

Taton dune field: wind selection across the Southamerican arid diagonal, Puna Argentina

O campo de dunas de Tatón: Seleção do vento ao largo da Diagonal Arida de Sudamerica, Puna Argentina.

Federico I. Isla^{ac}, Manuel F. Isla^{bd}, German R. Bértola^{ac}, José M. Bedmar^{af}, Luis C. Cortizo^{ag},
Reinaldo A. Maenza^{ah}

^aInstituto de Geología de Costas y del Cuaternario (UNMDP-CIC), Instituto de Investigaciones Marinas y Costeras (UNMDP-CONICET), ^bCentro de Investigaciones Geológicas (UNLP-CONICET)
^cfisla@mdp.edu.ar, ^dmisla@cig.museo.unlp.edu.ar, ^egbertola@mdp.edu.ar, ^fjosebedmar@gmail.com, ^gcortiz@mdp.edu.ar,
^hmaenza.r@gmail.com

Abstract

Fiambalá is a tectonic valley emplaced in the southern Puna region, Catamarca Province, Argentina. At the Western side of the valley, “bajadas” and tuff deposits are interfingered. Westerly winds cause an eastward sand transport, either by saltation or deflation. Sand is therefore accumulated eastwards, attached to the Fiambalá Range. This sand ramp located close to the Tatón village was surveyed in terms of its morphology and sand composition. The central section of the valley is occupied by the Abaucán River, which runs across the dune field. Three oases developed at these aggradation plains: Palo Blanco, Medanitos and Fiambalá. These localities however have been threatened by desertification processes in the last years. Three profiles were described along the aggradation plain of this valley. The transversal and longitudinal dunes of Tatón are composed of fine sand with 12-28% of volcanic ash, deposited within the last 5500 years. Grain-size selection was caused by aeolian transport processes. Dune ramps developed in areas dominated by sand transport while loess-sized material is deflated outside the valley.

Keywords: dune field; grain-size selection; Tatón; Fiambalá valley; Catamarca

Resumo

O vale de Fiambalá é tectônico e localizado na região da Puna, Província de Catamarca, Argentina. Ao oeste deste vale, “bajadas” e depósitos de tufos são interdigitados. Ventos do oeste produzem um transporte de areia, tanto por saltação quanto por deflação. A areia se acumula ao leste do vale, anexo a Serra de Fiambalá. Esta rampa de areia, localizada perto da vila de Tatón, foi descrita segundo morfologia e composição das areias. A seção central do vale é ocupada pelo rio Abaucán, que atravessa o campo de dunas. Três oásis se desenvolveram nesta planície: Palo Blanco, Medanitos e Fiambalá, hoje ameaçados por processos de desertificação. Três perfis foram descritos ao longo da planície de agradação deste vale. As dunas transversais e longitudinais de Tatón são compostas de areia fina com 12-28% de cinza vulcânica, depositada nos últimos 5500 anos. A seleção sedimentar é produzida pelo transporte eólico. As dunas foram desenvolvidas nas áreas dominadas por areia; o loess foi deflacionado fora do vale.

Palavras-chave: campo de dunas; seleção; Tatón; Fiambalá; Catamarca

1. Introduction

Fiambalá (“house of the wind” in the language of the original inhabitants), is a tectonic valley located in the southern portion of the geological region known as Puna, Catamarca Province, Argentina (27° 41’S; 67° 37’W; Figure 1). This partially-enclosed valley is protected by high-mountain ranges and presents from north to south three aligned oases: Palo Blanco, Medanitos and Fiambalá (Figure 1). The Tatón dune field is related to the Medanitos wetlands, and consists of transverse dunes that migrate eastwards climbing to the Fiambalá Range in response to dominant westerly winds (Isla and Espinosa 2017). The Medanitos oasis is affected by an intense desertification process (Rivero & Rivero 2010), that has been recently enhanced (Navone 1998). Local winds known as “Zonda winds” are

influenced by topographic features, and cause rapid changes in the air temperature, with gust speeds over 40 m/s (Puliafito *et al.* 2015). Although sand is dominant at the Fiambalá Valley, there is a grain-size selection in relation to other valleys located to the east (Vargas Aranibar & Niederle, 2010; Couso *et al.* 2011).

El Niño events were known before the Spanish colonized Peru because of their consequences on the anchovy fishery. They were known as seasonal heavy rainfalls and rapid floods. Immense volumes of water transported across the Pacific Ocean during, the so-called “El Niño” or ENSO years (Vargas *et al.* 2000; Andreoli and Kayano 2005). Bjerknes (1969) postulated that ENSO originates when Sea Surface Temperatures (SST) anomalies in the Pacific Ocean

cause trade winds to strengthen or slacken ocean circulation changes that at the same time induce changes in the SST. Although much information has been collected from different projects there are still some doubts about the interactions that triggered these ENSO events (Kleeman and Moore 1997; Neelin *et al.* 1998; Sheinbaum 2003, Dijkstra 2006). Although these anomalous years are known by their climatic and oceanographic consequences, their hydrological responses in South American rivers have not been carefully reported. One to the main reason is the lack of

information about rains records (Sun *et al.*, 2015) or about long and continuous hydrological records (Ward *et al.* 2016).

ENSO-triggered phenomena increased in frequency and magnitude during the end of the XX century compared to previous decades (Garreaud *et al.* 2009; Vargas *et al.* 2006; Isla 2018). According to Puna records (Southern Peru and Northern Chile), the ENSO related heavy rainfalls and debris-flow events occurred in 1925, 1940, 1982 and 1997-98 (Vargas *et al.* 2006).

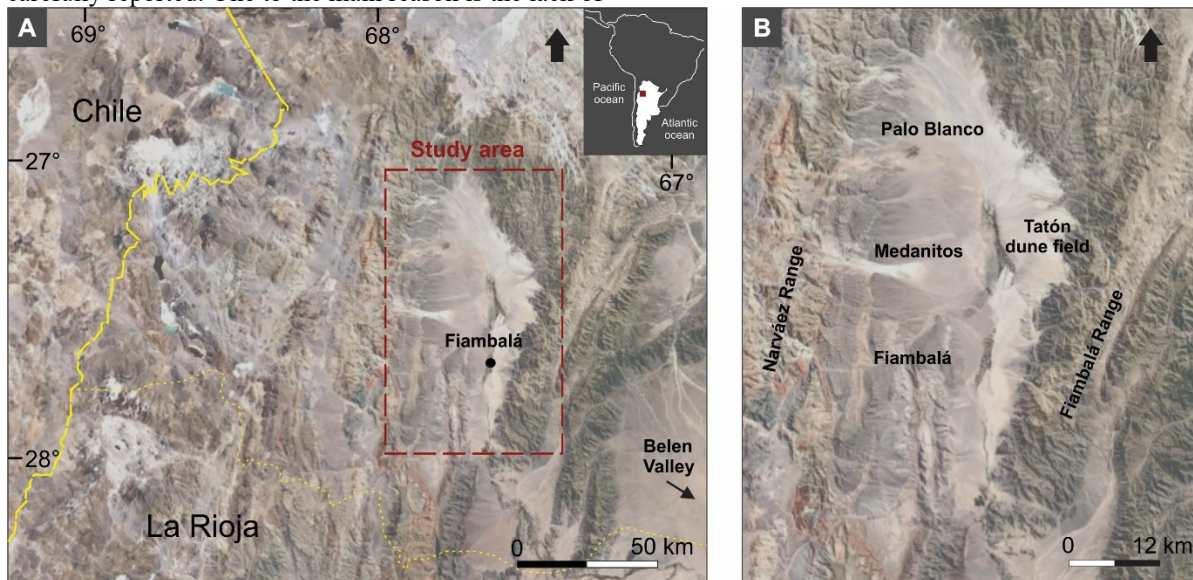


Figure 1: A) Location of the study area. B) Tatón dune field in relation to the three oases of the Fiambalá Valley.

Dune fields are widely distributed along the central-western part of Argentina (Tripaldi *et al.* 2010). This region is within the so-called South American Arid Diagonal (SAAD); an area extended from Peru to Patagonia with significant effects during ENSO anomalous years (Isla *et al.* 2003; Isla 2018; Isla & Espinosa 2021). Winds are thought to dominate the ocean circulation in the Southern Hemisphere due to the asymmetric distribution of continents and oceans. Westerly winds are more frequent and stronger than in Northern Hemisphere (Sijp & England 2009). Winds therefore control climate and the regional exchange of CO₂ between the Southern Ocean and the atmosphere (Russell *et al.* 2006; Sime *et al.* 2013; Hinojosa *et al.* 2017). This relationship wind-ocean became of special concern in the sense that it can affect the future climate controlling the CO₂ sinking efficiency towards the deep ocean (Kohfeld *et al.* 2013). Moreover, aeolian transport and their associated wind regimes are very important for the evolution of modern desert landscapes. Climate changes are of special concern to Central Argentina in relation to the origin of ancient lakes at altitudes above 3000 m (Garleff *et al.* 1993; Clapperton *et al.* 1997) and the desertification processes (also specially related also to recurrent volcanic eruptions) that controlled human occupation. These facts increase the importance of getting a better

understanding about climate and its relation to morphologic changes.

The aim of this paper is to analyse the origin, composition and dynamics of the dune field at Tatón, and also to discuss the deflation processes involved in transport of finer particles to other valleys from the region. In this sense, the sand deposits of the Fiambalá Valley are compared to the loess deposits of the Belén Valley to the east (Figure 1A). This information is also handled in order to understand environmental changes across the South American Arid Diagonal.

2. Setting

The Tatón dune field is located in the eastern side of the Bolsón de Fiambalá (Figure 1), a tectonic basin opened to the south (González Bonorino 1972). This valley, location of several archeological deposits, is surrounded by several ranges over 4000 m height: the Fiambalá Range to the east and the Narvárez Range to the west (Fig 1). The bottom of the valley is more than 1700 m above mean sea level (MSL) in the north and 1450 m in the south. The region has a high risk of earthquakes; at the Belén-Andalgalá-Pipanaco basin, immediately to the east (Figure 1), earthquakes are more common towards the ranges located to the north (Nobile, 2013). The most recent earthquakes recorded 5.8 Mw (May 28, 2002) at the Velasco Range, and 6.2 Mw (September 7, 2004) at the Ambato Range (Nobile 2013).

Precipitation is extremely scarce (50 to 160 mm/yr), exclusively concentrated during the summer months. The Zonda winds blow down the Andes, and load the atmosphere with dust eroded from arid soils (Puliafito *et al.* 2015). At tropical- subtropical latitudes, the Andes acts as a climate barrier with dry conditions to the west and moist conditions to the east (Garreaud *et al.* 2009). Between 15°S and 30°S the topographically driven filtering effect of the Cordillera de los Andes is at maximum. ENSO effects are more significant to the Western side of the Andes (Bennet *et al.* 2016).

The central part of the Fiambalá Valley is subject to aggradation where fluvial and eolian processes alternated during the Quaternary. In modern times, fluvial processes were diminishing (Isla & Espinosa 2017) while eolian effects were becoming dominant. The Abaucán River (also called Salado, Colorado or Bermejo) flows from north to south within this asymmetric valley (Navone 1998; Paoli *et al.* 2011), receiving the discharge of the Chaschuil and De la Troya rivers from the west. The watershed has an area of approximately 28,300 km². At Tinogasta, the mean river discharge was estimated in 2.54 m³/s with a maximum of 84.7 m³/s (1948-49) and minimum records of 0.96 m³/s (1941-42; Isla & Espinosa 2017). Discharge reduction in the last decades is in accordance with reported desertification processes (Ratto *et al.* 2013) and channel erosion (Niz 2003). These processes are affecting the three oases of the valley: Palo Blanco, Medanitos (Rivero and Rivero 2010) and Fiambalá, and are thought to occur since the Middle Holocene (Tchlinguirian & Morales 2013).

The ranges surrounding Bolsón de Fiambalá are composed of different lithologies: granites at Sierra de Fiambalá and Sierra de Zapata, high-grade metamorphic rocks at Sierra de Copacabana and Sierra de Zapata, and sedimentary and volcanic rocks at Cerro Negro de Rodríguez and Sierra de Narvárez (Carrapa *et al.* 2006; Castro 2007; Montero López *et al.* 2009). The region is characterized by low-angle thrusts faults associated with frequent earthquakes with magnitudes between 3 and 5 (Richter scale; Nobile 2013). Several volcanic and volcanoclastic Quaternary deposits were reported from the Laguna Blanca region (Turner 1973; Fajardo *et al.* 2018). The lowermost are composed of dacitic tuffs (Laguna Blanca Formation) overlain by andesitic and basaltic rocks (Negro Carachi and Los Rastrojitos formations; Turner 1973). Modern pumicite clasts were assigned to the eruption events of the Cerro Blanco, Buenaventura Range. This small dome, located to the north of the valley, has provided biotite, quartz inclusions and small percentages of volcanic glass and lithic fragments (Montero López *et al.* 2005). The last pumicite extrusions occurred after 5500 years BP (Montero López *et al.* 2010; Ratto *et al.* 2013).

The Fiambalá tectonic valley received coarse material from the west. Red sands composing remnants hills, covered by gravel are common at the bottom of the valley. Paraglacial megafans are also common

related to deep tectonic valleys and depressions (Suvires 2014). The coalescence of alluvial fans at the foot of the ranges of the west produces bajada deposits. A smaller fan is attached to the eastern side of the valley, attached to the Fiambalá Range, and close to the well-known thermal springs. Earthquakes recurrence can be confirmed by the convoluted lamination at the bottom of the Holocene shallow lakes (Ratto *et al.* 2013). At the Tinogasta area, a deposit of reddish sands was reported as Pleistocene (Sovic 1972). Another sand field (68 x 15 km) is attached to the ranges on the East side of the valley, and extends in a north-south direction. Desertification has been occurring during the last 4500 years (Montero López *et al.* 2009). Eolian deposits with lag gravels on top (Niz 2003) are very common close to Medanitos and confirm the frequency of deflation processes. Wind deflation is therefore considered as an ongoing process in the modern dispersal of sand and silt (Gaiero *et al.* 2013; Gili 2014).

3. Methods

A Digital Elevation Model (DEM), spatial resolution of 90 m, was downloaded from <http://srtm.csi.cgiar.org/>. This information was handled with the Global Mapper v.7.04 program (www.globalmapper.com). Historic Google Earth images were handled to analyse the dune changes at the Tatón sand ramp (Figure 1). Westerly-wind frequency in the Southern Hemisphere were reanalysed from NOAA monthly data (Kalnay *et al.* 1996; https://www.esrl.noaa.gov/psd/data/gridded/data.ncep_reanalysis.derived.surface.html). In order to test the ENSO effects on rivers of the region (San Juan, Mendoza, Tunuyán, Desaguadero) their monthly discharges were downloaded from <http://bdhi.hidricosargentina.gob.ar/> and analysed.

Sand samples were sieved at 0.5 phi intervals and evaluated according to ordinary statistical parameters (Folk & Ward, 1957). Mineral grain compositions from bulk samples were analysed using a petrographic microscope. Results were included in a data base managed with Geographic Information system (Arc View) procedures. Alos Palsar (SAR, Band L, 23 cm) images were analysed -and compared to OrbView images-, in order to search the groundwater flow and seepage phenomena within the Tatón sand field.

4. Results

4.1. Tatón sand ramp

The accumulation of sand in the eastern area of the valley denotes the action of intense and frequent winds. These sand ramps extend from altitudes of 1600 to 2600 m above MSL (Figure 1). Transverse and longitudinal dunes oriented in response to winds from the SW are common in the Eastern side of this valley close to the village of Tatón (Isla & Espinosa 2017). Subordinated, reverse-crested and triangular dunes are also common (Figure 2). Within this dune field,

interdune deposits are located 1.4 m above the present interdune depressions. Some of these deposits are multiple in the sense that they respond to several of these stability periods (Figure 2).

Fine sand dominates across the sand ramp although medium sand was sampled at the lee side of some dunes (Table 1). Several former interdune depressions are scattered at the dune field, also composed of medium sand. Coarse sand was located forming

granule ripples at the dune foot on the lee sides. Heavy minerals are segregated at the lee slopes of some dunes (Figure 3).

Fine sand from the Fiambalá Valley is dominantly composed of quartz 65-40 %), pumicite and volcanic glass (13-28 % together). Lithic fragments are only 8-11 %, feldspar 4-7% and opaques 3-6 %. Far from the Cabo Blanco fallout, in Tinogasta, the percentages of opaques increase to 20 % (Table 2).



Figure 2: a) Reverse dunes at Tatón; b) Triangular dunes. c) Interdune deposit composed of medium sand and elevated from the present interdune bottom; d) Two superimposed interdune deposits.

Table 1: Grain-size variations across the Tatón dune field.

	Grain flow	Fossil interdune	interdune	Hanged interdune	Lee side	Stoss side	Granule crests	Pumicite bearing sand
Samples	1	2	3	4	5	6	7	8
Mean (microns)	242.4	179.8	297.4	347.0	295.9	215.1	895.4	316.0
Mean (σ)	2.045	2.476	1.750	1.527	1.757	2.217	0.159	1.662
Sorting	0.467	1.812	0.787	1.299	0.903	0.488	1.354	0.570
Skewness	0.055	-0.103	0.084	0.032	0.431	0.012	0.688	0.360

Table 2: Mineral percentages (bulk samples) from sand dunes of the Fiambalá Valley

sites	Lat S	Long W	Mz	R	Qz	P+G	Lit	Opa	Fel	Lam	Pir	Gar	Tit	Tou
Taton	27°20'37"	67°32'19"	208	0.60	65	13	8	5	7	1	-	-	-	-
Agua del Medio	27°27'11"	67°34'44"	178	0.42	51	23	11	3	4	1	2	2	-	3
Abarcan River	27°30'34"	67°35'19"	132	0.30	45	28	10	6	6	4	-	-	1	-
Tinogasta	28°15'20"	67°26'29"	138	0.44	38	-	38	20	2	1	1	-	-	1

References: Mz: mean grain size (microns); R: roundness (chart of Krumbein and Sloss, 1963); Qz: quartz; P+G: pumicites + volcanic glass; Lit: lithic fragments; Opa: opaques; Fel: feldspar; Lam: lamprobolite; Pir: piroxenes; Gar: garnet; Tit: titanite; Tou: tourmaline.

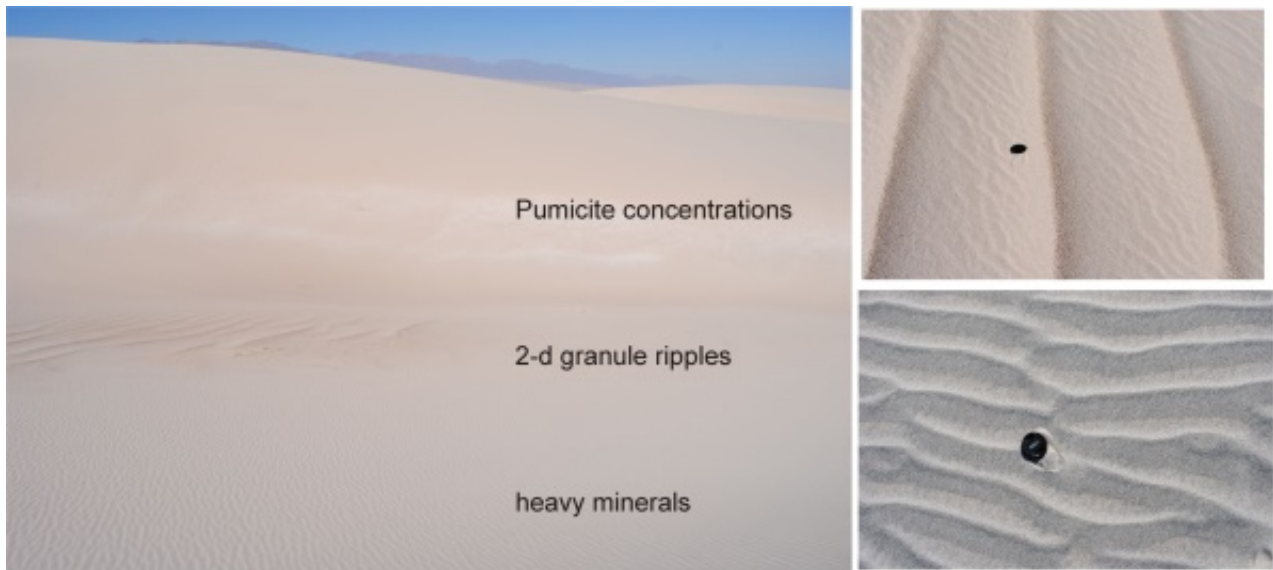


Figure 3: a) Segregations caused by wind action on a transverse dune field; b) 2D (anorbital) ripples with coarse sand on top of the crests; c) Heavy-mineral segregations across wind fine-sand wind ripples.

4.2. Fluvio-colian aggradation

Holocene sequences (La Hoyada and Ojo de Agua profiles) have been described and dated at the NW corner of the valley, attached to Sierra de Narvaez (Montero López *et al.* 2009; Figure 1). Along the Abaucán River, at the valley centre, which receives water from the west via the De la Troya and Colorado rivers, several Holocene aggradation sequences of “bajada” deposits (defined as coalescence of alluvial fans) were also described (Figure 4). Other alluvial deposits have been surveyed further south, close to Tinogasta (Sosic 1972; Niz 2003).

The Pampa Blanca profile is located north of the town of Fiambalá (27° 38' 45"S; 67° 36' 15"W; Figure 1). It starts with silty fine sands (0.1 m) ending with a disconformity on top (Figure 4). This level is overlain by approximately 2 m of medium-coarse sand with small-scale and trough crossbedding. Lag gravels occur at the base of some strata. Lenticular and wavy bedding also occur. After another disconformity, 0.67 m of silty sands with many burrows of up to 4 cm diameter were deposited. In a nearby outcrop, a diatomite layer of 0.13 m width is placed 1 m below the upper surface.

The Mayorazgo profile is about 8.4 m thick, located 18 km north of Tinogasta (27° 54' 50"S; 67° 36' 44"W). The outcrop was cut by the Abaucán River. The base is composed by 0.8 m of a polymictic conglomerate deposit with boulders up to 0.3 m. Overlying, there are 2.6 m of fine to medium sand, with gravel clasts, containing trough and diagonal crossbeds. After a lamination-bearing erosive limit overlays a 0.54 m thick deposit of coarse sand with some lenticular strata (Figure 4). It is followed by a 0.03 m layer of polymictic gravel with unsorted clasts of 2 cm diameter. The sequence continues with 3.4 m of medium to coarse sand with different primary structures (crossbedding, normal gradation, horizontal lamination). After another disconformity, the sequence finishes with 1 m of whitish sand.

Banda de Lucero profile (28° 10' 34"S; 67° 28' 37"W) is very close to Copacabana locality. The Abaucán River is here called Colorado. The described sequence initiates with massive, red silty sand (0.3 m). It continues with fine horizontally-laminated sand (0.2 m). Overlying, 0.5 m of stratified silty sand (strata of 5-10 cm) were measured. Towards the top, these sands contain root burrows (0.5) finishing with soil on top.

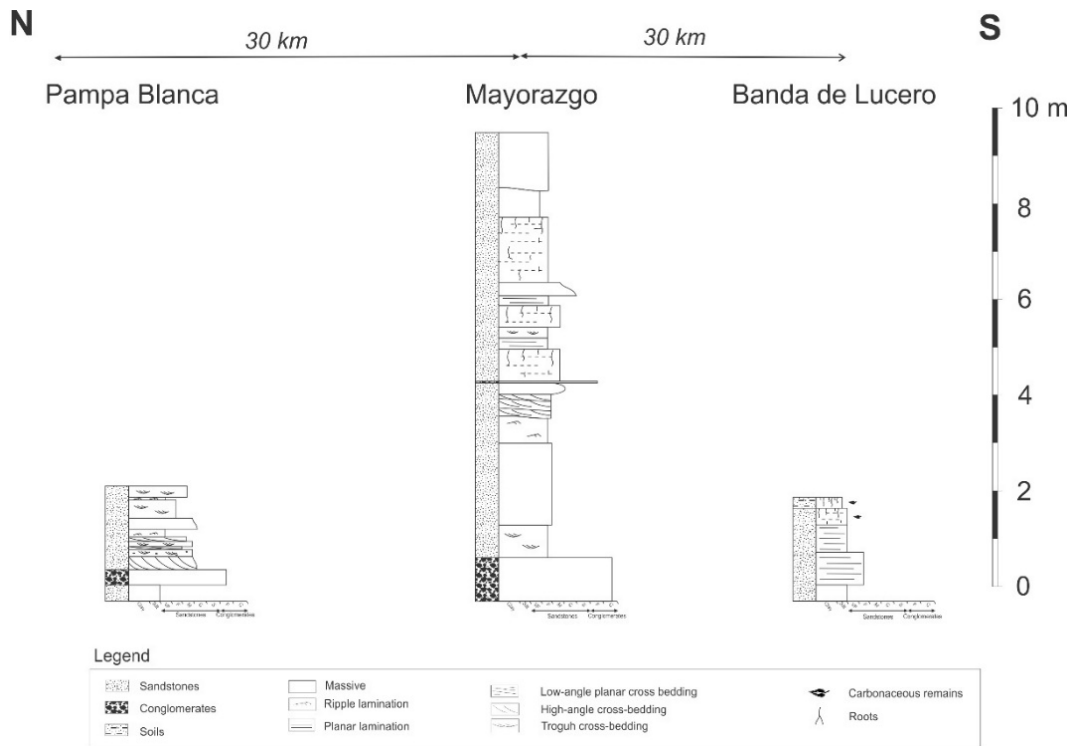


Figure 4: Schematic profiles of the deposits emplaced at the Abaucán-de la Troya rivers; a) Pampa Blanca, b) Mayorazgo, and c) Banda de Lucero.

The fate of the groundwater was analysed by the interpretation of SAR images. Considering the penetration of band L into the sorted fine sand of the dune field, it is clear that the Tatón River seeps under Holocene aeolian deposits after getting out of the Fiambalá Range (Figure 5).

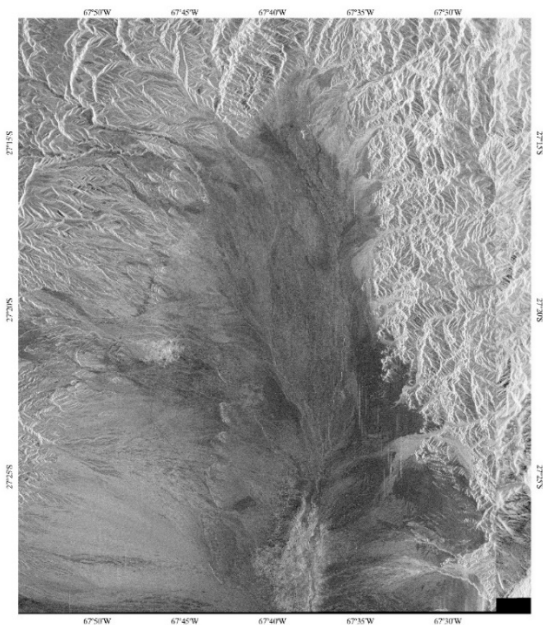


Figure 5: ALOS PALSAR SAR image from the northern Bolsón de Fiambalá. Band L reflects darker where groundwater is shallower.

4.3. Volcaniclastic inputs and loess segregations

Both Argentine loess deposits -the Pampean and the so-called Neotropical-, have significant volcaniclastic

components, either during the Holocene and during modern times. Some historic eruptions have deposited ash onto the Pampean and Chaco-Pampean plains (Sayago *et al.* 2001; Zárate 2003; Iriondo & Krohling 2007; Simonella 2013; Gili 2014; Milana & Krohling 2017; Isla *et al.* 2018; Figure 6).

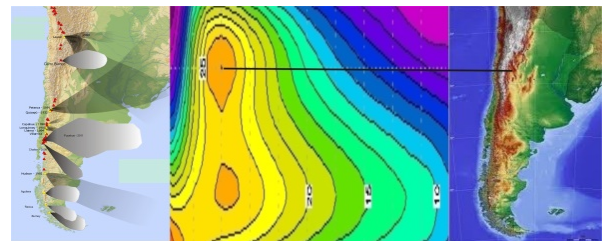


Figure 6: a) Historic and Holocene eruptions from Andean volcanoes (modified from Isla *et al.* 2018) b) Wind velocity frequencies (NOAA monthly data) derived from westerlies in the Southern Hemisphere c) South American arid diagonal.

The Pampean loess was defined by analogy to the European loess as derived from former glacial deposits (Frenguelli 1955); although lately the composition of this loess (and the Chinese's) was considered as completely different from the European one. The Neotropical Loess was defined for the fine sediments deposited on the Northern plains of Argentina between 20 and 30° S (Sayago 1995). The Andean piedmont, extending west of the Desaguadero-Salado-Curacó (DSC) fluvial system was indicated as the provenance area for this loess accumulation (Zárate & Tripaldi 2011). It extends from N to S along the South American Arid Diagonal (SAAD, Figure 6) and operating during glacial and interglacial periods (Gili *et al.* 2017). Today, the transition between the sand dunes

recognised at some tectonic valleys (Calchaquíes valleys, Tinogasta and Pipanaco depressions) and the loessic deposits of the east (Sayago *et al.* 2001) can be related to the concept of desert loess. At the Shinkal archaeological site (Belén Valley), coarse silty very fine sand was sampled. In this region, the downwind transition from sand to loess can be assigned to the deactivation of the DSC fluvial system. The transitions between sandy and loessic deposits were also reported for the Pampean loess, either in a spatial (Iriondo 1997) and temporal scales (Isla *et al.* 2010).

The contribution of volcanic glass and pumicites to these sand fields can be explained by their spatial relations to recent eruptions. Acid volcanoes are dominant within the Andean Cordillera of the Catamarca Province (Figure 7). Ash contribution occurred since the Miocene to the Holocene at the region of Cerro Blanco-La Hoyada (Montero López *et al.* 2010). Modern dunes contain up to 12-28% of pumicite clasts (Isla & Espinosa 2017). On the other hand, basaltic and acid volcanoes also characterised the Cordillera further south, between 27 and 33 degrees S (Figure 7). Modern ash fallouts from volcanoes of Patagonia, such as the Cordon Caulle Complex (eruptions of 1960 and 2011), Calbuco (1960) and Chaitén (2008), supplied significant quantities of tephra (Daga *et al.* 2014). Modelling of these pumice eruptions help to validate the probable contribution to the Pampean loess (Osorio *et al.* 2013). Although these models were improved in the last years there are processes of ash aggregation that can underestimate or overestimate the ash plumes (Brown *et al.*, 2012).

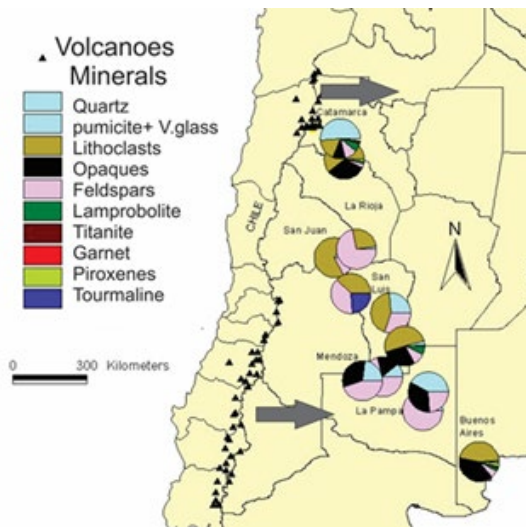


Figure 7: Sand composition of aeolian sand fields from central Argentina. Glass and pumicite distributions are assigned to the

location of active volcanoes in the Andes and the westerly wind dispersal (modified after Isla & Espinosa 2017).]

5. Discussion

Since the Holocene, eolian dispersal effects have caused significant problems to the inhabitants of the Fiambalá valley (Rivero & Rivero 2010). Ancient cultures were repeatedly threatened by desertification processes in the last 4500 years (Montero López *et al.*, 2009; Ratto *et al.* 2013). At the same time, since Mid Holocene there was an increasing influence of El Niño events (Vargas *et al.* 2006).

Along the SAAD, the rivers draining from the Andes (San Juan, Mendoza, Tunuyán, Desaguadero) have peak discharges in coincidence with ENSO anomalous years. These river discharges were explained in details in a previous report, being 1941, 1982/83 and 1997/98 the most significant peak discharges (Isla & Espinosa 2021; Table 3).

Table 3: Monthly peak discharges of rivers from the Colorado watershed

river	locality	Monthly peak discharges
San Juan	Km 101	1972, 1987, 1997
Mendoza	Cacheuta	1915, 1920, 1942, 1983
Tunuyán	Tunuyán	1964, 1973, 1983, 2006
Desaguadero	Desaguadero	1942
Desaguadero	Canalejas	1988, 1998, 2003

Sediment supply is the key variable for the build-up of dune fields, and the wind selection of loess grain sizes (Halfen *et al.* 2016), even in tropical areas (Crouvi *et al.* 2010). For example, the Cangagua Formation in Ecuador was reinterpreted as belonging to wind-driven fine sediment delivered mainly by volcaniclastic processes (Clapperton & Vera 1986), and were similarly related to the Pampean loess (Clapperton 1993).

There are significant differences in the grain-size composition of the aeolian deposits of the Fiambalá and Belén valleys (Figure 1): the former composed dominantly by sand while to the western side of the Belén Valley it is composed of loess (Nóbile 2013). This segregation of saltation-dominated sand to suspension-dominated loess has been assigned to the response of altitude variations (Pye 1995; Sweeney *et al.* 2005). The loess-sized particles are resuspended during high-energy wind events, entrained by deflation processes from the Fiambalá Valley, and settling to the east at the Belén Valley (Figure 8).

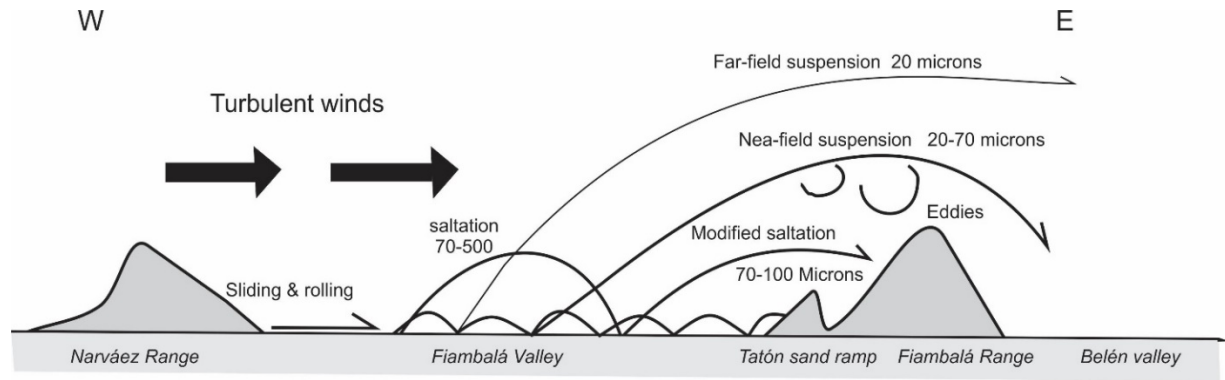


Figure 8: Modes of wind transport across the Fiambalá Valley (modified from Pye 1995; & Gili 2014).

However, these conditions are not so strict in their responses when considering turbulence effects. Quartz particles of 70 μm can be transported by saltation or modified saltation in flows having weak wind-derived shear and turbulence. However, they can be also transported in short-term suspension in flows with strong friction and turbulence (Ujvari *et al.*, 2016). Particles below 10-20 μm can be picked up and transported hundreds to thousands of kilometres by different modes of suspension transport: direct aerodynamic entrainment-resuspension, saltation bombardment/sandblasting and disaggregation/ auto-abrassion (Ujvari *et al.*, 2016).

The origin of fine sediment and the pathways of distribution and deposition by wind were described for several locations related to arid provenances (Wright 2001). The origin of the desert loess is an issue introduced during the 1980s (Tsoar & Pye 1987) and accepted in terms of the geomorphic mechanisms involved (Wright 2001). Although the suspended sediments collected in Puna were about 14 μm (Gaiero *et al.* 2013), samples collected south of the Puna were bimodal with one mode between 9-11 μm , and the other between 150 and 170 μm that were assigned to alluvial fans and borders of saline areas (Gili 2014). In this sense, significant climatic variations were recorded in Puna during Upper Quaternary and conditioned the aggradation of the tectonic valley (Schlidgen *et al.* 2016). The mid Holocene (5500-5300 years BP) was considered as an interval when the ENSO events dominate in Southern Peru and Northern Chile (Vargas *et al.* 2006). However, in this particular location of the Argentine Puna, this interval was dominated by volcanoclastic phenomena that should have buried any evidence of heavy rainfalls. The contorted structures of the ash layers from La Hoyada (8830-5480 years BP) and Ojo de Agua (5960-5040 years BP) profiles (Montero López *et al.* 2009) can be indicating humid conditions during the eruption of the Cerro Blanco Caldera. This ash availability at the Fiambalá Valley would have controlled the cultural gap between the Archaic Period (circa 5000 years BP) and the Incas occupation (circa 500 years BP; Montero López *et al.* 2009).

Deflation processes would have also played a significant role in the occupation, evolution and decayment of the unique archaeological Incas site known as Shinkal de Quimivil, Belén Valley, Catamarca (Couso *et al.* 2011). Conditions were more unstable for humans to the west, at the Fiambalá-Tinogasta valley, due to the mentioned explosive volcanism and the recurrent seismicity (Montero López *et al.* 2009; Ratto *et al.* 2013). Environmental conditions changed the water and vegetation availability and therefore the conditions for herbivores and hunters populations (Ratto *et al.* 2013). Although significant climatic fluctuations succeeded during the Holocene in Puna (Tchilinguirian & Morales 2013; Schlidgen *et al.* 2016), at the Fiambalá Valley the episodic processes conditioned the continuity of human occupations. It is clearly concluded that ancient societies were particularly sensitive to these episodic processes (Montero López *et al.* 2009).

6. Conclusions

1. The sand ramp of Tatón is composed of a fine fraction derived from former alluvial-fan deposits. Loess-sized sediments were blown outside the Fiambalá valley to the neighbouring valleys to the east.
2. The sand ramp is modern considering that it is composed dominantly by ash blown in the last 5500 years.
3. These tectonic valleys of high altitude and oriented transverse to the westerly winds induce a grain-size selection from sand to loess.
4. Dacitic-trachitic volcanoes supplied ash and pumicite clasts to the Panpean and/or Neotropical loess.

References

- Andreoli, R. V. and Kayano, M. T., 2005. Enso-related rainfall anomalies in South America and associated circulation features during warm and cold Pacific Decadal Oscillation regimes. *International Journal of Climatology* 25, 2017–2030.
- Bennett, M., New, M., Marino, J., Sillero-Zubiri, C., 2016. Climate complexity in the Central Andes: A study case

- on empirically-based local variations in the Dry Puna. *Journal of Arid Environments* 128, 40-49.
- Bjerknes, J., 1969. Atmospheric teleconnections from the Equatorial Pacific. *Mon. Weather Rev.* 97, 163-172.
- Brown, R. J., Bonadonna, C., Durant, A. J., 2012. A review of volcanic ash aggregation. *Physics and Chemistry of the Earth* 45-46, 65-78.
- Carrapa, B., Strecker, M. R., Sobel, E. R., 2006. Cenozoic orogenic growth in the Central Andes: Evidence from sedimentary rock provenance and apatite fission track thermochronology in the Fiambalá Basin, southernmost Puna Plateau margin (NW Argentina). *Earth and Planetary Science Letters* 247, 1, 82-100.
- Castro, M. A., 2007. Estudio hidrogeológico en base a prospección geoelectrónica. Area Tinogasta - Palo Blanco, Departamento Tinogasta, Catamarca, 16 pp.
- Clapperton, Ch. M., 1993. *Quaternary Geology and Geomorphology of South America*. Elsevier, 779 pp.
- Clapperton, Ch. M., Vera, R., 1986. The Quaternary glacial sequence in Ecuador: a reinterpretation of the work of Walter Sauer. *Journal of Quaternary Science* 1, 1, 45-56.
- Couso, M. G., Moralejo, R. A., Giovanetti, M. A., Del Papa, L. M., Paez, M. C., 2011. Inka occupation of closure 1-Kancha II, at El Shinkal de Quimivil (Catamarca, Argentina). *Quaternary International* 245, 159-169.
- Crouvi, O., Amit, R., Enzel, Y., Gillespie, A. R., 2010. Active sand seas and the formation of desert loess. *Quaternary Science Reviews* 29, 2087-2098.
- Daga, R., Ribeiro Guevara, S., Poire, D. G., Arribére, M., 2014. Characterization of tephra dispersed by the recent eruptions of volcanoes Calbuco (1961), Chaitén (2008) and Cordón Caulle Complex (1960 and 2011), in Northern Patagonia. *Journal of South American Earth Sciences* 49, 1-14.
- Dijkstra, H. A., 2006. The ENSO phenomenon: theory and mechanisms. *Advances in Geosciences, European Geosciences Union* 6, 3-15.
- Fajardo, D., Isla, F., Iriondo, M., Kröhlhling, D., 2018. Cuaternario. *Lexico estratigráfico de la Argentina*. Vol. XIII, Asociación Geológica Argentina, Segemar, Buenos Aires, 190 pp.
- Folk, R.L., Ward, W., 1957. Brazos river bar: a study in the significance of grain size parameters. *Journal of Sedimentary Petrology* 27, 1, 3-26.
- Frenguelli, J., 1955. Loess y limos pampeanos. *Facultad de Ciencias Naturales y Museo, serie técnica y didáctica* No.7, 88 pp.
- Gaiero, D.M., Simonella, L., Gassó, S., Gili, S., Stein, A. F., Sosa, P., Becchio, R., Arce, J., Marelli, H., 2013. Ground/satellite observations and atmospheric modeling of dust storms originating in the high Puna - Altiplano deserts (South America): Implications for the interpretation of paleo-climatic archives. *Journal of Geophysical Research: Atmospheres* 118, 3817-3831.
- Garleff, K., Singl, H., Veit, H., 1993. New dates on the Late Quaternary history and landscape and climate in the Bolsón de Fiambalá. NW Argentina (Province Catamarca). *Zbl. Geol. Paläont. Teil 1/2*, 333-341.
- Garreaud, R. D., Vuille, M., Compagnucci, R., Marengo, J., 2009. Present-day South American climate. *Palaeogeography, Palaeoclimatology, Palaeoecology* 281, 3, 180-195.
- Gili, S., 2014. El polvo atmosférico del sur de Sudamérica: Evaluación de sus fuentes y su presencia en registros paleoclimáticos del Hemisferio Sur. Tesis doctoral inédita, Universidad Nacional de Córdoba, Córdoba, 173 pp.
- Gili, S., Gaiero, D. M., Goldstein, S. L., Chemale, F., Jweda, J., Kaplan, M. R., Becchio, R. A., Koester, E., 2017. Glacial/interglacial changes of Southern Hemisphere wind circulation from the geochemistry of South American dust. *Earth and Planetary Science Letters* 469, 98-109.
- González Bonorino, F., 1972. Descripción de la hoja 13c, Fiambalá. *Boletín* 127, Dirección Nacional de Geología y Minería. Subsecretaría de Minería, Ministerio de Industria y Minería, República Argentina, Buenos Aires.
- Halfen, A. F., Lancaster, N., Wollfe, S., 2016. Interpretations and common challenges of aeolian records from North American dune fields. *Quaternary International* 410, 75-95.
- Hinojosa, J. L., Moy, C. M., Stirling, C. H., Wilson, G. S., Eglinton, T. I., 2017. A New Zealand perspective on centennial-scale Southern Hemisphere westerly wind shifts during the last two millennia. *Quaternary Science Reviews* 172, 32-43.
- Iriondo, M. H., 1997. Models of deposition of loess and loessoids in the Upper Quaternary of South America. *Journal of South American Earth Sciences* 10, 1, 71-79.
- Iriondo, M. H., Krohling, D. M., 2007. Non-classical types of loess. *Sedimentary Geology* 202, 352-368.
- Isla, F. I., 2018. ENSO-triggered floods in South America: correlation between maximum monthly discharges during strong events. *Hydrol. Earth Syst. Sci. Discuss.*, <https://doi.org/10.5194/hess-2018-107>.
- Isla, F. I., Dondas, A., Taglioretti, M., 2010. Medáanos relictos intrapampeanos en Daireaux y Centinela del Mar, Buenos Aires. *Revista de la Asociación Geológica Argentina* 68, 1, 58-64.
- Isla, F. I., Espinosa, M., 2017. Upper quaternary evolution of the dune field of the Bolsón de Fiambalá, Catamarca: Sand dispersal at the Andes piedmonts. *Quaternary International*, 442, 59-66.
- Isla, F. I., Espinosa, M. A., 2021. Misfit rivers under ENSO regimes: The deactivation of the Colorado River system of Argentina. *Journal of Arid Environments* 188, 104474.
- Isla, F., Quiroz Londoño, O. M., Cortizo, L. C., 2018. Groundwater content within loessic deposits: the coastal springs of Los Acatilados, Mar del Plata, Argentina. *Environ. Earth Sciences*, 77: 610. <https://doi.org/10.1007/s12665-018-7766-y>
- Isla, F., Ruiz Barlett, E., Marquez, J. y Urrutia, A., 2003. Efectos ENSO en la transición entre el espinal y la pradera cultivada en la Diagonal Sudamericana, Argentina central. *Cuaternario y Geomorfología, Asociación Española de Geomorfología y Cuaternario*, 17, 1-2, 63-74.
- Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, D., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Leetma, A., Reynolds, R., Dennis, J., 1996. The NCEP/NCAR 40-years reanalysis project. *Bull. Am. Meteorol. Soc.* 77, 437-472.
- Kleeman, R., Moore, A. M., 1997. A Theory for the limitation of ENSO predictability due to stochastic atmospheric transients. *J. Atmospheric Sci.* 54, 753-767.
- Kohfeld, K. E., Graham, R. M., De Boer, A. M., Sime, L. C., Wolff, E. W., Le Quéré, C., Bopp, L., 2013. Southern Hemisphere westerly wind changes during the Last Glacial Maximum: paleo-data synthesis. *Quaternary Science Reviews* 68, 76-95.
- Milana, J. P., Krohling, D. M., 2009. First data on volume and type of deflated sediment from Southern Puna

- Plateau and its role as source of the Chaco-Pampean loess. *Quaternary International* 438, 126-140.
- Montero López, M. C., Hong, F., Segiarro, R., Marrett, R., Ratto, N., 2009. Relación entre vulcanismo y los registros arqueológicos en el Bolsón de Fiambalá (Departamento de Tinogasta, Catamarca). En Ratto, N. (Comp.) *Entrelazando ciencias: Sociedad y ambiente antes de la conquista española*, Cap. V. Ed. Eudeba, 131-158.
- Montero López, M. C., Hongn, F., Brod, J. A., Seggiaro, R., Marrett, R., Sudo, M., 2010. Magmatismo ácido del Mioceno Superior-Cuaternario en el área del Cerro Blanco-La Hoyada, Puna Austral. *Revista de la Asociación Geológica Argentina* 67, 3, 329-348.
- Montero López, M. C., Marrett, R., Hongn, F. D., 2005. Geología y estructura del extremo este de la Sierra de San Buenaventura, Puna Sur (Catamarca). *Actas XVI Congreso Geológico Argentino*, La Plata, I, 185-190.
- Navone, S. M., 1998. Identificación de la erosión eólica mediante el análisis de imágenes satélite. *Investigaciones Agrícolas: Prot. Vegetal* 13, 3, 253-263.
- Neelin, J. D., Battisti, D., Hirst, A. C., Jin, F., Wakata, Y., Yamagata, T., Zebiak, S. E., 1998. ENSO theory. *J. Geophys. Res.* 103, C7, 14,261-14,290.
- Niz, A. E., 2003. Geomorfología del sector meridional del Departamento de Tinogasta, Provincia de Catamarca, Argentina. Tesis doctoral inédita, Universidad Nacional de Catamarca, 152 PP.
- NóBILE, J. C., 2013. Tectónica y sedimentación Pliocena-Cuaternaria en las Sierras Pampeanas Septentrionales (27°- 29°LS), Argentina. Unpubl. Thesis, Universidad Nacional de Córdoba, Córdoba, 243 pp.
- Osores, M.S., Folch, A., Collini, E., Villarosa, G., Durant, A., Pujol, G., Viramonte, J. G. 2013. Validation of the FALL3D model for the 2008 Chaitén eruption using field and satellite data. *Andean Geology* 40 (2): 262-276.
- Paoli, H., Elena, H., Mosciaro, J., Ledesma, F., Noé, Y., 2011. Cuenca: "Abaucán - Colorado - Salado". Subcuenca "El Salitral". INTA, EEA Salta, 5 pp.
- Pye, K., 1995. The nature, origin and accumulation of loess. *Quaternary Science Reviews* 14, 653-667.
- Puliafito, S. E., Allende, D. G., Mulena, C. G., Cremades, P., Lakkis, S. G., 2015. Evaluation of the WRF model configuration for Zonda wind events in a complex terrain. *ATMOSPHERIC RESEARCH* 166, 24-32.
- Ratto, N., Montero, C., Hongn, F., 2013. Environmental instability in western Tinogasta (Catamarca) during the Mid-Holocene and its relation to the regional cultural development. *Quaternary International* 307, 58-65.
- Rivero, C., Rivero, A. R., 2010. Categorización de la localidad de Medanitos. Medanitos, Tinogasta, Catamarca. Informe inédito Universidad Nacional de Catamarca, 12 pp.
- Russell, J. L., Dixon, K. W., Gnanadesikan, A., Stouffer, R. J., Toggwiler, J. R., 2006. The Southern Hemisphere westerlies in a warming World: Propping open the door to the deep ocean. *Journal of Climate* 19, 6382-6390.
- Sayago, J. M., Collantes, M. M., Karlson, A., Sanabria, J., 2001. Genesis and distribution of the Late Pleistocene and Holocene loess of Argentina: a regional approximation. *Quaternary International* 76/77, 247-257.
- Sheinbaum, J., 2003. Current theories on El Niño-Southern Oscillation: A review. *Geofísica Internacional* 42, 3, 291-305.
- Schildgen, T. F., Robinson, R. A. J., Savi, S., Phillips, W. M., Spencer, J. Q. G., Bookhagen, B., Scherler, D., Tofelde, S., Alonso, R. N., Kubik, P. W., Binnie, S. A., Sttrecker, M. R., 2016. Landscape response to late Pleistocene climate change in NW Argentina: Sediment flux modulated by basin geometry and connectivity. *Journal of Geophysical Research*, 121, 392-414.
- Sijp, W. P., England, M. H., 2009. Southern Hemisphere westerly wind control over the ocean's thermohaline circulation. *Journal of Climate* 1277-1286.
- Sime. L. C., Kohfeld; K. E., Le Quére, C., Wolff, E. W., De Boer, A. M., Graham, R. M., Bopp, L., 2013. Southern Hemisphere westerly wind changes during the Last Glacial Maximum: model-data comparison. *Quaternary Science Reviews* 64, 104-120.
- Simonella, L. E., 2013. La geoquímica del Fe en sedimentos eólicos y cenizas volcánicas del sur de Sudamérica coo contribución al estudio del ciclo del C en el océano. Tesis inédita, UNC, Córdoba, 240 pp.
- Sosic, V. J., 1972. Descripción geológica de la Hoja 14d, Tinogasta, provincias de Catamarca y La Rioja. *Boletín 129, Servicio Nacional de Minería Geológico*, Buenos Aires, 322 pp.
- Stuiver M., Reimer P. J., Reimer, R.W., 2005. *Calib 5.0.1*. calib.qub.ac.uk/calib
- Sun, X., Renard, B., Thyer, M., Westra, S., Lang, M., 2015. A global analysis of the asymmetric effect of ENSO on extreme precipitation. *Journal of Hydrology* 530, 51-65.
- Suvires, G. M., 2014. The paradigm of paraglacial megafans of the San Juan river basin, Central Andes, Argentina. *Journal of South American Earth Sciences* 55, 166-172.
- Sweeney, M. R., Busacca, A. J., Gaylord, D. R. 2005. Topographic and climatic influences on accelerated loess accumulation since the last glacial maximum in the Palouse, Pacific Northwest, USA. *Quaternary Research* 63, 261-273.
- Tchilinguirian, P., Morales, M. R., 2013. Mid-Holocene paleoenvironments in Northwestern Argentina: Main patterns and discrepancies. *Quaternary International* 307, 14-23.
- Tripaldi, A., 2002. Sedimentología y evolución del campo de dunas de Médanos Grandes (provincia de San Juan, Argentina). *AAS Revista* 9, 1, 65-82.
- Tripaldi, A., Reijenstein, H., Ciccioni, P. L., 2005. Estudio geomorfológico y sedimentológico preliminar del campo eólico de Belén, Provincia de Catamarca, Argentina. *Actas XVI Congreso Geol. Argentino*, La Plata, III, 537-544.
- Tripaldi, A., Ciccioni, P. L., Alonso, M. S., Forman, S. L., 2010. Petrography and geochemistry of late Quaternary dune fields of western Argentina: Provenance of aeolian materials in southern South America. *Aeolian Research* 2, 33-48.
- Tsoar, H., Pye, K., 1987. Dust transport and the question of the desert loess formation. *Sedimentology* 34, 139-153.
- Turner, J. C. M., 1973. Descripción geológica de la Hoja 11d, Laguna Blanca. *Boletín 142, Servicio Nacional Minería Geológico*, Buenos Aires, 444 pp.
- Ujvari, G., Kok, J. F., Varga, G., Kovacs, J., 2016. The physics of wind-blown loess: Implications for grain size proxy interpretations in Quaternary paleoclimate studies. *Earth-Science Reviews* 154, 247-278.
- Vargas Aranibar, A., Niederle, H., 2010. Relevamiento de la disponibilidad de recursos hídricos superficiales de cuenca Salar de Pipanaco, Cuenca Abaucán-Colorado-Salado y cuencas faldeo oriental del Ancasti. Informe final, INA Centro Regional Andino, 546 pp.
- Vargas, G., Ortlieb, L., and Rutlant, J., 2000. Aluviones históricos en Antofagasta y su relación con eventos El

- Niño/Oscilación del Sur. *Revista Geológica de Chile* 27, 2, 157-176.
- Vargas, G., Rutlant, J., Ortlieb, L., 2006. ENSO tropical - extratropical climate teleconnections and mechanisms for Holocene debris flows along the hyperarid coast of western South America (17° - 24°S). *Earth and Planetary Science Letters* 249, 467-483.
- Ward, P. J., Kumm, M. and Lall, U., 2016. Flood frequencies and durations and their response to El Niño Southern Oscillation: Global analysis. *Journal of Hydrology* 539, 358-378.
- Wright, J. S., 2001. "Desert" loess versus "glacial" loess: quartz silt formation, source areas and sediment pathways in the formation of loess deposits. *Geomorphology* 36, 231-256.
- Zárate, M. A., 2003. Loess of southern South America. *Quaternary Science Reviews* 22, 1987-2006.
- Zárate, M. A., Tripaldi, A., 2012. The aeolian system of Central Argentina. *Aeolian Research* 3, 401-417.
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