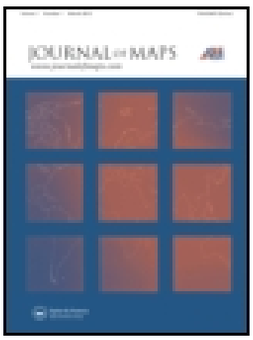

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SCIENCE

Geomorphology of the alluvial fans in Colalao del Valle-Quilmes area (Santa María Valley, Tucumán Province, Argentina)

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ABSTRACT

The geomorphological map of the alluvial fans in the Colalao del Valle-Quilmes area represents the first detailed map of the Santa María Valley, Northwest Argentina. The map was made using photointerpretation of aerial photographs and Google Earth images. The initial working scale was 1:10,000 and then reduced to 1:27,000 to fit ISO A1 size. Final drawings were produced using FreeHand 11. The area is characterized by the presence of coalescent alluvial fans developed on four levels. These fans end at the floodplain of the Santa María River. Sand mantles and dunes are present in this area, with old channels of the main river forming abandoned wetlands. A Holocene fault affects the distal area of some fans, whilst the apices of several alluvial fans have archaeological settlements. This study area presents an excellent example of regional Holocene evolution. Recent and present fluvial dynamics, aeolian activity, and the Holocene fault show high geomorphological activity. As a consequence, the information contained in the geomorphological map may be relevant to the establishment of risk areas for human settlements. Moreover, the map could be useful for planning conservation measures for the Prehispanic villages.

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Geomorphology; alluvial fans; Holocene; archaeology

1. Introduction

The geomorphological map presented in this work is the result of a research project performed in Northwest Argentina, aimed at establishing the relationships between geomorphological evolution and archaeological settlements. The area was surveyed during the spring seasons 2013–2016 and constitutes the first detailed cartography of the area. Mapping includes information on the morphosedimentary units, morphogenetic and morphodynamic processes, chronologic sequences, and archaeological sites.

The Santa María Valley is an elongated tectonic basin with a south–north trend. It is bordered by the Sierra de Aconquija and Cumbres Calchaquíes to the east and the Sierra de Quilmes to the west, reaching 3000–5000 m above sea level. Our study area is located in the central piedmont of the Sierra de Quilmes, limited by the Santa María River (see Main Map). The area has arid characteristics with mean annual precipitation of 130–185 mm and a mean temperature of 15–16°C.

Geologically, the study area is part of the Sierras Pampeanas, composed of low to medium grade metamorphic rocks with granitic intrusions. In the piedmont, fluvial deposits of Pleistocene and Holocene age form a sector of coalescent alluvial fans. From north to south, it is possible to recognize alluvial fans of the rivers Anchillos, Managua, Pichao, Las Chilcas-Talapazo, Las Cañas, and Quilmes rivers. The bottom of the valley is occupied by the Santa María River and its floodplain. The regional geomorphology is similar to that of other arid regions in Northwest Argentina (Maldonado, Neder, & Sampietro Vattuone, 2014; May, 2008; May, Zech, Schellenberger, Jull, & Veit, 2011; Peña-Monné et al., 2015; Sancho, Peña-Monné, Rivelli, Rhodes, & Muñoz, 2008).

2. Methodology

The geomorphological map was produced using black and white aerial photographs (scale 1:50,000) and Google Earth, following the criteria proposed by Peña-Monné (1997). After photointerpretation and field survey, the information was manipulated using QGIS 2.14.2. The final map was drawn using FreeHand 11.

Given the difficulties in recognizing the different alluvial fan levels in the distal areas, the working scale was around 1:10,000. Due to this characteristic, the cartographic work required extensive field survey to differentiate between the different geomorphological units. In addition, the lack of roads made it difficult to access the study area.

The edited map was reduced to 1:27,000 to fit ISO A1 format. The map is composed of a colored base layer corresponding to the bedrock; other colored layers overlying it correspond to Quaternary accumulations (alluvial fans, floodplains, fluvio-aeolian mantles). Finally,

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symbols and lines are superimposed to define different specific geomorphological features, such as slopes, wind direction indicators, fluvial network, faults, etc., as well as roads, archaeological sites and contemporary human settlements.

3. Results and conclusions

The alluvial fans deposited at the piedmont of the Sierra de Quilmes show high dynamism because although their basins are middle-sized, their channels have steep gradients. These circumstances favor the development of strong sediment discharges related to low frequency-high intensity rainfalls.

The dynamics of the area facilitated the development of a wide alluvial fan system between Colalao del Valle and Quilmes localities. These alluvial fans were built during the Quaternary period, and several stages were identified, as represented on the geomorphological map.

3.1. Alluvial fans and morphosedimentary units

The oldest surveying evidence of alluvial fan deposits are of Pleistocene age. They are present at the confluence of the Managua and Pichao rivers in the vicinity of El Pichao village. These deposits are around 100 m higher than the next alluvial fan level (Figure 1(a), *Pleistocene alluvial fans* on the map). These aggradational stages are composed of thick sedimentary deposits. They have an inclination of about 8.5–9%. These old alluvial fans could be correlated with high levels in the upper course of the Managua River, upstream of El Arbolar, and Talapazo localities.

The next unit is the *H1 alluvial fan*, which is best represented by the deposits of El Pichao village (Peña Monné, Sampietro Vattuone, Maldonado, & Cano, 2016) (Figure 1(b,c)). This unit has less extent at the apex of the Talapazo alluvial fan and some relict terraces in the inner section of Las Cañas River. In the upper area of El Pichao River, the alluvial fan reaches an inclination of about 11.5% and a thickness of about 35 m (Figure 1(b)). Downslope the inclination is around 7–8%. Basement is never visible in the outcrops left by river incisions. The deposits of this unit are coarse formed by metamorphic and granitic blocks with fine matrix without visible sedimentary structures, mainly deposited by debris flow processes. The blocks reach large sizes and are a little rounded.

This unit covers a time span from the Final Pleistocene to the Middle Holocene (*ca.* 13,000–4200 BP). Its age was established by the presence of volcanic ash layers of known age (*ca.* 10,000 and *ca.* 4200 BP) interbedded in the same stage as the alluvial fans of the Tafí Valley (Peña Monné & Sampietro Vattuone, 2016). This ash has been observed in El Pichao and Managua alluvial fans (Figure 2(a)).

As shown on the map, the *H2 alluvial fan* is the most extensive unit across the study area (Figure 1(c)). This stage was developed after an incision phase that cut into the *H1* deposits. The *H2 alluvial fans* have a 5% longitudinal gradient at the apices, diminishing to 4–3% in the middle and distal sections. They are composed by coarse materials (blocks and gravels) diminishing their size in the distal sections, where silt and sand are dominant. The presence of channels, cross bedding, and imbricated gravel layers together with chaotic deposits (debris flows) shows a mixed genesis involving fluvial and debris flow processes (Figure 2(b,c)). In some places it is possible to observe a 4 m-thick deposit. The materials are mainly taken from the older alluvial fan, showing the same lithologies.

In chronological terms, the *H2* sediments are overlapping the volcanic ash dated to *ca.* 4200 BP, as observed in some outcrops in El Pichao, El Arbolar, and the Quilmes areas (Figure 2(a)). This ash was identified as belonging to one of the eruptions of the Cerro Blanco Volcanic Complex dated to *ca.* 4200 BP (Báez et al., 2015; Fernández-Turiel et al., 2012, 2013; Sampietro-Vattuone et al., 2016). There are no features related to the final period of the *H2 alluvial fan* deposits in the region. However, according to the evolutionary models proposed for the Tafí valley, radiocarbon dates establish the end of the *H2* sedimentation after 630 ± 30 BP (Sampietro-Vattuone & Peña-Monné, 2016).

A new incision phase was followed by the accumulation of a new aggradational cycle. The *H3 alluvial fans* are represented by temporarily active bars and channels. Topographically they lie only 0.5–2 m over present channels (Figure 1(c)). The development of this phase has been related to Little Ice Age climate change (Peña Monné & Sampietro Vattuone, 2016).

Finally, it is possible to identify functional sectors represented by the main and secondary channels of the streams flowing from the range. They are characterized by the presence of wide braided and steep channels, with low sinuosity, adapted to high tractive charge (Figure 1(c)). The channels tend to widen by lateral erosion of the non-cohesive margins formed by blocks, gravels and fine sediments. For this reason, there are several inner bars that change their shape in each flood, favoring channel migration and avulsions.

3.2. The floodplain of the Santa María River

The Santa María floodplain is located at the bottom of the valley, where alluvial fans end. Its main channel is a wide (over 500–600 m in some places) shallow channel that transports fine sediments (silt, sand, and clay) (Figure 3(a)). It was possible to observe abandoned beds of the main river in several locations. These old channels tend to receive water during exceptional floods and form wetlands. The margins of the river have fluvio-aeolian mantles that cover the distal section of the

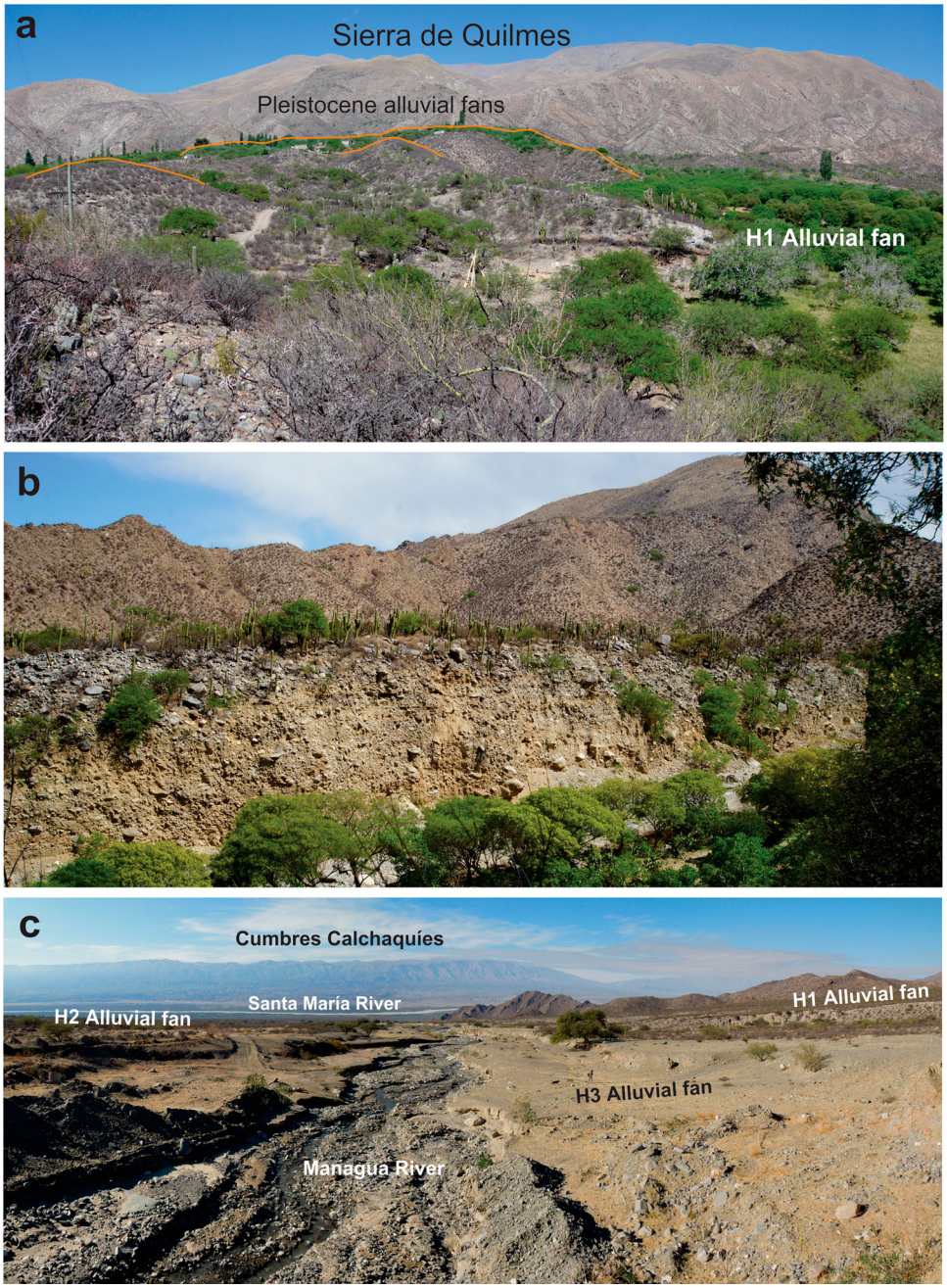

Figure 1. (a) General view of the Pleistocene alluvial fans at El Pichao; (b) thick fluvial terrace of *H1* at Pichao River; (c) panoramic photo of Managua River alluvial fan from the road bridge at El Pichao village.

previously described alluvial fans and the main river margins. In some cases it is possible to see small active dunes. These mantles and dunes are built by the sand transported from the riverbed by the prevailing wind coming from the north and northeast. The same dynamics were described in other sectors of the valley like El Paso, to the south (Maldonado et al., 2016) and Cafayate to the north (Peña-Monné et al., 2015).

3.3. Holocene tectonics

El Bañado active fault affects the distal section of the southern alluvial fans of our study area (around 5 km from Talapazo to El Bañado-NNW-SSE trend). This fault could be drawn under the alluvial layers of the Santa María River, as it appears across the river again maintaining the same trace and trend. The fault is deforming the *H2 alluvial fan*, developing a 20–25 m-high step. This step is accompanied by several springs, giving rise to the development of wetter sectors. The only available dating yielded Late Holocene age (radiocarbon dated to 2190 ± 530 BP; 1470 ± 50 BP) (Strecker, 1987).

3.4. Slope dynamics

The Sierra de Quilmes has high metamorphic lithological homogeneity that gave rise to sharp water divides among the watersheds. The dominant morphology are denudational slopes. During the Quaternary,

Figure 2. (a) Volcanic ash (*ca*. 4200 BP) interbedded between stages *H1* and *H2* in the alluvial fan of Managua River, El Arbolar village; (b) outcrop of a debris flow belonging to the *H2 alluvial fan* of Pichao River in the middle-apical area; (c) view of the debris flow of *H2 alluvial fan* of the Talapazo River in the middle area.

these slope dynamics fed the fluvial systems with large amounts of sediment, facilitating the development of the alluvial fans.

At present there is an increase in denudational activity. It is possible to identify several slopes affected by very active scar erosion, as represented on the map (Figure 3(b)). These features are generated by sporadic rainstorms that favor the occurrence of debris flows and mudflows along the river course, affecting roads and agricultural fields.

3.5. Archaeology

Several archaeological sites were identified in the aerial photos. These archaeological sites belong mainly to the Regional Development (1000–1490 AD), Inca (1490–1535 AD), and Spanish (1535–*ca.* 1660 AD) periods. Among the most extensive are El Pichao, Talapazo, Las Cañas, and Quilmes. All of them are settled over the apices of the *H2 alluvial fans*, taking advantage of permanent access to water resources. These archaeological sites have been defined by Maldonado et al. (2016) as *persistent places* given the fact that all of them show the overlapping of all periods in the same settlement. The location of Prehispanic villages is due to a different conception of space, which was abruptly changed when the Spanish arrived and founded the current-day villages located at the bottom of the valley. The archaeological sites are affected by present geomorphological dynamics with serious conservation problems (Peña Monné et al., 2016; Rodríguez, Sampietro-Vattuone, & Peña Monné, 2016).

4. Map relevance

This cartography is the first detailed geomorphological map of the area. The morphology and classification of the morphosedimentary units that generate the evolution of the alluvial fans of the Santa María Valley was unknown until this work. The map shows disperse relicts of Pleistocene cumulative stages, thereby constituting the first identification of these ancient evolutionary phases. Besides, the morphosedimentary units that compose the Holocene sequence and their ages, neither have been cartographically represented or described before. The graphical representation proposed in this study provides new information about the evolutionary morphology of the coalescent alluvial fans that characterize the fluvial dynamics in Northwest Argentina.

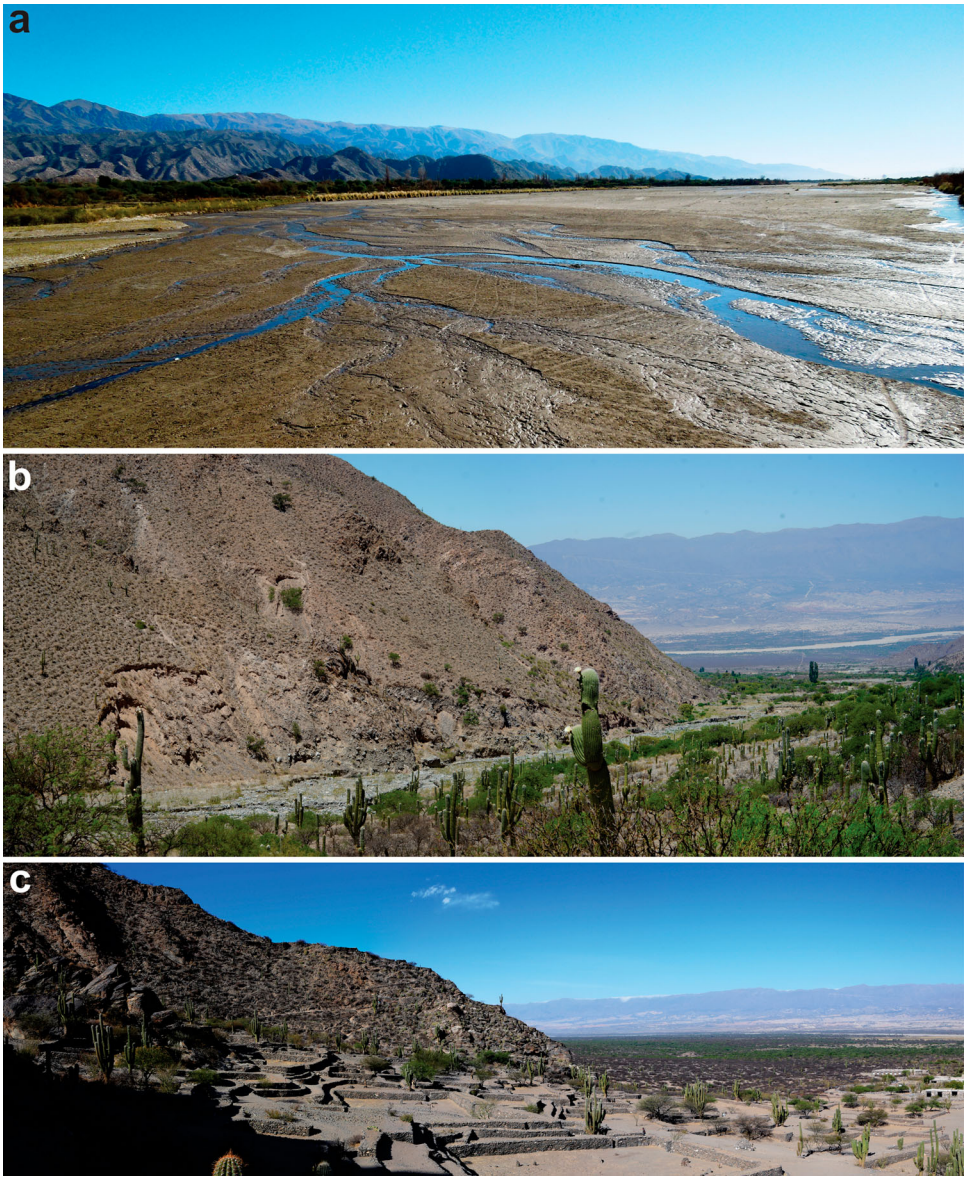

Figure 3. (a) Floodplain of the Santa María River with the Sierra de Quilmes in the background; (b) slope slide scars at the Managua River, El Arbolar village; (c) rebuilt archaeological structures at the Prehispanic City of Quilmes, located at the apex of one of the Quilmes River tributaries.

Additionally, the Santa María Valley is geomorphologically interesting because of its wide system of active alluvial fans, with the main river as base level. Recent and present fluvial dynamics, aeolian activity, and the presence of El Bañado fault show high geomorphological activity. As a consequence, the information contained on the map may be of interest to the establishment of risk areas for human settlements. Moreover, the map could be useful for the planning of conservation measures for the Prehispanic settlements present in the area. These areas are at serious risk due to the dynamics of the geomorphological processes operational on the alluvial fans.

Software

QGIS 2.14.2 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 author.

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