are moderately acid (4.5–6.9), with the exception of the uppermost sample (7.9) (Fig. 7B). The presence of anthropogenic activity is well-recorded both macro- and microscopically at SU2. Though some micro-bones were recorded at the pre-human SU3, their anthropogenic nature cannot be ruled out (Table S2).

4.2. Magnetic properties

The magnetic parameters Hc and Hcr of Baño Nuevo 1 suggest the presence of magnetite and/or titanomagnetite along the analysed section (Fig. 7A), whereas some Hcr values are also compatible with high-coercivity minerals such as hematite, especially at SU6, SU5 and SU4 (here the presence of hematite is also suggested by the $S_{ratio} = 0.6$; Phillips, 2017).

A relatively high paramagnetic mineral content (X_{para}) is observed at SU3 and SU1. In the case of SU3, a small increase in pyroxenes (Table S4) and lithotyes 1 and 2 (andesites/basalts; Fig. 4C) could have contributed to that peak in the paramagnetic signal. On the other hand, the total magnetic susceptibility (X) does not present substantial variations along the section, though the magnetic susceptibility versus field suggests the existence of titanomagnetite (i.e., igneous origin) at SU6, following by SU2 and off-site samples (Fig. 7C). Due to the macro- and microscopic volcanic glass at this level (Fig. 5A), titanomagnetite content could be related with volcanic input.

Extensive parameters (Ms and Mrs) decrease at SU4, a fact that could be explained by a relative increase on the coercivity, and a decrease on the total (X) and paramagnetic (X_{para}) susceptibility. The magnetic signal of SU4 could be thus related with postdepositional processes of detrital magnetic mineral depletions (favoured by the higher porosity of SU4; Fig. S6C) and high-coercivity minerals neoformation. In fact, dusty clay coatings observed at SU5 thin section suggest translocation of fine materials and solutions from above (SU4). Magnetic mineral depletion suggests, in turn, humid conditions at SU4. Extensive parameters increase at SU3, associated with a Hcr decrease, are likely explained by a relative increase on the magnetic mineral concentration and a relatively high particle size of the magnetic fraction. Even though the fact that %TOC is relatively high at this level (so ferrimagnetic mineral dissolution may occur), it seems that anthropogenic and/or natural magnetic mineralogy inputs balance depletion processes. The Ms, Mrs and X_{para} decrease at SU2 could also be related to depletion processes promoted by organic acids (Orgeira et al., 2011), in this case related with subaerial sheep excrements. Day plot shows the presence of pseudo-single domain particles size along the section (Fig. S2).

Magnetic parameters of the Cueva de la Vieja site show the presence of titanomagnetite and/or magnetite along the studied section. High-coercivity minerals, particularly at SU4, are inferred from the S_{ratio} (0.68–0.88), so a generalized oxidation is indicated. Extensive parameters (X, Mr. and Mrs) and coercivity values (particularly Hc) show a consistent behaviour, so their increase could respond to relatively large particle size of the magnetic fraction. With the exception of SU6 and the two off-site samples, magnetic susceptibility versus field shows very low titanomagnetite concentration along the section (Fig. 7D).

At SU4, extensive parameters increase, likely associated with large particle sizes (due to low Hc values) and thus interpreted as magnetic material input. Relatively high oxidation processes can be observed at this level through a relative S_{ratio} decrease. At the middle-SU2, another additional magnetic material input is observed, likely caused by anthropogenic combustion as observed through charcoals and burnt bones (Table S2).

Another increase on extensive parameters associated with a decrease on Hc and Hcr is observed at the lower-SU1, so a relative large magnetic particle size is inferred. The Day plot shows the presence of single-domain plus superparamagnetic particle sizes (Fig. S2), probably due to superparamagnetic particles or a mixture of high/low coercivity minerals. As the S_{ratio} indicates generalized oxidation processes along the section (i.e., hematite), the second scenario seems to be more likely.

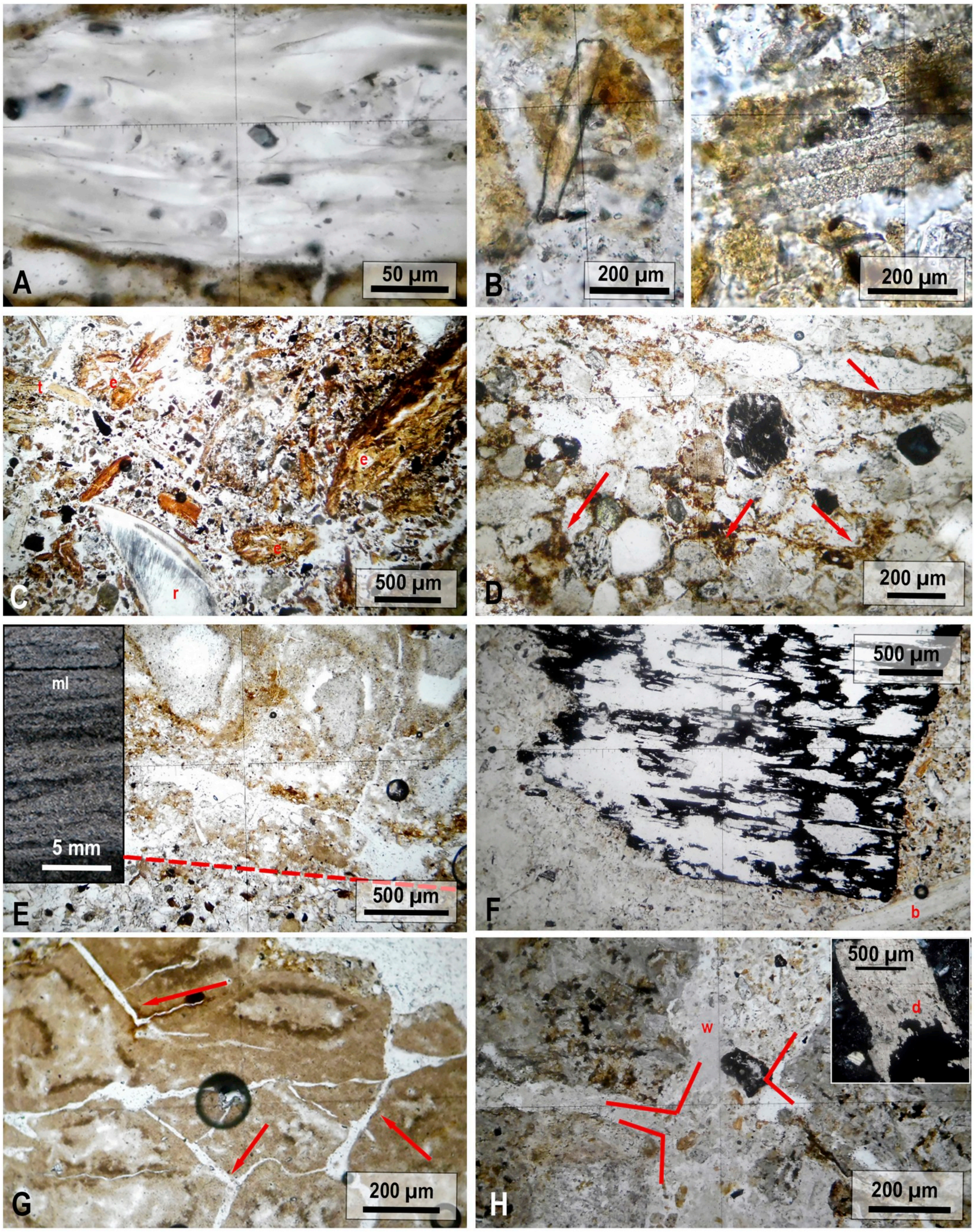

Fig. 5. Microphotographs of the Baño Nuevo 1 (plane "PPL" and cross "XPL" polarized light): A) Well-preserved pumice fragment; SU6 (PPL). B) Well-preserved single (left) and articulated (right) phytoliths of non-diagnostic elongated morphotypes; SU4 (PPL). C) Evidence of high-bioactivity: rodent tooth (r), poorly-preserved tissue remains (t) and soil fauna excrements (e); SU3 (PPL). D) Arrows point to dirty coatings of fine material mixed with highly weathered organic matter and Fe/Mn oxides in voids; SU5 (PPL). E) Silty/clay and fine sand micro-layers; macroscopic view (ml); SU6 (PPL). F) Fragment of well-preserved (anthropogenic?) charcoal and a micro-bone (b); SU3 (PPL). G) Arrows point to drying fissures from the silty/clay micro-layer of SU6 (PPL). H) In situ gravel fragmentation caused by physicochemical weathering (w) (PPL); and carbonate dissolution (d); SU4 (XPL).

5. Discussion

5.1. The Baño Nuevo 1

The presence of rhythmic laminations of sands and silty-clays observed both macro- and microscopically in the basal SU6 (older than ca. 16,200 cal yr B.P.), along with other sedimentological (i.e., well sorting, allochthonous mineralogy), micromorphological (i.e., vesicles and fissures, diagenetic features, etc.) and magnetic evidence (i.e., high Hcr values), supports the existence of periodical low-energy water currents flooding the cave and forming ephemeral water ponds, characteristic of a marginal lake sub-environment. Geomorphological data suggest sedimentation associated with a proglacial lake setting during the late Pleistocene deglaciation process (García et al., 2019). Additionally, the lack of coarse material weathered from the cave roof/wall (Fig. 4A) supports cold/dry scenarios (Dessert et al., 2003; Li et al., 2016) and/or rapid sedimentation processes. The scarcity of bioactivity may also respond to such periodical floods under deglacial conditions (Markgraf et al., 2007; De Porras et al., 2012).

The ephemeral nature of these water bodies is indicated by the

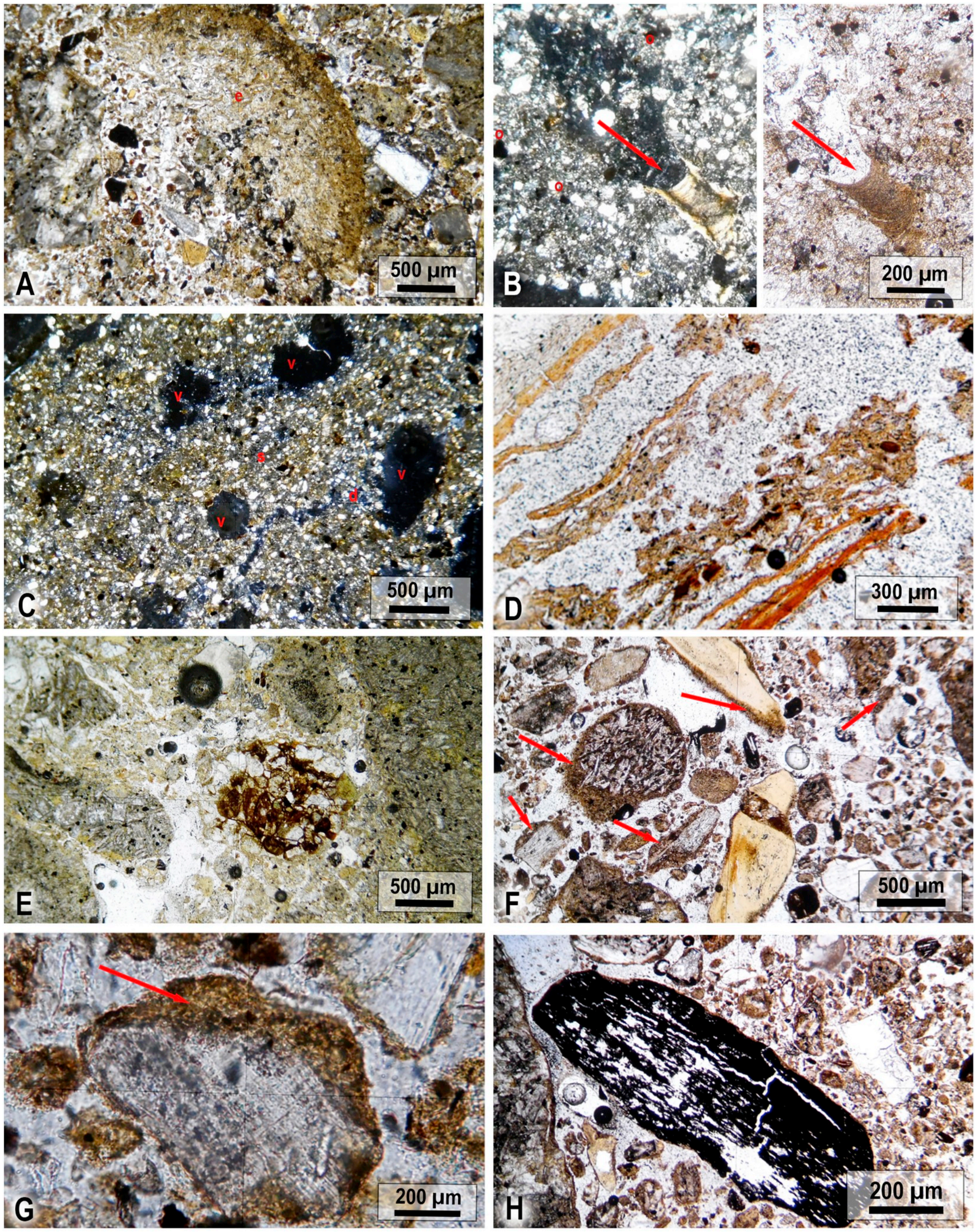

Fig. 6. Microphotographs of the Cueva de la Vieja: A) Bioturbated deposit, note the fragmented meso-fauna excrement (e) in a poorly-sorted matrix; SU2 -lower half- (PPL). B) Dusty clay coating in voids of well-oriented clay domains (left –XPL- and right –PPL-); note opaque minerals (o); SU4. C) Vesicles (v) in well-sorted matrix with stains (s) and Fe/Mn oxide depletion (d) zones; SU4 (XPL). D) Highly-degraded tissue remains, replaced by Fe/Mn oxides; SU3 (PPL). E) Fe/Mn oxide stains in a poorly-sorted matrix; note the in situ fragmentation of gravels; SU3 (PPL). F and G) Dirty coatings and cappings of fine material mixed with organic matter, sand grains and bone fragments; SU2, upper half (PPL). H) Rounded charcoal particle in a poorly-sorted matrix; SU2 –upper half- (PPL).

presence of desiccation cracks in silty-clay layers (Fig. 5G) and Fe/Mn oxide precipitations. Opaque minerals observed as fine beddings embedded in sandy micro-layer could be attributed to magnetite grains deposited when the water energy decreases (e.g., Goldberg et al., 2015; Toffolo et al., 2017), which may, in turn, explain the relatively high magnetic susceptibility at this level (Fig. 7A).

Based on the SU6 chronological frame, the presence of volcanic glass observed microscopically (Fig. 5A) –with a conspicuous magnetic signal of titanomagnetite (Fig. 8C)- could be related with the Melimoyu (> 19,670 cal yr B.P.), Mentolat (> 17,340 cal yr B.P.) or Hudson (17,370 cal yr B.P.) eruptions (Stern et al., 2015 and references therein; Fig. 1A). Finally, the highest sedimentary rate at SU6 of 0.18 mm/yr (last 19,000 years, excluding SU1 due to preservation bias) can be explained by highly dynamic processes of the deglaciation landscape (Table S6).

The SU5 (ca. 16,200–13,000 cal yr B.P.) shows weak bioactivity, so some climatic amelioration and environmental stability could be inferred. In fact, the regional palaeoecological record indicates a relative increase on the summer temperature and effective moisture (Markgraf et al., 2007; De Porras et al., 2012, 2014). The presence of gravels resulting from the cave roof/wall weathering (Fig. 4A) and several collapses from the roof at the top of SU5 could also indicate moisture

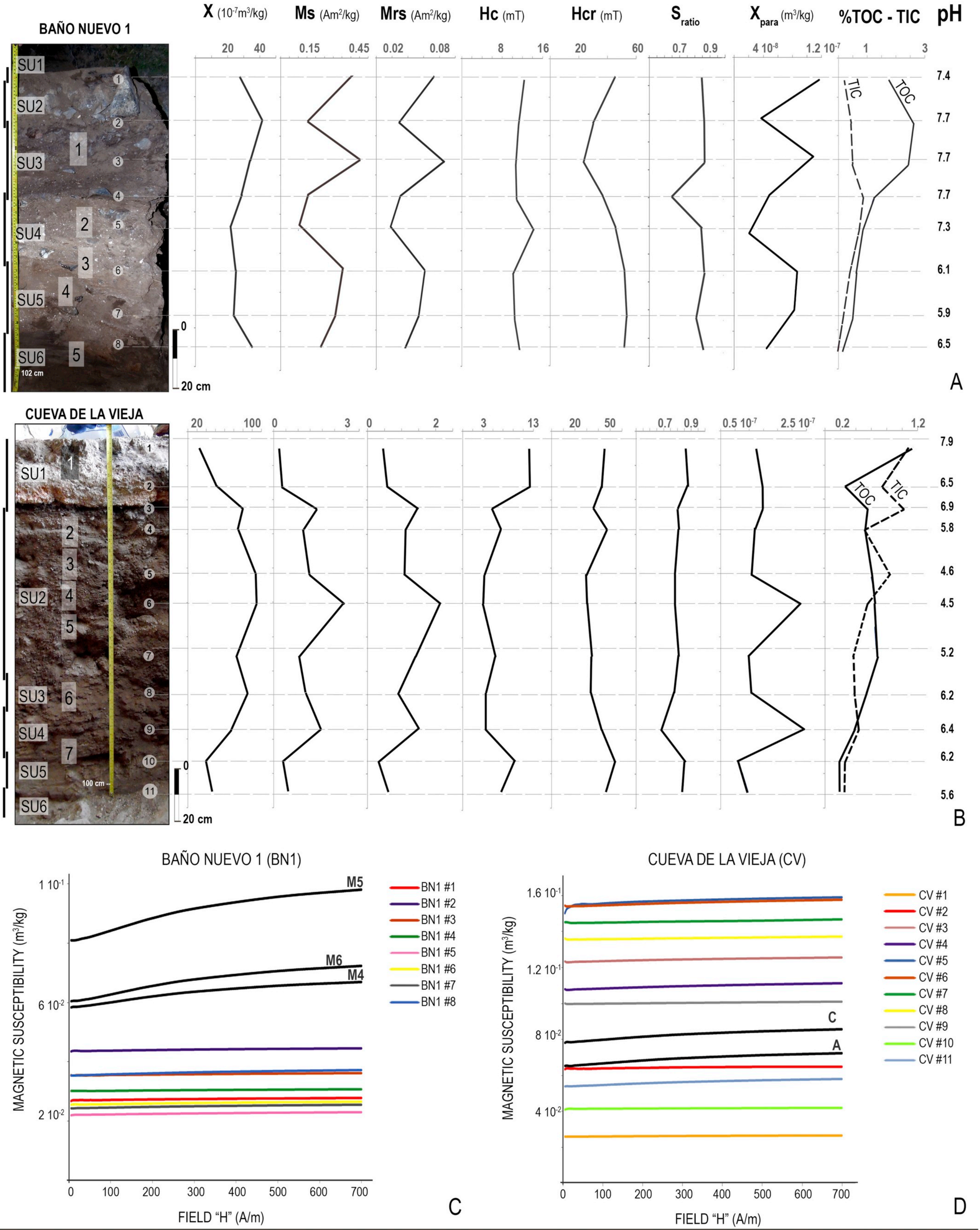

Fig. 7. Magnetic properties, %TOC-TIC and pH of A) Baño Nuevo 1 and B) Cueva de la Vieja. Magnetic susceptibility versus field of C) Baño Nuevo 1 and D) Cueva de la Vieja. "BN1 #1… #8" = bulk samples (see section above); "CV #1… #11" = bulk samples (see section above) (Table S7, S8; Fig. S3).

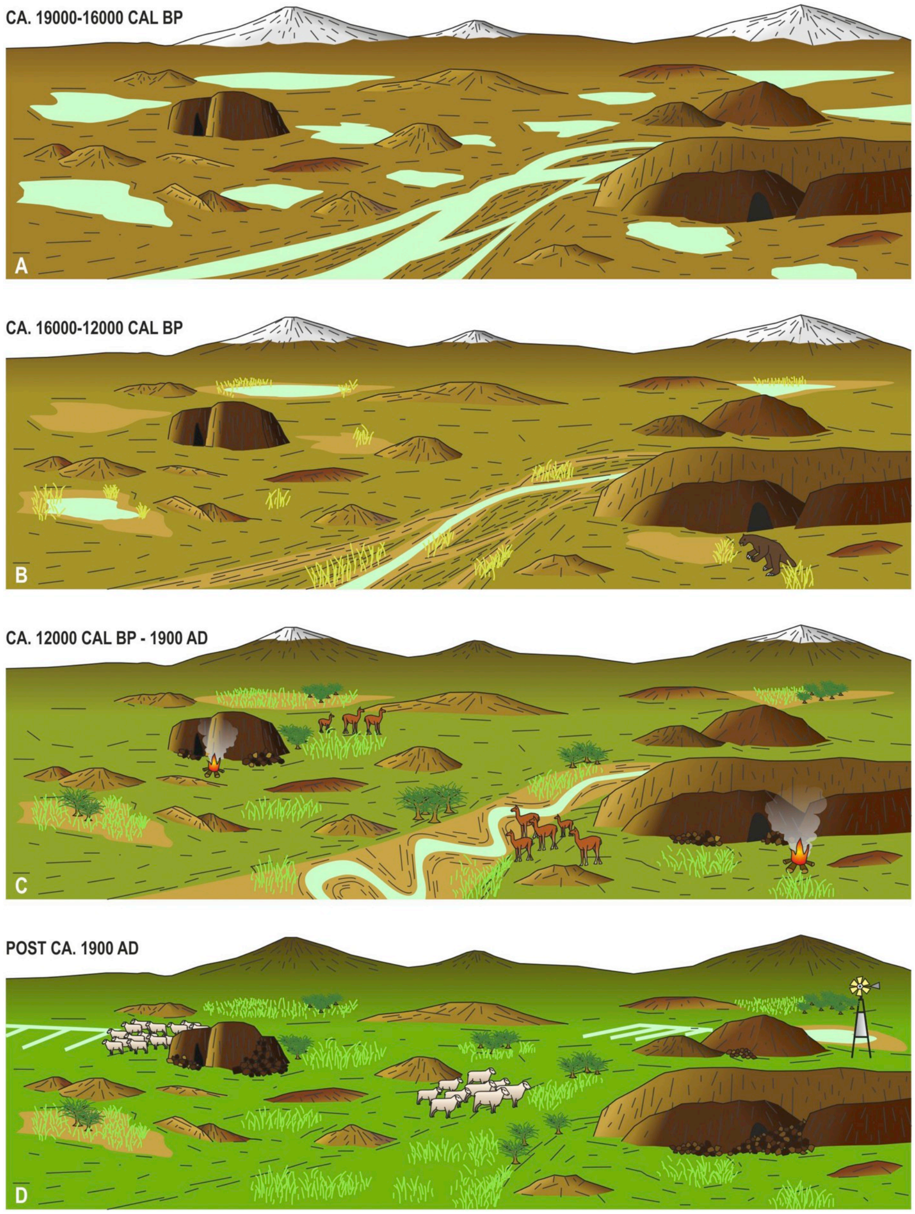

Fig. 8. Schemes corresponding to main environmental changes interpreted from cave deposits. A- Pro-glacial landscape (ca. 19,000–16,000 cal yr B.P.). B- Open steppe (ca. 16,000–12,000 cal yr B.P.). C- Steppe (ca. 12,000 cal yr B.P.–1900 CE). D- Present (after ca. 1900 CE).

fluctuations (e.g., Farrand, 1975; Collcutt, 1979; Polo-Díaz et al., 2016), since temperature and water are the main factors controlling basalt weathering (Dessert et al., 2003; Li et al., 2016). Wet/dry cycles are also evidenced by frequent Fe/Mn mottling, carbonate nodules, clay translocation processes and the presence of high-coercitivity minerals (i.e., hematite), attributed to diagenesis in an oxidizing environment. On the other hand, the clay content, higher than in the overlying and underlying units (Fig. 4A), indicates neoformation (e.g., Farrand, 1975) and/or illuviation processes. Along with endogenous processes, the presence of significant amount of quartz grains and lithotype 4a (dacite/rhyolite) (Fig. 4C) also suggests an external sediment source. An open steppe landscape with adequate ecological conditions to support mega-fauna should have been established by this time, since SU5 presents megafauna remains (e.g., López Mendoza and Mena, 2011; López Mendoza et al., 2015; Westbury et al., 2017).

Relatively high effective moisture and temperature are interpreted from a substantial increase on both bioactivity and gravel fraction from the bedrock weathering in SU4 (ca. 13,000–10,800 cal yr B.P., Mena and Stafford, 2006) (Fig. 4A). Moister conditions are also supported by abundant carbonate nodules, derived from weathering of basalts with carbonate veins (lithotype 3), some of which are partially dissolved (Fig. 5H). Likewise, dusty clay coatings of the underneath deposit (SU5) indicate illuvial processes took place at SU4 (Figs. 4A and 5D). The presence of carbonate veins in the basalt/andesite bedrock recorded by lithotype 3 could result from water percolation, further supporting an increase in humidity. In addition, the presence of hematite shown by magnetic properties, indicates oxidation processes (Fig. 7A), so dry/wet cycles can be inferred.

The fine material of SU4 seems to derive from both exogenous and endogenous sources, the latter resulting from in situ weathering. Similarly, a high proportion of the sand fraction came from outside (quartz, microcline and granitoid rocks corresponding to lithotype 5), while other sand grains formed in situ, by the weathering of gravel particles (Fig. 5H). The lowest sedimentary rates at SU4 (0.02 mm/yr) could be attributed to pedogenesis under relatively more stable geomorphological postglacial conditions (Table S6). Biological post-depositional processes also took place at SU4, as evidenced by burrowing action, which may mix sediments across SUs, thus explaining the presence of burnt bone fragments from the overlying anthropogenic deposit. Fossorial animal activity (e.g., nesting) may also account for the presence of isolated and articulated phytoliths with no signals of digested corrosion (Fig. 5B).

Signals of bioactivity increase in SU3 (ca. 10,800–2900 cal yr B.P.; Mena and Stafford, 2006). Macro- and microscopic record of grasses, straws and phytoliths could be explained by burrowing, nesting, feeding and excretion of rodents, other small mammals and/or bird raptors such as owls (Fig. 5C), though some plant macro-remains could have been introduced by humans (Mena and Quemada, 1999; Belmar et al., 2017). Meso-soil fauna and small mammal action, coupled with human activities, may have produced an intense mixing, hence neither macro- nor microscopic differences can be observed within SU3. However, a drop in the gravel frequency is recorded in the upper half of SU3, suggesting a decrease on weathering rates and, thus, a certain period of relatively low-humidity and/or cold conditions.

A substantial decrease on the frequency of exogenous quartz particles and the record of lithotype 4a (dacite/rhyolite) could respond to new sediment sources available due to changes in the external vegetation cover and/or wind intensity/direction. On the other hand, the presence of angular blocks from the roof, forming discontinuous layers, could be interpreted as rock-fall episodes, likely triggered by extreme natural events (e.g., earthquakes, exceptional storms).

The increase of X_{para} signal could be attributed to intense diagenesis associated with organic acids (Fig. 7A), whereas the increase on the magnetic mineral concentration/size could have been favoured by anthropogenic activities (Dalan and Banerjee, 1998). However, relatively low magnetic susceptibility may indicate few or low-intense anthropogenic combustion features, which are expected to promote high magnetic susceptibility if temperatures are higher than ca. 600 °C (Oldfield and Crowther, 2007).

The SU2 (ca. 2900 cal. yr B.P. – pre-XX century, Mena and Stafford, 2006) was deposited by gravity-driven processes acting in the talus slope (Fig. 2A), probably triggered by exceptional modern geological or meteorological events (e.g., earthquake, exceptional storm). Since palaeoecological record indicates a predominance of dry conditions between ca. 3000–2000 cal yr B.P. (De Porras et al., 2012, 2014), intense precipitations in this arid/semi-arid landscape could have favoured the developed of such talus cone. At this level, magnetic data show the presence of titanomagnetite (Fig. 8C) probably ascribed to volcanic materials and, hence, the colluvium could be more or less contemporaneous with any Late Holocene volcanic eruption. Finally, the present floor (SU1) comprises sheep refuges established since the early XX century, when the locality became a ranch, under the high climatic variability that characterized the last centuries (Martinic, 2005; De Porras et al., 2014).

5.2. Cueva de la Vieja site

Aeolian processes under cold and/or dry conditions might generate the basal SU6 at the Cueva de la Vieja, as suggested by a well-sorted massive deposit and the rare presence of gravels coming from the weathering of the bedrock (Dessert et al., 2003; Li et al., 2016). These evidences likely indicate a scarce vegetation cover under cold/dry proglacial or periglacial conditions. At this level (and at off-site samples), magnetic data show the presence of titanomagnetite (Fig. 7D). This signal shows similarities with the case of Baño Nuevo 1, so volcanic inputs could be also inferred here, beyond the fact that microscopic volcanic glass was not observed. Indeed, the presence of titanomagnetite only at this basal level and in the soil profile outside the cave may discount the possibility to be a consequence of the cave weathering contribution, which is observed all along the profile through the gravel frequency (Fig. 4B). Therefore, this possible volcanic input could be contemporaneous with the one observed in SU6 of the Baño Nuevo 1 (see above), related with the Melimoyu (> 19,670 cal yr B.P.), Mentolat (> 17,340 cal yr B.P.) or Hudson (17,370 cal yr B.P.) eruptions (Stern et al., 2015 and references therein), as SU6 corresponds to the Late Pleistocene. If so, a preliminary temporal framework between ca. 19,670–16,200 cal. yr B.P. could be proposed for SU6. This scenario is consistent with the beginning of the deglaciation process of the Rio Cisnes Glacier, located immediately north of the study area and dated at ca. 19000 cal yr B.P. (De Porras et al., 2012; García et al., 2019).

The substantial increase of loam material in SU5 (Figs. 4B), along with its weak lamination, macro-porosity (vesicles with manganese coatings) and the geometry (Table S2) suggest low-energy water currents. The presence of local erosional surfaces at the base of SU5 could also be explained by local water flows, probably associated with proglacial lake fluctuations during the deglaciation of the Ñirehuao valley, inferred between ca. 14,000–12,900 cal yr B.P. (García et al., 2019). Indeed, the lowest sedimentary rate interpreted at SU6 of 1.2 cm/kyr (last 19,000 years, excluding SU1 due to preservation bias) could be related with such erosion processes (Table S6). Alternatively, SU5 deposit could be attributed to sedimentation at ephemeral ponds by flooding of the cave, such as SU5 of the Baño Nuevo 1, constrained between ca. 16,200–13,000 cal yr B.P. In any case, very low contents of TOC, similar to those of the underlying SU6 and the SU6 of the Baño Nuevo I, suggest cold and/or arid conditions, likely associated with periglacial or open steppe environments (Fig. 7B).

New data presented here further support previous interpretations regarding the genesis of SU4, concerning the entrance of water-driven by gravity processes (i.e., surface runoff) taking placed along the talus (Méndez et al., 2018). In this sense, magnetic analyses show a significant increase on extensive parameters, associated with larger particle sizes, interpreted as magnetic material input from outside the cave. Moreover, surface runoff might be periodic (seasonal rainfall and/or summer snow melting), as suggested by the presence of limpid laminated clay coatings in voids (Fig. 6B). In this context, the presence of (Fig. 6C) could be attributed to rapid and/or abundant water infiltration. Additionally, an increase on bedrock weathering (Fig. 4B) and evidence of oxidation processes (Fig. 7B) may indicate moister and/or warmer conditions than in underlying units, also supported by moderate bioactivity observed through channel microstructures and highly degraded organic matter (Fig. 6A, D).

An exogenous source of material is indicated by well-sorted fine sands of quartz, and lithotypes 4b and 5, the latter of which are only recorded at SU4 and thus indicate a change in the sediment source (Fig. 4B; Table S5, Fig. S1). These sedimentary data suggest aeolian deposition, probably reworking palaeo-fluvial deposits, as suggested by rounded/sub-rounded particle shapes. Considering the chronology proposed for the underlying deposit, SU4 might have begun accumulating after ca. 13,000/12900 cal yr B.P.

In contrast to previous SUs, SU3 presents intense evidence of bioactivity (macro- and micro record of bone fragments, plant tissue remains, isolated and articulated phytoliths, spores, diatoms), bedrock weathering and abundant in situ precipitation of opaque minerals and Fe/Mn oxides (Figs. 4B, 6E; Table S4), indicating a further increase in temperature and/or humidity. At this unit, sand grains are mainly explained by in situ weathering of coarser fractions, while a small proportion might be transported by wind, as indicated by the presence of lithotype 6 (andstone of the Apeleg Formation; Figs. 3 and 4D) and quartz particles (Fig. 4D). This drop in aeolian input with respect to SU4 could suggest more stable geomorphological conditions, namely, a well-developed vegetation cover.

The anthropogenic combustion feature located at the top of SU3, dated between ca. 12,100–11,800 cal yr B.P. (Méndez et al., 2018), suggests ecological and climatic conditions which may have enabled the arrival of human groups, most likely from eastern population cores (Méndez, 2013; Méndez et al., 2018). Since the earliest age for SU2 is ca. 12,000 cal yr B.P. (based on anthropogenic features; Méndez et al., 2018), the SU3 chronology could be tentatively bracketed between ca. 13,000/12900–12,000 cal yr B.P. This temporal framework may satisfactorily explain physical properties of SU3, corresponding to clear signals of wetter and/or warmer conditions which characterized the Pleistocene-Holocene transition (between ca. 14,700–8000 cal yr B.P.; De Porras et al., 2012). Indeed, the highest sedimentary rate at SU4 (16.7 cm/kyr) and SU3 (15 cm/kyr) could be explained by an increase of endogenic input related with wetter conditions (i.e., cave weathering), along with additional material entering into the cave by surface runoff (Fig. 6B). This contrasts the Baño Nuevo 1 sequence, where the beginning of the Holocene is associated with a sedimentary rate decrease (Table S6).

The SU2 (before ca. 12,000 cal yr B.P.; Méndez et al., 2018) can be associated with an even more stable landscape, interpreted through a relative decrease of aeolian sediments (lack of quartz particles and scarcity of exogenous lithotypes; Fig. 4D). Likewise, bedrock weathering increases (Fig. 4B) and highly degraded organic matter is observed, also suggesting more humid and/or warmer conditions, probably in the context of the regionally recorded moisture increase around 8000–7500 cal yr B.P. (De Porras et al., 2012, 2014; McCulloch et al., 2017).

The presence of silty/clay cappings over gravel particles in the upper half of SU2 (Fig. 6G) could indicate rapid percolation processes across the section, maybe as the result of surface runoff (Courty and Vallverdú, 2001). In fact, gravity-driven processes are also evidenced by dirty silty/clay coatings around gravel and bone fragments, interpreted as rolling (Fig. 6F). This exogenous sediment source, as well as the anthropogenic activity (i.e., combustion; Fig. 6F, H), could thus explain the additional magnetic input (Fig. 7B). The mentioned micromorphological features of the upper half of SU2, associated with increase in precipitations (rain or snow), likely coincide with the modern seasonality established after ca. 5000 cal yr B.P. (De Porras et al., 2012). Interestingly, the human re-occupation of the cave after a ca. 2300 years abandonment, occurred at ca. 5700 cal yr B.P.

Finally, sheep refuges and modern combustion anthropogenic activities produced by herding since the early XX century defined SU1 (Martinic, 2005; De Porras et al., 2014). This deposit is mainly composed by fresh and burnt organic matter, abundant gravels and coarse sands coming from the cave weathering, and fine sands (mainly plagioclase), likely resulting from weathering of lithotype 1 (Fig. 4D; Table S6). By considering all data, SU1 deposit is almost entirely formed and modified by endogenous materials and processes.

5.3. Palaeoenvironmental evolution and human trends

The studied cave deposits show processes which took place since the last deglaciation. Beyond some differences, sedimentological, petrographic, chemical, micromorphological and magnetic properties of SUs enable comparisons between the two caves and also between them and the regional palaeoenvironmental record. The SU6 at Baño Nuevo 1 and SU6/SU5 at Cueva de la Vieja represent pro-glacial/periglacial environments, with very rare signals of bioactivity and a dominance of exogenous material (i.e., fluvioglacial, lacustrine and aeolian). Cold/arid conditions, a poorly integrated drainage and an almost absence of pedogenesis characterize this first scenario (Fig. 8A). Then, SU5 (Baño Nuevo 1) and SU4 (Cueva de la Vieja), comprising last millennia of the Pleistocene, may record an open steppe landscape (Fig. 8B), whose primary productivity allowed supporting mega-fauna (López Mendoza et al., 2015). Available ages on extinct fauna show no local persistence beyond 13,000 cal yr B.P. (Borrero et al., 2019).

At the beginning of the Holocene, wetter and warmer conditions are clearly observed in SU4 and SU3/SU2 at the Baño Nuevo 1 and Cueva de la Vieja, respectively. This climatic amelioration is mainly inferred by an increase on the cave weathering, macro- and micro-signals of bioactivity and by a decrease in exogenous input. Ecological conditions established during the Early Holocene, namely the establishment of a steppe (though drier than today), may explain first ephemeral and discontinuous human occupations at the top of SU3 (Cueva de la Vieja), probably under an exploration phase starting at 12000 cal yr B.P. (Fig. 8C). Surface (undated) archaeologcial material elsewhere in the basin, further supports this ephemeral human presence (Méndez et al., 2019). Logistical movements of small human groups across an unknown landscape could explain the lack of such early evidence at the Baño Nuevo, whose dimensions might offer better shelter conditions (Borrero et al., 2019). The more favourable environmental and climatic conditions recorded after ca. 11,500 cal yr B.P. (De Porras et al., 2014) took place along with a relatively increase in the human occupation intensity, which was not restricted, but observable elsewhere in the region (Méndez et al., 2016, 2018).

The entire Holocene is recorded at SU4/SU3 (Baño Nuevo 1) and at SU2 (Cueva de la Vieja), but no physical differences are observed within the deposits. In other words, these cave contexts do not seem to be sensitive to the Holocene climatic/environmental variations recorded in lake/mire sedimentary cores (e.g., Markgraf et al., 2007; De Porras et al., 2012, 2014; McCulloch et al., 2017). The greater incidence of bioactivity (from soil fauna to mammals), along with the human occupations, possibly obliterated such variations. Nevertheless, it is worth mentioning the cave weathering drop recorded in the upper half of SU3 and SU2 (Baño Nuevo 1 and the Cueva de la Vieja, respectively), likely attributed to relatively colder and/or more arid conditions. The cold phase observed by McCulloch et al. (2017) at ca. 7400–6500 cal yr B.P., contemporaneous to the archaeological hiatus, could explain such decrease, though further investigation is required to confirm such relation. Consistently, there is no record of human occupations between ca. 7800–6500 cal yr B.P. at the Baño Nuevo 1, Cueva de la Vieja and Casa de Piedra Roselló (Castro Esnal et al., 2017; Fig. 1A) sites. Further, the abandonment of the El Chueco 1 site (~90 km northeast of the sites herein discussed; Fig. 1A) between 8000 and 7000 cal yr B.P (Méndez et al., 2016), adds to the potential significance of this discontinuity in the regional archaeological record (Méndez et al., 2018). In this sense, changes of human mobility systems could be explained by an ecological deterioration promoted by climatic conditions.

The final major change recorded in the cave deposits appears at the beginning of the XX century and can be attributed to the onset of the Anthropocene (Crutzen and Stoermer, 2000). By this time, the area became a sheep ranch (of about 45,000 ha.), which promoted hydrological modifications (i.e., channelling), clearance, soil erosion and the replacement of native flora and fauna by exotic species, among others (Fig. 8D). The use of caves as refuges for sheep and herders altered their sedimentological, chemical, micromorphological and magnetic properties with a magnitude similar to the deglaciation process or the beginning of the Holocene.

6. Conclusions

This contribution discussed the genesis and diagenesis of two volcanic cave deposits located in the west-central Patagonian steppes. By considering a detailed multi-scale evaluation of the stratigraphy, from microscopic analysis up to the geomorphology, data allowed correlating the Baño Nuevo 1 and Cueva de la Vieja sequences, comprising ca. 19,000 years, with no evidence of major erosional unconformities. Main regional palaeoclimatic changes were observed in these microenvironments, namely, the deglaciation processes, the Pleistocene-Holocene transition, the Holocene amelioration and the onset of the Anthropocene. A low sensitivity was observed in these systems, since no distinctive variations were recorded within the Holocene. However, biological processes and human occupations could have obliterated such variations.

In these volcanic cave microenvironments, the distinction between endogenous versus exogenous material was particularly powerful as a palaeoenvironmental proxy, particularly related with the geomorphological stability. The latter, in turn, could be interpreted as part of the complex feedback associated with climatic changes. In the same direction, cave weathering rates observed through vertical variations of the gravel fraction, along with signals of bioactivity recorded by %TOC and micromorphological analysis, allowed interpretations concerning temperature and/or humidity, which were consistent with available regional information.

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Appendix A. Supplementary data

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