



## Geomorphology of Tafi valley (Tucumán Province, Northwest Argentina)

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### ABSTRACT

Tafí valley is an elongated tectonic basin of about 450 km<sup>2</sup> located in NW Argentina in a mountainous frame of metamorphic and granitic Precambrian-Paleozoic rocks belonging to Sierras Pampeanas. This study presents the first detailed geomorphological map of the area. The most representative landforms date to the Lateglacial-Holocene, with four differentiating aggradative units separated by incision phases. Among these phases, it is possible to identify the units H1 (Lateglacial-Early and Middle Holocene) and H2 (Upper Holocene until ca. 600 cal BP). These units are composed of slopes, fluvial terraces, and alluvial fans, forming a coupled system. In some areas, this system is complemented with fluviglacial and glacial landforms. More recent units (H3 and H4), together with active processes, contribute to the great variety of morphologies represented in the area.

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## 1. Introduction

Tafí valley is a N-S elongated tectonic basin of around 450 km<sup>2</sup> located in Tucumán Province, Northwest Argentina. It is part of the northern section of Sierras Pampeanas, surrounded by the northern section of Sierra de Aconquija (4600 m asl) to the west, Cumbres Calchaquies (4600 m asl) to the east, and bounded in the south by Cerro Ñuñorco Grande (3300 m asl). The center of the valley is dominated by the independent relief of Loma Pelada (2680 m asl), which divides the central section into two related areas, Las Carreras valley and Tafí valley proper (Figure 1). The valley floor is located between 1800 and 2300 m asl. The main river, Río Tafí, crosses the valley from north to south. At Tafí del Valle village, it receives the waters from Río Muñoz coming from the western side of the valley before reaching La Angostura reservoir. The artificial lake also receives the waters of Río Mollar from the southern section of Las Carreras valley. Finally, Río Tafí flows to the Tucumán plains through La Angostura, where its name changes to Río Los Sosa (Figures 1 and 2(a)).

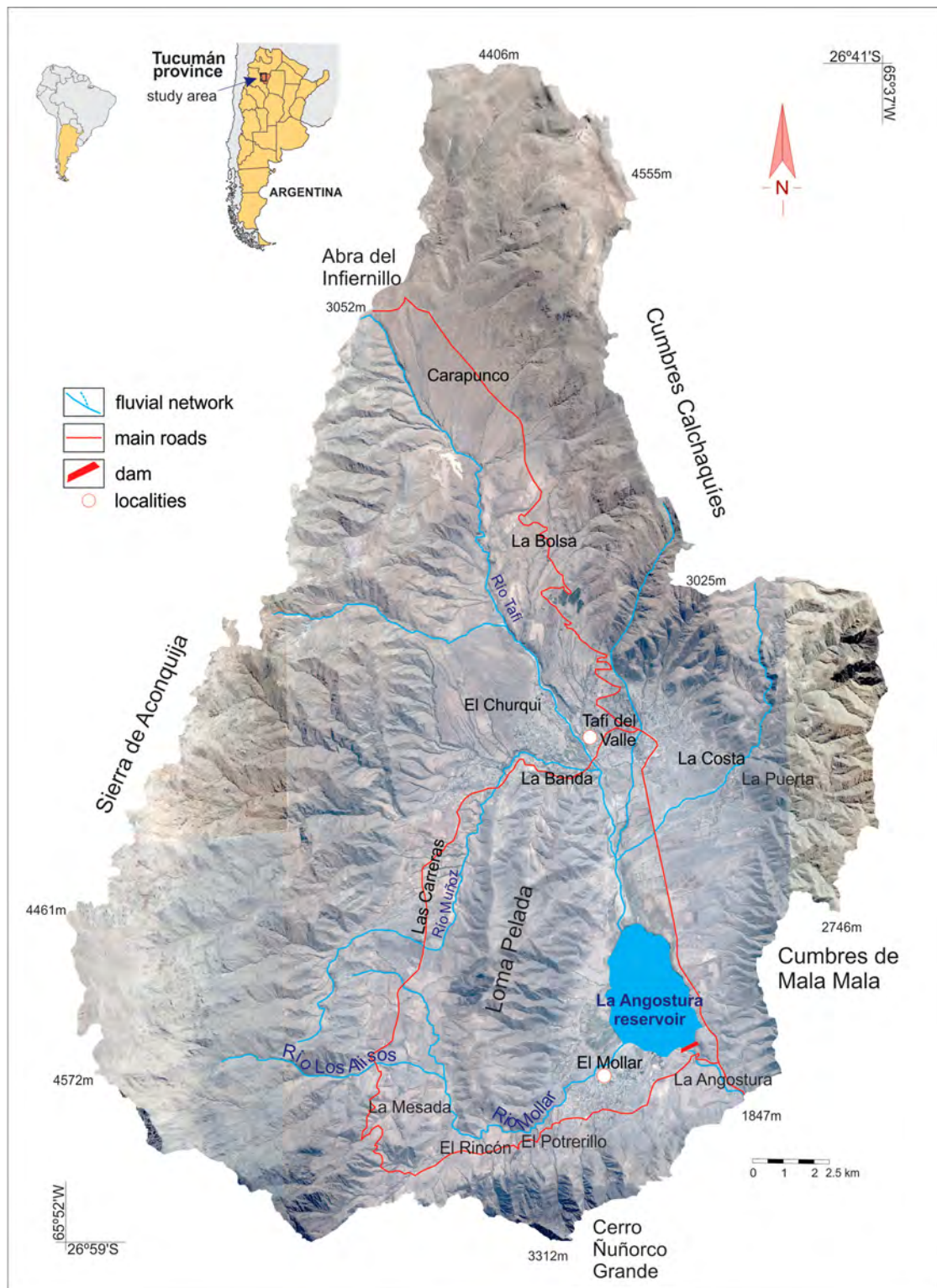
The climate of the region is semiarid with an annual rainfall average of 400 mm, reaching 550 mm in the uplands (Tafí del Valle: 476 mm). Most rain falls in the summer between November and March (around 82% of total annual precipitation) with wet winds blowing from the SE. The annual average temperature is 13.1 °C (Peña-Monné, Sampietro-Vattuone, Sánchez-Fabre, & Bertini-Sampietro, 2018). The vegetation mainly comprises grasslands with alder (*Alnus acuminata*) and queñoa (*Polylepis australis*) in the ravine woodlands.

The purpose of this paper is to present the first detailed geomorphological map of Tafí valley. It contains information about the geomorphological units, morphogenetic and morphodynamic processes, and chronological sequences.

Although there is some previous research on this area (Collantes, 2001; Collantes & Sayago, 1987; Sayago & Collantes, 1991), recent geomorphological studies (Peña Monné & Sampietro Vattuone, 2016, 2019a; Sampietro-Vattuone, Sola, Baéz, & Peña-Monné, 2017; Sampietro-Vattuone, Peña-Monné, Báez, & Sola, 2019; Sampietro-Vattuone & Peña-Monné, 2016; among others) have notably improved the chronological and paleoenvironmental information in the region with an appropriate methodology and field controls, resulting in the present geomorphological map.

### 1.1. Regional setting

Tafí valley depression has tectonic origins and Quaternary neotectonic reactivation. The main fault, named Tafí del Valle fault, is N-S oriented and located in the NE border of the valley. It is accompanied by other parallel faults in the Aconquija and Loma Pelada margins (Gutiérrez & Mon, 2004). The mountainous relief is composed of granitic and metamorphic rocks (granite, granodiorite, biotitic and moscovite schist, phyllite, and banded schists) of Precambrian and early Paleozoic ages (Ruiz Huidobro, 1972). Small detritic outcrops dated to the Middle-Upper Paleocene appear in the SSE sector of the valley (González, 1997).



**Figure 1.** Location map and main geographical features.

The Pleistocene is represented by some remains of old alluvial fans and loess deposits. This loess, dated to 1.15 Ma (Schellenberger, Heller, & Veit, 2003), could reach 50 m in thickness (Kemp et al., 2003, 2004). Holocene deposits were described by Peña Monné and Sampietro Vattuone (2016) and Sampietro-Vattuone and Peña-Monné (2016). According to these studies, four aggradational stages (named H1–H4 from oldest to youngest age) separated by incision phases developed during the Holocene. This

evolutionary model has archaeological and environmental relevance (Peña Monné and Sampietro Vattuone, 2019a) and represents the regional evolution (Sampietro-Vattuone et al., 2018).

## 2. Methodology

The geomorphological map of the study area was produced following the criteria proposed by Peña-Monné (1997) at 1:25,000 scale using Google Earth images



**Figure 2.** (a) South view of the Tafi valley, note main geomorphological evolutionary units; (b) tors and castle rocks in Sierra de Aconquija; (c) main abrasion surface in the summits of Cumbre Calchaquíes with glacial features; (d) oblique view of old abrasion surface in Sierra de Aconquija with glacial features: glacial cirques, (m) moraines, and (rg) rock glacier.

2003–2016, aerial photographs at 1:50,000 (SPAR-TAM, 1969) and 1:10,000 scales (5th Brigada Aérea de Paraná, 1987). In addition to images taken from a private flight, several vertical and oblique photographs were taken from drones (DJI Phantom 4, Mavic Pro, and Phantom 4 Pro). A systematic field survey was undertaken to give accurate field control of previously observed features. One hundred and fifty morphosedimentary profiles were described in order to have an

accurate record of each landscape unit. A working scale of 1:10,000 was used within QGIS v.2.18, and then reduced and adapted to its final edition with Freehand 11 (the final scale was 1:20,000). The thematic map is composed of a colored base layer corresponding to bedrock, while overlying layers correspond to Quaternary accumulations (glacial and periglacial morphologies, aeolian accumulations, fluvial and slope forms and deposits). Finally, symbols and lines are

superimposed to define specific features such as human activities. Radiocarbon datings were presented in previous papers and performed at Laboratorio de Radiocarbono (Universidad Nacional de La Plata) and Direct AMS Laboratory (USA) (Sampietro-Vattuone & Peña-Monné, 2016). Tephrae were mineralogically and geochemically characterized at INECO (CONICET-UNSA).

### 3. Results and discussion

The relief around Tafí valley derived from the relatively homogeneous Precambrian-Paleozoic lithologies, without important structural scarps. Water divides and deep V-shaped valleys are common in most Sierra de Aconquija, Loma Pelada, Cerro Ñuñorco Grande, and Cumbres Calchaquíes mountains (Figure 2(a)). The fracture network affects this relief and directs the fluvial network. Some pegmatite dykes form elongated resistant reliefs, mainly over the Sierra de Aconquija. Tors of castle rock type are frequently found together with subrounded boulders (Figure 2(b)), possibly inherited from Neogene wetter and warmer climates (Sierra de Aconquija and Ñuñorco Grande). Grus residues from rock weathering as well as rounded granite blocks moved by mass movement processes are commonly found in later deposits on the valley floor and piedmont. Later, some sectors on the summits of Sierra de Aconquija and Cumbres Calchaquíes with surfaces of old erosion surfaces were retouched by glacial abrasion processes (Figure 2(c)). The basement fracture network can be seen on the summits surfaces (Main Map).

The glacial morphologies were dated to the Younger Dryas (G1) and Neoglacial phases (G2) (Peña-Monné & Sampietro-Vattuone, 2019c). Most glacial features are located in the south-central sector of the eastern side of Sierra de Aconquija and the uppermost western sector of Cumbres Calchaquíes (Main Map, Figure 2(c, d)). In some valleys of Sierra de Aconquija there are fluvio-glacial terraces that continue downstream as fluvial terraces, as is the case of Río Los Alisos and Río Muñoz (Main Map).

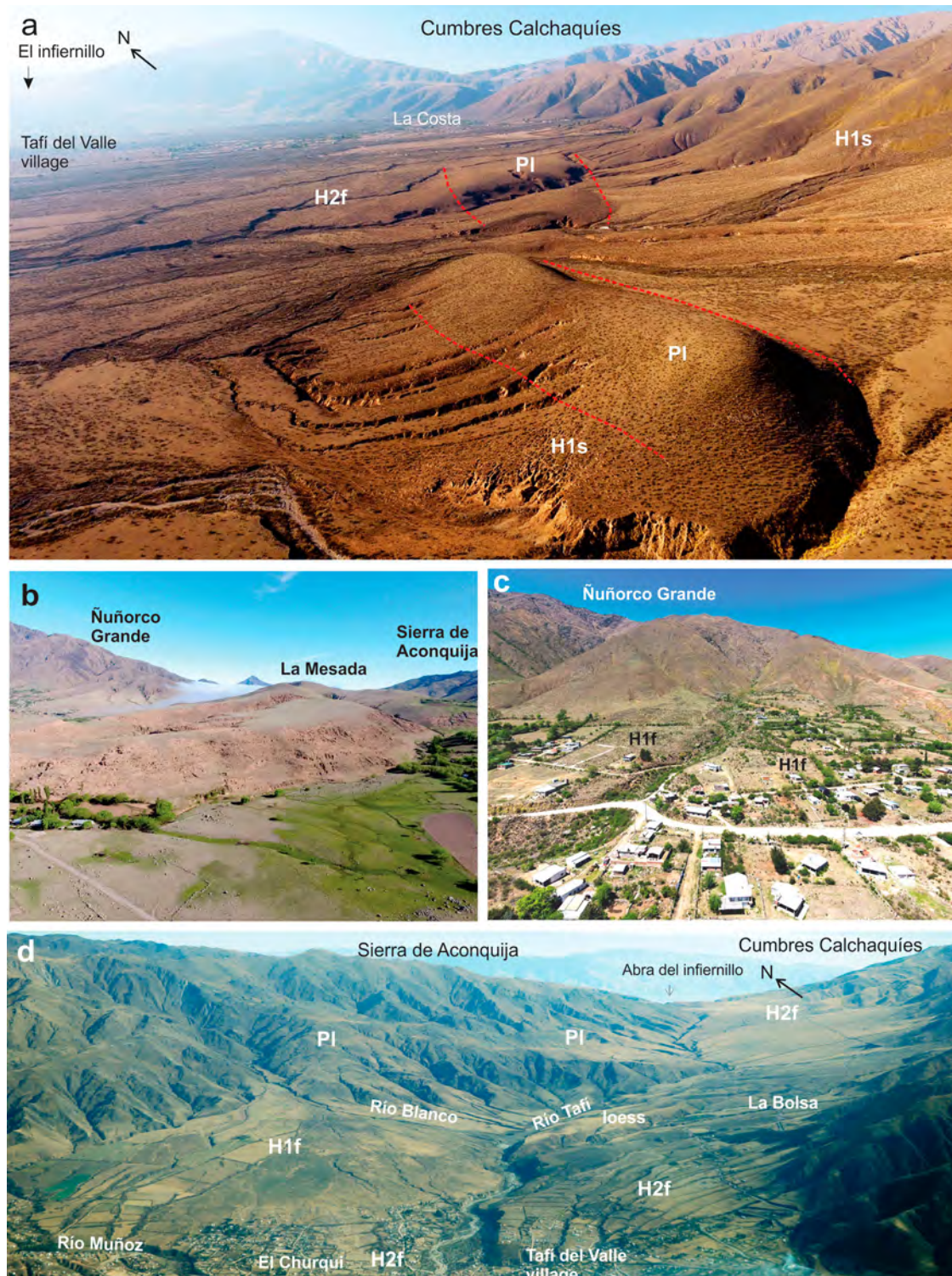
However, most of the valley surface is dominated by a great variety of recent landscape units located in the piedmonts and on valley floors (Main Map) and represented by aeolian accumulations as well as fluvial and slope landforms and deposits. The Pleistocene period is only represented by remnants of alluvial fans and loess deposits. The first ones are located in the upper section of some rivers and in the northern area of the valley and smaller deposits uplifted by Holocene faults on the valley floor (Unit Pl-Main Map; Figure 3(a)). The main loess deposits form isolated platforms in the different valleys (La Mesada, El Rincón, La Bolsa, La Angostura), but most loess deposits were covered by other sediments or reworked, and

at present they are part of the Holocene slopes, terraces and alluvial fans, mixed in several cases with grus and gravels transported from valley heads, depending on the location of the deposit.

Neotectonic activity has geomorphological significance in Cumbres Calchaquíes piedmont favoring the uplift of old Pleistocene alluvial fans (Figure 3(a)). Meanwhile, in Sierra de Aconquija it played an important role in the generation of fluvial capture processes by Las Carreras fault activation (Peña-Monné & Sampietro-Vattuone, 2019b).

The evolutionary geomorphological model developed by Sampietro-Vattuone and Peña-Monné (2016) and Peña-Monné and Sampietro-Vattuone (2019c) of the Lateglacial and Holocene accumulations is spatially represented in the valleys. As mentioned above, four aggradational stages were identified. The earliest stage is represented by H1 accumulations, where it is possible to distinguish between slopes (H1s) and slopes developed over fine sediments (H1sl) (settled over loess accumulations in the upper piedmont of Sierra de Aconquija and the western sector of the upper piedmont of Cerro Ñuñorco) (Main Map), terraces (H1t), and alluvial fans (H1f) (Main Map, Figure 3(c)). In greater detail, unit H1 could be divided into two subunits. Subunit H1A spans from the Lateglacial to the Early Holocene (ca. 13 ky cal BP to 10 ky cal BP) and is characterized by wetter environments, coincident with the G1 glacial phase (Peña-Monné & Sampietro-Vattuone, 2019b). This stage ended after the fall of a tephra layer named V0 (Sampietro-Vattuone et al., 2017). Besides, the subsequent subunit H1B shows features of a drier environment, encompassing the second half of the Early Holocene and Middle Holocene (between ca. 10 ky cal BP and 4.2 ky cal BP). During this stage, a glacial readvance occurred in the Sierra de Aconquija (Neoglacialiation). Unit H1B also ended with a tephra fall (V1) (Sampietro-Vattuone et al., 2019) resulting from a Plinian eruptive event from the Cerro Blanco Volcanic Complex (Fernández-Turiel et al., 2012). Despite its long-term evolution, H1 stage is only represented on the Main Map by the H1s slope because this stage was buried in the valleys and alluvial fans by later accumulative stages, mainly unit H2. Therefore, in alluvial fans and terraces, H1t and H1f accumulations are only visible inside incisions under later deposits, except for Río Blanco alluvial fan (El Churqui) (Figure 3(d)) and the Cerro Ñuñorco Grande piedmont, located to the NE of Tafí del Valle village, belonging to H1f unit (Main map).

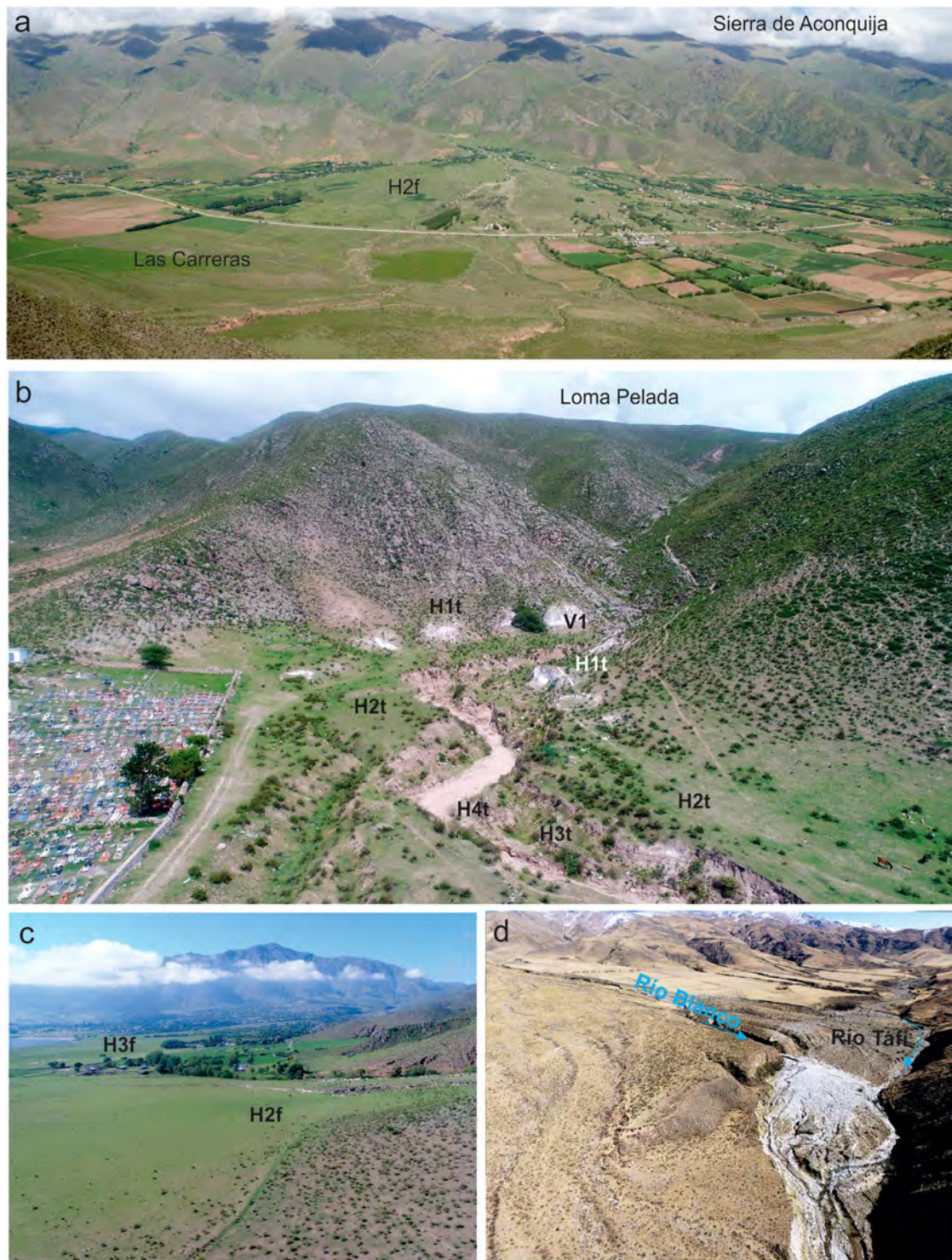
After an incision phase ca. 4200 cal BP, another set of slopes (H2s), fluvio-glacial terraces (H2fg), terraces (H2t), and alluvial fans (H2f) developed between ca. 4200 and the fourteenth century, that is, during the Late Holocene. This well-represented stage in the valley is the most extensive unit in the piedmont and on



**Figure 3.** (a) Oblique drone photograph of the southeast area of the Tafi valley: (PI) Pleistocene alluvial fans, (H1s) slopes of H1 unit, (H2f) alluvial fans of H2 unit; (b) La Mesada loess deposit; (c) alluvial fans of H1 unit in the foot of Cerro Ñuñorco Grande; (d) general view of the north area of Tafi valley, note the large H2 unit surfaces.

valley floor surfaces (Main Map; Figures 3(d) and 4(a)). Unit H2 shows a lower section (H2A) that ends with a well-developed soil dated to  $2480 \pm 110$  14C BP ( $2760\text{--}2188$  cal BP) by Sampietro Vattuone (1999). This paleosol played a great regional role in the development of early agricultural societies (Formative Period). In Tafi valley, it favored the development of Tafi Culture (between 2435 and 2059 cal BP and 957–811 cal BP)

(González & Núñez Regueiro, 1960; Roldán, Maldonado, Urquiza, Vattuone, & Sampietro Vattuone, 2016). Above this soil, H2B accumulation extends until *ca.* 600 BP (Sampietro-Vattuone & Peña-Monné, 2016). In previous papers, this unit was linked to landscape overexploitation by Prehispanic agricultural peoples, which triggered accelerated morphodynamic processes (Sampietro-Vattuone et al., 2018).



**Figure 4.** (a) West view of Las Carreras valley, note the large H2 alluvial fans; (b) nested terraces in the east side of Loma Pelada; (c) H2 and H3 units in the foothill of Loma Pelada; (d) confluence between Río Blanco and Río Tañi, note the active alluvial fan.

The next unit, H3, was dated to the Little Ice Age by Peña Monné and Sampietro Vattuone (2019a) and tends to be confined to small terraces (H3t) forming nested terraces with previous units, like in Loma Pelada eastern piedmont (Main Map; Figure 4(b)). It is also represented in H3f alluvial fans in restricted areas of La Costa, the eastern sector of Cerro Ñuñorco Grande piedmont and some parts of the southern area of the eastern side of Loma Pelada (Main Map; Figure 4(c)).

A new volcanic tephra is interbedded in unit H3 (V2), whose age was estimated at *ca.* 500 cal BP (Sampietro-Vattuone et al., 2019). Finally, the last stage (H4) is formed by active floodplains and recent debris flow events present along Río Tañi, at the outlet of Río Blanco (Figure 4(d)), some sectors of Las Carreras, and Los Alisos alluvial fans (Main Map).

The set of slopes/terraces/alluvial fans (in some cases including glacial and fluvio-glacial deposits)

tends to form coupled systems linked in the transmission of sediments from the upper sectors of the valley to the bottom (Sampietro-Vattuone & Peña-Monné, 2016; Peña-Monné and Sampietro-Vattuone (2019b)). This relationship was used on the Main Map to establish the contemporaneity among units and facilitate the interpretation of the Holocene morphologies. The presence of volcanic ashes in different evolutionary units played an important tephrochronological role for correlation purposes. Its representativeness on the map is scarce because most deposits are interbedded as thin layers, with exceptions. They can be seen on the eastern side of Loma Pelada (Figure 4 (b,c)) and Cumbres Calchaquíes piedmont (Main Map).

Finally, the present active processes also include landslides, and the development of badlands and sectors of runoff erosion. Erosion is especially active in the ravine formation due to centuries of overgrazing, since the valley has been intensively used for cattle breeding since colonial times after 1535 (Peña Monné & Sampietro Vattuone, 2016). Small landslides are more frequent in the Cumbres Calchaquíes (Main Map) and areas with abundant loessic deposits. Present human settlements are dispersed over the entire valley. The main villages are Tafi del Valle, located on Río Blanquito alluvial fan with high flood hazard (Peña-Monné et al., 2018). Other densely populated areas are El Mollar on Cerro Ñuñorco piedmont and La Banda sector in the confluence of Las Carreras and Tafi valleys.

#### 4. Conclusions

Tafi valley is an excellent geographical area to perform geomorphological cartography due to its long evolutionary history and great variety of identifiable landforms. Landforms related to the lithology and the geological structure shape the mountainous units that surround the valley. Remarkable among them are tors, flattened summits, and some glacial features. However, the most relevant forms are those from Lateglacial-Holocene periods, with 4 aggradational phases separated by incision stages. The oldest unit (H1) spans between the Lateglacial and the Early and Middle Holocene (*ca.* 13 ky cal BP – *ca.* 4.2 ky cal BP), and is stratigraphically divided into two stages. This unit includes two glacial advance phases (G1 and G2) together with a wide spectrum of accumulative forms such as slopes, terraces, and alluvial fans. This unit also includes two tephra layers (V0 and V1) with great spatial continuity and value for chronological correlation. Unit H2 has the greatest representation on the map. It belongs to the Late Holocene (*ca.* 4.2 ky cal BP to *ca.* 600 cal BP). The two younger units (H3 and H4) are less noteworthy and have less presence on the Main Map.

#### Software

QGIS 2.18 was used for processing and interpreting the spatial data, with the final version of the map produced using Freehand 11.

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#### Disclosure statement

No potential conflict of interest was reported by the authors.

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