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Fluvial and aeolian dynamics of the Santa María River in the Cafayate depression (Salta Province, NW Argentina)

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ABSTRACT

A geomorphological cartography of the Cafayate depression (NW Argentina) at a scale of 1:20,000 is presented. The Main Map was made with satellite images from 2009 to 2016 and aerial photographs from various dates. The area was classified into three categories of geomorphological dynamics according the type of fluvio-aeolian interaction. Anastomosing channels and crevasse splays are dominant in the southern section of the Santa María River, while meandering channels develop in the northern section. Extensive dune fields interacting with fluvial deposits have developed in the central sector of the depression. The Main Map also reflects the main human features and can be used as a tool for preparing hazard maps.

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1. Introduction

Geomorphological maps are an excellent tool for the detailed representation of floodplains. These graphical representations of fluvial forms provide a complete image of the various related processes and landforms. Interactions between aeolian and fluvial processes (A-F interactions) play a fundamental role in shaping the surface of the Earth over a range of local to regional scales – especially in dryland, desert, and dunefield margins (Al-Masrahy & Mountney, 2015; Liu & Coulthard, 2015; Roskin, Katra, Agha, Porat, & Barzilai, 2014; Roskin, Bookman, Friesem, & Vardi, 2017; Vardi et al., 2018).

Northwest Argentina is a dry environment where two geomorphological agents – water and wind – are the main modelers of the landscape. However, there is no geomorphological cartography available for the river and dune field dynamics, although some research has been conducted on its Pleistocene (May, 2008; Sampietro Vattuone & Neder, 2011; Sancho, Peña-Monné, Rivelli, Rhodes, & Muñoz, 2008) and Holocene (Peña Monné et al., 2016) deposits and evolution.

This paper presents the main geomorphological features and describes the landscape evolution of the Cafayate depression, in the northern sector of the Santa María valley, using a geomorphological map as the key tool. The cartography highlights fluvial and aeolian landforms and their dynamic interactions. This map could also be of assistance in the preparation of hazard maps for limiting damage to road structures, populations, and farms.

1.1. Regional setting

The Cafayate depression (1683 m asl) is in the northern section of the Santa María valley. It is an elongated S-N tectonic depression located in the northern area of the Sierras Pampeanas and is part of the Calchaquíes valley in the Northwest Argentina (Figure 1a). The east is bordered by the Cumbres Calchaquíes (Hollada, 4177 m), and the west by the Sierra de Quilmes (Cerro Chuscho, 5468 m). The Santa María River runs in a south–north direction along the depression (Figure 1b) until merging with the Calchaquí River and then flowing east through El Paso (Figure 1c).

Geologically, the surrounding ranges are composed of low-medium grade metamorphic rocks and Precambrian-Lower Cambrian granites (Rapela, 1976; Toselli, Rossi, & Rapela, 1978). On the eastern side of the basin, the continental detrital and carbonated rocks of the Salta Group (Upper Cretaceous-Miocene) were deposited (Bossi, Georgieff, Gavriloff, Ibáñez, & Muruaga, 2001; Salfity & Marquillas, 1999) with detrital deposits from the Santa María Group (Pliocene) (Galván, 1981). Finally, the bottom of the basin and piedmonts of the depression are covered by Quaternary deposits. Over the Cumbres Calchaquíes piedmont it is possible to identify large Pleistocene pediments and alluvial fans (Sampietro Vattuone & Neder, 2011; Strecker, 1987), while over the Sierra de Quilmes piedmont are Holocene alluvial fans (Peña- Monné et al., 2015, 2016). In addition, large dune fields are found across the lower section of the valley and the sides of the Santa

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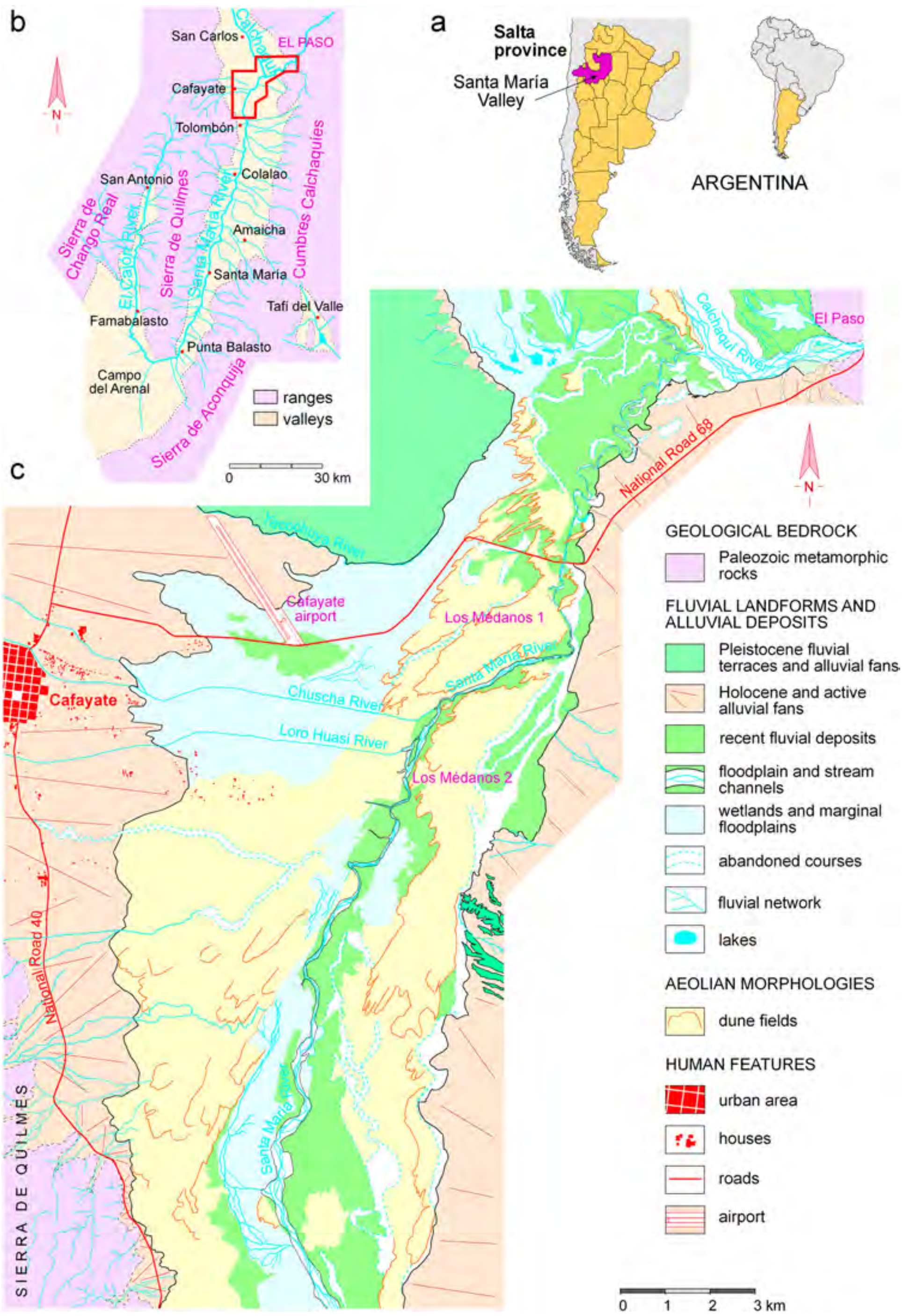

Figure 1. Study area location map: a) Northwest Argentina; b) study area inside Santa María valley; c) synthetic geomorphological map of the Cafayate depression.

María River floodplain. Some remains of lacustrine deposits are preserved in the NE of the study area.

The area has a very dry climate. According to the Köppen classification, the Cafayate climate is type Bwk' (arid with an average temperature of less than 18°C and cool winters) (Minetti, Poblete, & Longhi, 2005). Average annual temperature is 17.1°C, oscillating between 21.5°C (February) and 9.7°C (July) and annual precipitation only reaches 207 mm – and mostly occurs during summer. The mean annual evapotranspiration is 700 mm, generating a substantial water deficit of around 550 mm/yr. These values mean that aquifers are unable to recharge except in summer (Tineo & Ruiz, 2015). Dominant winds are from the N and NE and can reach maximum values of 100 km/h (Peña- Monné et al., 2015). Vegetation belongs to the 'Ecoregión de Monte' and is composed of carob trees (*Prosopis nigra*) and *jarillas* (*Larrea divaricata* and *Larrea cunneifolia*). Vegetation changes to thorny and shrub steppe with cardon (*Trichocereus atacamensis*) in the lower areas (Mendoza, 2005). Given the low annual precipitation totals, fluvial flow is low. However, summer floods are common. The main cause of river flow loss is the high permeability of the sands and silts of the Santa María floodplain, as well as lateral overflow. Flow data is scarce and comes from the Pie de Médano gauging station, located 109 km to the south of the study area. The mean annual discharge is 2.5 m^3/sec, with high inter-annual irregularity (0.6–4.8 m^3/sec), reaching a total annual flow of 85 hm^3/yr (Tineo & Ruiz, 2015).

2. Methodology

The Main Map of the study area was produced following the criteria proposed by Peña-Monné (1997) using Google Earth images of the years 2003, 2009, and 2016, and aerial photographs scale 1:50,000 (SPARTAM 1969). Satellite images from 2012 to 2016 were georreferenced using QGIS v.2.18 to serve as base for the geomorphological cartography. An image from 22 December 2012 was especially important to establish the fluvial dynamics as it was taken after two large floods (2–3 March 2011, and 13 December 2012). The 2016 image was used to update the information. Several vertical and oblique photographs obtained by reconnaissance flights with a drone (DJI Phantom 4) and a plane served to interpret some specific details.

Field work was conducted between 2013 and 2017 to obtain geomorphological data and verify the map information. Stratigraphic profiles were described and topographical data was taken using a Garmin Montana 650 GPS. Previous information was available about texture, mineralogy, and chronology of the dune fields (Osácar, Sancho, Peña-Monné, García, & Rubio, 2006; Peña- Monné et al., 2015).

The Main Map working scale was 1:10,000 using QGIS v.2.18, and the scale was then reduced and adapted to its final edition with Freehand 11 (the final scale was around 1:20,000). The Main Map is composed of a colored base layer corresponding to the geological bedrock, while overlying layers correspond to Quaternary deposits (alluvial fans, fluvial terraces, floodplains, fluvio-aeolian mantles, and dune fields). Finally, symbols and lines are superimposed to define specific features such as dune direction, dune fronts, and features due to human activities on the geomorphological dynamics.

3. Results and discussion: present geomorphological dynamics

The active dynamics could be classified into three categories of geomorphic dynamics. Two are related with the dominance of fluvial dynamics (anastomosing channels and crevasse splays to the south, and meandering channels in the northern section), and the third with wind activity dominance (dune fields and their relationship with fluvial dynamics). Most of the Main Map key is dedicated to these dynamics and to which human activity is added.

3.1. Anastomosing channels and crevasse splays

The Cafayate depression is the widest part of the tectonic graben where the fluvial confluence of several tributaries coming from the mountainous sides of the main valley is produced. These fluvial channels transport relatively large amounts of sediments through distributary channels across their alluvial fans, and whose distal sections reach the Santa Maria floodplain. The same shape dynamics were described in the south in the Colalao del Valle-Quilmes alluvial fans (Peña-Monné & Sampietro-Vattuone, 2016). In some floodplain sections, there are no fluvial terraces, and so it is very difficult to delimit in the cartography the Santa María riverbed sediments from the silty-clay sediments of fluvio-aeolian origin. Dunes are generated from the river lateral deposits and these dunes progress to the lower part of the alluvial fans; in several cases they serve as lateral levees. During overbank flows in the rainy season, the main river floods and creates apertures in the river banks. These outlets favor the generation of avulsions and crevasse splays.

The development of these forms occurs in the southern section of the Santa María River (see the Main Map and Figure 2) where the floodway is mainly a straight channel some 150–200 m wide and composed of fairly straight channels between vegetationless microbars. The average gradient is around 0.25%, according to field data. The river could be classified as a braided river with fine granulometry. A sandy fringe floodplain is preserved in some sections and this results in lateral bars and several central isles that contain herbaceous vegetation. In the same way, there are some slightly higher fluvial accumulations (1–2 m) that are composed of sand and silt sediments and form an overland floodplain that is partially covered by an aeolian sand mantle. Old flood channels of the Santa María River cross these areas – revealing the river's strong capacity for lateral displacement and avulsion. On the eastern side of the river, the overland floodplain is bordered by a 2–3 m high scarp formed by the lateral erosion of the distal section of the lateral alluvial fans descending from the Cumbres Calchaquíes. An old riverbed borders the scarp and some active dunes are fed from this area. On the western side is an inactive dune field that reaches the distal section of the alluvial fans that cover the piedmont of Sierra de Quilmes. During the largest summer floods, the water overflows the scarps and breaks through the levees at various points to generate avulsions and crevasse splays. The existence of these lateral channels is also favored by the topographic position of the main river floodway, which is usually higher than the marginal areas and so facilitates river overflows. During such floods, the river reaches 1–1.4 km in width, as measured in the 2012 Google Earth image.

Figure 2. a) General view of the anastomosing channels and crevasse splays areas of Santa María River; b) Santa María River floodplain with three lateral breaks caused by crevasse splays. A dune field developed in the splay is located to the left; c) view of the crevasse splay channels with dry silts and clays showing the area of dispersion; d) view where sediments reach 1.5–2 m thick and cover the trunks of the carob trees.

The Main Map reflects the river dynamics very well. Several crevasse splays breached the small natural levee located on the west river bank. Hundreds of micro channels join to form a parallel course with multiple channels and bars flowing northwards for almost 5 km and ending in a terminal lobe surrounded by vegetation (Figure 2a). Several bars or islands separate these channels from the main river floodplain. Wetlands or marshes remain during long periods because these lateral channels are lower than the main river. These areas are locally known as *bañados* and some of these wetlands develop seasonal lakes. On the right bank, a large crevasse splay has transformed into a small dune field (Figure 2b).

According to fluvial characteristics, the southern section of the river could be classified as an anastomosing type. Although these channels can develop in various climates, drylands are one of the most common environments in which they are found (Li & Bristow, 2015; Malavoi & Bravard, 2010).

Anastomosing channels also develop in the northern section of the study area. The Yacochuya River flows around a high Pleistocene terrace located at the confluence of the two main rivers, and produces a large floodplain in the form of successive crevasse splays along its right bank. The area extends to the Santa María floodplain, accumulating fine sediments (up to 2 m thick) in an area (Figure 2c) occupied with carob trees (whose trunks are partially buried as a result) (Figure 2d).

3.2. Meandering channels in the northern section

Some seven kilometers before the confluence with the Calchaquí River, the Santa María River takes a S-N direction and forms a five-kilometer-long meander belt with 23 meanders, a total channel length of 9.12 km, and an average gradient of 0.19% that varies according to the different meander sections. Its sinuosity index (P_{ind}) is 1.8 according the classic calculation (Malavoi & Bravard, 2010) and 1.1 using the Allen (1984) index. The meander belt starts with three bends before reaching the bridge of the National Road 68 (Figure 3a). To the north of the bridge, there are another 20 meander loops before confluence (see Main Map). In general terms, the meandering dynamics of the northern section seem to be the consequence of the river's adaptation to a lower gradient near the Calchaquí River confluence.

The Santa María River flows among the distal section of the alluvial fan of the Colorado River – which has been eroded by several meanders that have produced arched escarpments over the alluvial fan (Figure 3b). These scarps reach 3–4 m height and are composed of reddish gravels, sands, and silts – having formed from the Tertiary deposits eroded from Cumbres Calchaquíes. Due to this color, it is possible to identify relicts of the alluvial fan of the Colorado River on the western side of the Santa María River. Moreover, several paleochannels are also located on the alluvial fan (see the Main Map). The distributary channels of the Colorado River alluvial fan reach the Santa María River, and it is worth highlighting those channels close to El Paso that have deeply incised and terminal cones over the Calchaquí River floodplain after the confluence with the Santa María River.

In the northwestern part of the Santa María River, the overland floodplain is limited to the west by the Pleistocene terrace of the Calchaquí River (Peña-Monné et al., 2015). The scarp of this terrace is almost 30 m above the present floodplain of both rivers and above the crevasse splay area formed at the confluence with the Yacochuya River. The geomorphological complexity of the area can be appreciated in the Main Map. The area contains several abandoned fluvial channels together with areas covered by fine sediments coming from the crevasse splays of the Santa María River. In addition, there are relicts of older deposits partially occupied by dunes emerging from the paleochannels in a SW direction (Figure 3c). Their fronts advance over the intermediate vegetation mainly composed of carob trees (*Prosopis nigra*).

The erosive activity of these meanders is intense and this is because the river banks are not resistant and high curvature morphologies are created as a result of their displacements (Figures 3a, b). Meander scars and oxbows linked to meander cut-offs are the result. The formation of this meandering river section is very recent because aerial photographs of the Santa María River from 1969 show that the river was located on the northern margin of the alluvial plain.

The dynamics of these meanders produces considerable problems at several points. One is the bridge of the National Road 68, the only road crossing the river in the northern section (Figure 3a). Given the characteristically free meanders and lack of cohesive levees, when floods occur the water reaches the sides of the bridge and sometimes the road is cut by the river. The most recent critical situation was during a flood between 28 February and 1 March 2011. This flood was followed by another on the 13 January 2012. On this second occasion, road damage was avoided, and concrete and gabion defenses were built on the sides of the bridge. Simultaneously, a rectilinear cut-off was excavated leaving artificial levees fixed with *Tamarix gallica* (see Main Map and Figures 3a, b).

However, the old lateral displacements observable in the floodplain show the difficulty in fixing the floodway in one specific direction. The aerial photograph from 1969 shows how the river had a N direction but this course was abandoned (see Main Map and Figure 3c). This riverbed must have remained in this position for a long time because it developed a complex

Figure 3. Photographs of the meandering northern section; a) Google Earth image (2012) of the meanders near the National Road 68 bridge after a flood, and where the artificial cut-off can be seen; b) aerial image of the meander belt near the Colorado alluvial fan; c) Google Earth image shows where old dunes (yellow, 1969) generated by the old riverbed can be differentiated from present dunes formed from the current riverbed (red, 2016); d) detail of the same current dunes (2017) fed by river sediments.

meander belt, with several abandoned courses joining the Calchaquí River further north than at present. This section is currently part of the extensive floodplain of the Calchaquí River and forms a wetland and lakes area. The functional floodplain is located to the north-east and is more than 1 km wide (while its overland floodplain reaches 6 km in width). The older riverbeds, as well as the newer beds of both main rivers, are the source for the aeolian sediments in the area (Figures 3c, d).

3.3. The dune fields and their relationship with the fluvial dynamics

The aeolian deposits are another typical geomorphological feature from the Cafayate depression. They cover a large part of the floodplain (Figure 4a) and are one of the most intensively farmed areas (mainly vineyards). The dust tends to be suspended by the wind in strong turbulent convective currents that form dust devils in the afternoons after the soil has been heated during the day. The dust is composed of fine to very fine sands (Cortelezzi, Pavlicevic, & Rivelli, 1984; Osácar et al., 2006; Peña- Monné et al., 2015).

Since the dominant winds are almost constant from NE or NNE, the floodplain sediments are moved upstream by the wind to form nebkas and dunes that climb the lateral levees. In several places, many yardangs (Figure 4b) and deflation corridors are formed. In the lateral riverbeds and distal sections of the alluvial fans, the wind selects and extracts the fine sediments – leaving stone pavements (although the formation of fluvio-aeolian deposits is more usual). Finally, the most efficient sand movement and major dune formation is produced when the Santa María River floodplain is transversal to the main wind direction (SW-NE

Figure 4. a) Aerial view of north section of the Santa María floodplain, with Los Médanos 1 and 2 dune fields and confluence with the Loro Huasi River; b) yardangs in the fluvial sands and silts of the Santa María floodplain; c) eroded fluvial sands in the interdune sectors of the Los Médanos 2 dune field; d) parabolic dunes with vegetation in Los Médanos 1 dune field; e) front of the barchan dunes advancing over fluvial deposits at Los Médanos 2.

or W-E). For instance, to the north of the area of anastomosing channels, the river banks narrow and turn to the northeast for almost 4 km before arriving at the area where the meander belts begin. This fluvial section (see the Main Map) and the older riverbeds located to the east, provide material for the formation of the Los Medanos 2 dune field (which extends to the southern area with dune fronts facing NE to SW). In the middle area, the dune field reaches the floodplain of the Santa María River and even crosses the plain. When the river floods, the aeolian sediments are transported downstream to restart the aeolian process.

In the middle section of the study area, the Chuscha and Loro Huasi rivers converge. These rivers are artificially channeled between rectilinear levees and reach the main river to form alluvial cones. At this point, highly dynamic interactions are produced by the interference between the rivers and the aeolian process. This point coincides with the eastern side of the La Estancia Golf Course. Linear and transversal defenses for the golf course on the margin of Santa María River were built around a decade ago. However, they are currently in a very poor state of conservation (Figure 4a and Main Map). Powerful dune field dynamics enable the appearance of interdune spaces where is possible to see the sand and silt of old riverbed deposits (Figure 4c). Barchan and parabolic dunes have formed over these deposits (Figure 4d).

The second dune field (Los Médanos 1) is on the left bank of the Santa María River and the sand source is the first part of the area of active southern meanders and the old riverbed (whose direction transverses the dominant wind). The most active area is close to the Chuscha River (see Main Map) with fronts formed by parabolic dunes. These dunes are partially covered by *Prosopis nigra, Saueda sp., Sporobolus rigens, Heliotropum mendocinum* and other plant species (Hueck, 1950) (Figure 4e). The area has been declared protected, but it remains very affected by fires, overgrazing, and vineyard growing. The high level of activity of this dune field made it necessary to change the course of the National Road 68, which some years ago crossed the dune field to the south. These dunes overlay older dunes (that are dominant to the south of the Chuscha River) and extend up to the distal sections of the piedmont of Sierra de Quilmes. The OSL datings made by Peña- Monné et al. (2015) show the existence of four phases of dune activation: the oldest is dated to 1010 ± 80 AD, and three other more recent phases are dated to 1360 ± 60, 1590 ± 40/1650 ± 50, and 1780 ± 80 AD. The old dunes are only visible when strong winds produce deflation corridors that expose outcrops showing compact dark yellow sands with signs of roots (newer sand, in contrast, is almost white in color).

4. Conclusions

The lower area of the Cafayate depression is formed by a wide floodplain whose main components are the result of the Holocene evolution and a high level of current geomorphological dynamics. These dynamics could be classified into three categories, two of dynamics related to fluvial dynamics and the third to aeolian activity.

The legend of the Main Map reflects these features and shows the most active geomorphological processes. In first place, the fluvial dynamics of the Santa María River, are dominated in the south by the development of anastomosing channels and crevasse splays. In the northern section, close to the confluence with the Calchaquí River, a meandering channel develops.

The fluvial activity is mainly during the rainy summer with floods triggering the functioning of the anastomosing channels of the southern section of the study area and the meandering belt to the north. The river mobility on its overland floodplain is reflected on the Main Map by the large number of old channels, wetlands, crevasse splays, and recently abandoned meanders.

Wind dynamics are present in the entire area, with dune fields extending across the depression. These dune systems are related to the fluvial dynamics because the riverbed provides fine sediments after each flood. Moreover, in the case of Los Médanos 1, the sand transported upstream by the wind returns to the river and is then carried again downstream.

Due to its high level of mobility, the main environmental hazards are centered in the northern meander belt. The main risk is situated at the bridge over the National Road 68 because of the possible repercussions on road structures. Moreover, there is the possibility that the Santa María River may move further north, as it was in 1969, and this could create difficulties that exceed the current containment measures.

Software

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

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