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First data on volume and type of deflated sediment from Southern Puna Plateau and its role as source of the Chaco-Pampean loess

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ABSTRACT

This paper presents the first attempt at qualitatively and quantitatively evaluating the sedimentary contribution of the Puna plateau to the loess and soils of the Argentinean Pampas. The origin of the Pampean sediment has been traditionally ascribed to northern Patagonia, but new evidence supports a dual supply: western Central Andes/North Patagonia and Puna/Altiplano Plateau. Three different lines of evidence show here that Puna dust supply is active and produces significant sedimentary deposition up to places like Buenos Aires city. The first evidence is meteorological and we show here one event related to an abnormal rainfall that deposited large quantities of a reddish-brownish silt eroded out from the Puna, calling the attention of the environmental agency of Buenos Aires city. The second evidence is the sampling of active wind transport collecting extremely coarse material carried out in the saltation layer, suggesting the fine grained material escapes the area as fugitive dust. This also demonstrates that observed gravel-bearing bedforms of the Puna are active, and that the transport system seems to be activated by polar fronts only. Results show that the saltation curtain is abnormally thick and coarse, suggesting that the kinetic energy peaks ca. 7–10 times higher than for normal saltation, while the transported grain size coincides with the lagged sediment in this basin composing different bedforms, varying between sandy gravel and gravelly sand. The third evidence is the quantification of the exported material by defining a reference surface as the initial time of evolution, and the present day surface. The initial surface is an alluvial surface of an estimated age of 11–12 ka. BP. Volume balance was achieved by a detailed topographic, stratigraphic and geophysical survey, reconstructing old alluvial and present surfaces. Two gridding methods were used, and more conservative results of the volume balance, indicate a total erosion of ca. 3.386 hm^3 of sediment in 72 Ha, spliced in 0.963 hm^3 of sediment that was left within the place forming gravel dunes, while the remaining volume of ca. 2.423 hm^3 is sediment truly exported from the surveyed area. Results imply a continuous blanket of ca. 4 m thick of sediment exported out of this basin in the Holocene. These findings prove that the Puna contribution to the Chaco-Pampean plain is significant, although not unique. Thus, true proportions of sediment contribution to soils and loess from these multiple sources should be better evaluated in future studies.

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1. Introduction

The loess of the Pampa region (Argentina) is the most extensive in the Southern Hemisphere. The Pampean Aeolian System, generated during the Last Glacial Maximum, is the best representing Quaternary aeolian systems of South America, covering more than 600,000 km^2 in the central Argentine plains (Fig. 1a; Iriondo and Kröhling, 2007). The northern part of this system comprises a loess belt, ca. 2000 km long and 300 km wide, bordering a large sand sea to the southwest (Iriondo, 1990). Based on luminescence datings, the most representative loess units of the Pampa region comprise ages between the end of the Marine Isotopic Stage (MIS) 3 to the end of the MIS 2 (Last Glacial Termination). The identification of the loess sources contributes to the analysis of environmental conditions, especially those related to the dominant wind patterns during that period.

First sedimentological and geochemical data (Teruggi, 1957; Iriondo, 1990; Zárate and Blasi, 1991; Kröhling, 1999; Morrás, 1999) suggested multiple source areas for the Pampean loess,

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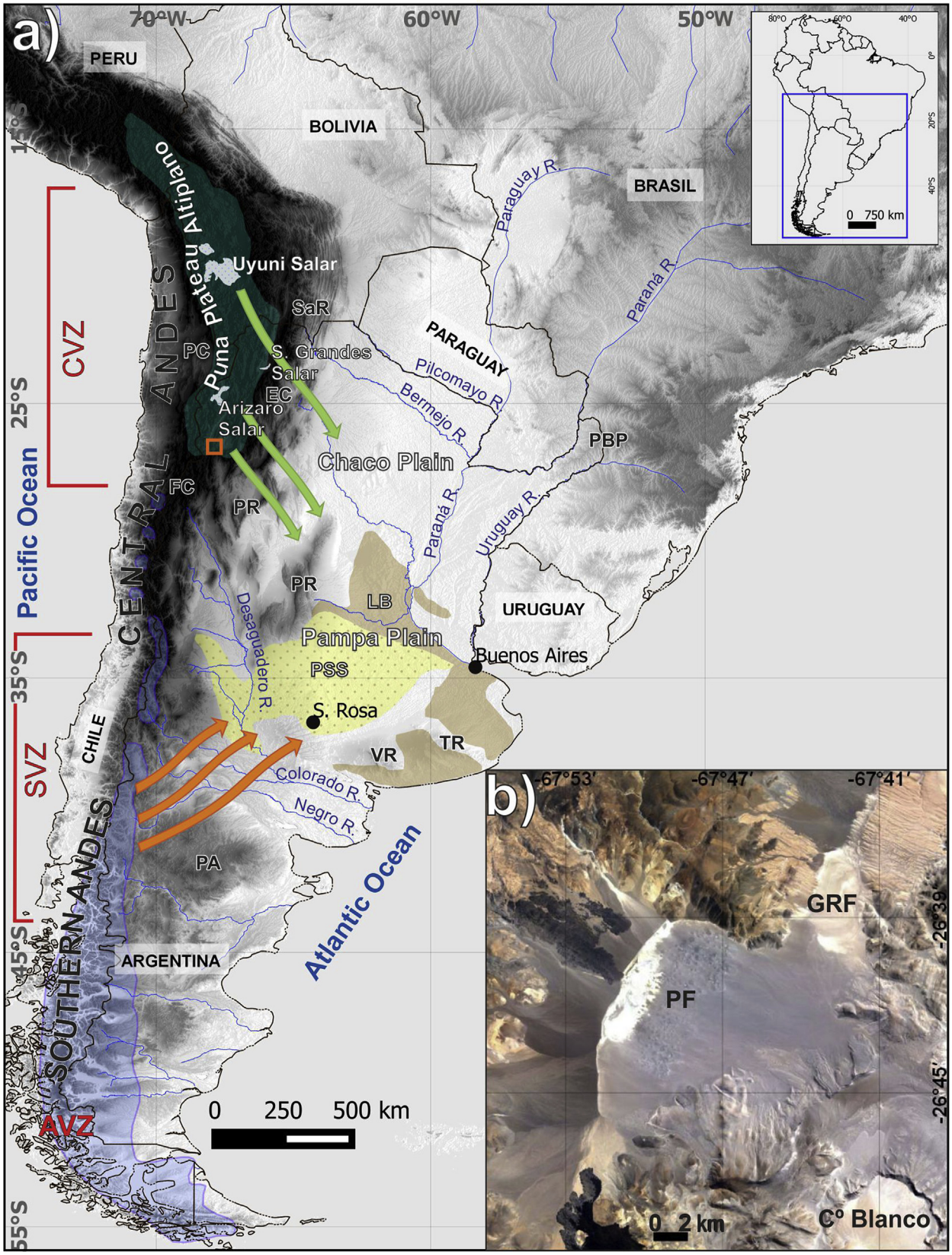


Fig. 1. a) Location map in shaded relief map (DEM-SRTM). The location of the study area is marked by the orange quadrate at the southern area of the Puna-Altiplano Plateau. General pattern of the Pampean Eolian System during the LGM taken from Iriondo and Kröhling (2007): LB: Loess Belt and PSS: Pampean Sand Sea. Arrows indicate the trajectories of dust from the main source areas to the Chaco-Pampa Plain. Andean icefields during the LGM are mapped in blue. Abbreviations of geologic provinces: PC: Principal Cordillera, SaR: Sub-Andean Ranges, EC: Eastern Cordillera, FC: Frontal Cordillera. PR: Pampean Ranges. PBP: Paraná Basaltic Plateau. PA: Patagonia. VR: Ventania Range. TR: Tandilia Range. Areas of Quaternary volcanism (Clapperton, 1993): CVZ: Central Volcanic Zone; SVZ: Southern Volcanic Zone; AVZ: Austral Volcanic Zone. **b)** Inset of satellite image of the study area extracted from Google Earth showing the gravel megaripple fields in the Purulla area (Puna Plateau). PF: Purulla MR field. GRF: Giant ripples field. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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although it was mainly linked to a North Patagonian source due to several lines of evidence. The first evidence is the worldwide known presence of strong winds (Westerlies) that although usually are directed eastward, periodically turn into a North-East direction. The second evidence is the existence of large troughs, 50–70 m deep, which are elongated WSW-ENE, located in the Santa Rosa city area (La Pampa Province), central Argentina. In fact, many lakes are located along these depressions and their design leaves no doubt about their deflation origin (Stutz et al., 2014). The third is the widespread presence of draas and linear dunes showing an advance from SW, indicating that there was copious transport from the northern Patagonian Andes and foothills into the Argentinean Pampas (Iriondo, 1990; Zárate and Blasi, 1993; Iriondo et al., 2011, among others).

Iriondo and Kröhling (1996, 2007) indicated that the primary source of the materials of the Late Pleistocene-Early Holocene loess was generated by physical weathering in a periglacial environment of the Central Andes. Fine sediments were transported by meltwaters to the South along the Cordilleran piedmont by the Bermejo–Desaguadero–Salado fluvial system (Fig. 1a). This system has tributaries draining Andean source regions dominated by Tertiary volcanic rocks. Such materials spreading out in terminal sand flats and alluvial plains constitute the direct source of fine sediments which were deflated by southwesterly winds blowing from the northern Patagonian cordillera and reaching the Pampa region. The sand sourced from these sedimentary bodies is excepted from debate, as there is strong evidence that they contributed the bulk of the sand units in the southern Pampa, forming dune complexes of a morpho-sedimentological system defined as the "Pampean Sand Sea" (Iriondo and Kröhling, 1996). Zárate and Blasi (1993) refrained from designating the Bermejo-Desaguadero-Salado as a main source of alluvial materials. Instead, they referred that the extensive alluvial plains of the Negro and Colorado Rivers (Fig. 1a) would have supplied large amounts of fine-grained clastic sediments and subsequently would have been driven northwards by southerly and southwesterly winds to the southern Pampa during glacial times. The general SW-NE trend in grain size decreases throughout the Pampean Aeolian System and the high participation of volcanoclastic materials support the Andean piedmont/Northern Patagonia source. Isotopic data also proved this source (Smith et al., 2003). Secondary sources were Paleozoic-Mesozoic metamorphic-igneous rocks from the Córdoba Pampean Ranges and the Paraná River basin in the northern Pampa (Iriondo and Kröhling, 1996, 2007; Kröhling, 1999; Morrás, 1999), and Ventania and Tandilia Ranges (Zárate, 2003) in the southern Pampa, mainly through the deflation of fine materials of floodplains and alluvial fans. The contribution of fine pyroclastic materials from Andean volcanoes was also considered (e.g. Zárate, 2003; Iriondo and Kröhling, 2007).

However, the dust provenance building the Pampean loessic soils, famous for being highly fertile due their large content of first cycle minerals, might be another story as the distribution systems is not necessarily the same: while sand tends to move near the ground, dust could well move at stratospheric levels. Thus, those sediment fractions use different wind pathways of distribution. In fact, dust sourced from the alluvial fans located in the foothills of the Andes would probably be multicyclic, thus first cycle loess should be contributed directly from the northern Patagonian volcanic eruptions, However, again these eruptions would provide low volumes as the transport into the Pampas is quite occasional, and its reworking might already provide weathered grains due to the effect of the humid weather reigning in northern Patagonia. Therefore, looking at a second and perhaps the main source of dust for the loess formation in the northern Central Andes has received special attention in the last years, since all deflation structures there are clearly pointing to the Pampas. Moreover, the average altitude of the Altiplano-Puna Plateau (Central Andes; Fig. 1) (4000–4500 m a.s.l.) creates perfect conditions for placing the dust in direct suspension in the atmosphere, where the winds progress linearly to the Southeast, sometimes moving in a completely different direction from the low-level winds near the surface (0–2000 m a.s.l.). The second interesting aspect from the Altiplano-Puna Plateau is its hyper-aridity that would inhibit the mineral weathering due to the general lack of water. Consequently any resuspended material exported out of older volcanic or volcanoclastic deposits would appear to be first cycle.

The source of materials in the Pampean loess related to the Central Argentine-Chilean Andes (Altiplano-Puna Plateau) was first proposed by Bloom (1990), based on the existence at the present day of high velocity tropospheric winds that cross the Puna Plateau transporting dust released by weathering processes in a NW-SE direction over long distances. According to Clapperton (1993, pp. 183–215), such winds would have existed throughout the Quaternary, augmented during glacial times by katabatic winds generated by mountain ice caps. Transport of fine materials to the Chaco-Pampean plains would have also involved the subtropical westerly jet stream, which crosses the Andes at about 25°S (Clapperton, 1993). There, wind velocities may exceed 25 m/s, more than four times the threshold for entraining sand grains. The regional airflow may be locally accelerated through turbulent vortices induced by the passage of the airstream around neighboring stratovolcanoes and by flowing across the abrupt changes in slope produced in this tectonically active region (Goudie and Wells, 1995). Focusing in the southern Puna Plateau (25–27° S and 68°30′-66°30′ W), the region has been individualized among different regions of the world for showing the most impressive effects of aeolian erosion for several decades (Wells and Zimbelman, 1989). The yardangs and aeolian scars are so impressive that they have been compared to the huge effects of wind erosion on Mars (e.g. de Silva et al., 2010; Milana, 2009; Milana et al., 2010a). Hence, the Puna region has great potential for analogue studies linked to depositional and erosional aeolian processes.

Early research of NW–SE trending linear geomorphic features within the Altiplano–Puna volcanic complex (APVC; Chile and Argentina; Fig. 1a) done by Greene (1995) identified most of them as yardangs elaborated on a Late Pleistocene ignimbrite-dominated landscape. Goudie and Wells (1995) determined that numerous small depressions, salt flats and large playa basins are currently being excavated by wind erosion in the Altiplano-Puna. A veneer of freshly-deposited aeolian material is a constant feature extending from the leeside margins of many salt flats (Goudie and Wells, 1995). They also cited the existence of impressive yardangs and other wind-fluted surfaces, along the rim of the Potrerillos Depression (Chilean Altiplano) indicating a formative northwesterly wind.

The Puna-Altiplano source of materials of the loess sequences in a small inter-montane valley (Tafí del Valle) in Tucumán, northern Pampean Ranges (Argentina), was also suggested by Wagoner (2000) and Smith et al. (2003). To the Northeast, Iriondo (1997) describes a Last Glacial Maximum (LGM) loess unit, covering a large part of the western Chaco region and the eastern slopes of the Sub-Andean Ranges in northwestern Argentina and southern Bolivia (Fig. 1a). Iriondo (1997) interpreted that sediments of the floodplains of the Parapetí, Pilcomayo and Bermejo fluvial systems were deflated by northerly winds and transported to the Chaco region. Easternward, Iriondo and Kröhling (1997, 2007) described the tropical loess, an aeolian fine-grained deposit, mainly LGM in age, covering the Paraná Basaltic Plateau in eastern Paraguay, northeastern Argentina, southeastern Brazil and northern Uruguay. Those authors proposed the materials of alluvial plains of large rivers (Paraná, Paraguay and Uruguay) as one of the main sources of

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the tropical loess, but a Puna Plateau source is very probable.

Smith et al. (2003) examined the source regions of Argentinean loess from five loess locations (28–38°S) based on geochemical data. They concluded that Sr-Nd isotopic data from the loess north of 37°S are distinct from Patagonian loess compositions, indicating a northward change from Patagonia-like rare-earth element patterns and isotopic values away from volcanogenic signatures and towards those that are more like the continental crust. Results from Smith et al. (2003) are consistent with the conclusions of previously- cited authors that multiple sources are involved, also including the Chilean Altiplano Plateau as a source for the North Pampa-Chaco loess accumulation. According to Gaiero (2007), a mixing isotopic model between dust exported from Patagonia and the Puna-Altiplano Plateau-like sediments reproduce the composition of the Argentine loess well.

Prospero et al. (2002) examined the Total Ozone Mapping Spectrometer product (TOMS, sensor on the Nimbus 7 satellite) to map the global distribution of absorbing aerosols over a 13-year period (1980–1992) and discriminate major atmospheric dust sources. In South America, the dust sources regions identified by the authors are the Altiplano in Bolivia (at 20°S and 67°W, centered directly over the Uyuni and Coipasa Salars) and two source areas in Argentina, with a moderately well-defined seasonality and geometry and a considerable transport in the winter months. These areas are: the northeastern of Patagonia (38°- 48°S, mainly comprising the Somuncurá Plateau) and the region located along the eastern flanks of the Andes, western Argentina (27°-34°S, comprising the Bermejo-Desaguadero-Salado fluvial system). Recently, Gaiero et al. (2013) provided a first description of the sources, extension of the dust cloud and deposition of two major dust events (July 2009 and 2010) originating from the Puna-Altiplano Plateau occurring in an extended drought associated with La Niña conditions (El Niño-Southern Oscillation –ENSO- cycles, a large-scale climatic phenomena originated in the tropical Pacific through interactions between the ocean and the atmosphere). Chemical composition of sediments from potential dust sources shows distinct signatures within the plateau, being the Puna sector (northwestern Argentina) clearly different from the Altiplano (southwestern Bolivia). In addition, both sources are markedly different from the Patagonian chemical fingerprint (Gaiero et al., 2013).

Despite the enormous evidence of wind erosion, defining the type, timing and approximate volume of exported material out from the Puna Plateau, could be a very difficult task due to the lack of data or instrumental measurements on the location. This paper presents the first data to evaluate this process, by studying the type of material being placed in transport by the wind, and initiation of quantifying the type and amount of sediment exported out of the Puna, by using a small but well-known training area (Fig. 1a and b).

2. Geological setting

The Puna-Altiplano Plateau is a major geologic province at the southern end of the Central Andes structural domain. It is the second largest plateau on Earth, ca. 1500 km long and 300 km wide, an average surface elevation of ca. 3700 m a.s.l. The plateau comprises broad depocenters separated by meridional-trending mountain ranges, often in excess of 6000 m a.s.l. These sedimentary basins are presently internally drained and contain thick sequences of continental evaporites and clastic deposits (Alonso et al., 2006). The Central Andes blocks westbound moisture-bearing winds, generating humid eastern sides and aridity within the plateau. The Puna-Altiplano region causes summertime climate and atmospheric circulation over northwestern Argentina to be governed by the South American monsoon system (e.g., Zhou and Lau, 1998). The region is also dominated by a subtropical high-pressure anticyclone (Bolivian High) and a low-level trough (Chaco Low, Garreaud et al., 2003). El Niño and La Niña events (ENSO) can modify this pattern, being the major sources of interannual climate variability over South America.

According to Tchilinguirian and Olivera (2014), the landscape of the Southern Puna (24–27° S and 66.3–68° W) is characterized by high altitude (ca. 3400–4600 m a.s.l.), endorheic drainage, and a "flatter" topography in comparison to the neighboring regions. It is formed by ignimbritic rocks (Mio-Pliocene) associated with volcanic calderas. Tectonic depressions of the plateau are occupied by shallow or dry hypersaline lakes (salars) and Plio-Quaternary alluvial fans. The aridity of the Southern Puna is due to a combination of the extreme rain-shadow effect of the eastern margin of the circum-Puna Cordillera, blocking the advection of subtropical moisture from the Atlantic Ocean and the Amazon Basin and moisture related to the South Atlantic Convergence Zone during the summer. This adds to a mid-latitude tropical desert geographic position, a limited influence of advection of moisture from the South and southwest due to the presence of semi-permanent South Pacific Anticyclone, and the constraint of the eastern penetration of Pacific moisture by the cold Humboldt Current (Salati et al., 1979; Vuille et al., 2003).

The Pururulla depression in Southern Puna (Fig. 1b) represents a unique natural laboratory for the development of extreme aeolian landforms. It is located to the East of the largest tectonic depression of Southern Puna (Peinado-Antofalla Salar alignment), in the province of Catamarca (Argentina). The Pururulla internally-drained basin is mainly filled by Late Pleistocene pyroclastic deposits, bounded by volcanic and metasedimentary rocks. The basin is controlled by evaporation, and comprises a playa salt lake (Pururulla lake; 3800 m a.s.l.). The southeastern limit of the basin is formed by the La Hoyada volcanic complex (Pliocene to recent; 4100 m a.s.l.). The basin comprises an uncommon aeolian field formed by coarse gravel bedforms (megaripples and dunes) called the Pururulla aeolian field (ca. 80 km^2; Fig. 1b; Milana, 2009). Deflation has partially removed a pre-existing alluvial cover in most of the basin, exposing the Pururulla (ca. 23 ka. BP) and El Médano (ca. 12 ka. BP) rhyolitic ignimbrites (Arnosio et al., 2008). Both ignimbrites are poorly unconsolidated and show deflation corridors of 20–25 m deeply-excavated during the Holocene (Milana et al., 2010a). The central and eastern parts of the basin is entirely covered by medium-scale megaripples, mainly composed by gravels of dense lithics (volcanic and metasedimentary clasts up to 2.5 cm in diameter, and density of 2.5 g/cm^3) and coarse low-density pumice clasts (up to 5–5.5 cm in diameter, density of 0.9 g/cm^3). Megaripple (MR) trains have ca. 15 m wavelengths and 60–80 cm amplitudes on average. Upwind MR slopes are 10°–15° and are capped by well-sorted darkly-varnished volcanic pebbles with a predominant (80%) mode at 6–10 mm. Lee faces dip 22°–25° near the crest, decreasing rapidly to 10°–15°, showing more light-density pumice gravel and sand as in troughs (Milana, 2009).

First data related to the gravel dunes of the Pururulla field were presented by Milana et al. (2010b, 2011). The authors refer to them as a special type of dune ("aerodynamic dune"), with an atypical morphology and abnormal grain size, which involves a significant amount of gravel of different densities. The longitudinal profile of these gravelly dunes is similar to a yardang, but in this case these landforms are partly constructive and not produced by aeolian erosion. They show a crescentic plain shape, resembling the morphology of a barchan but in this case, the concavity looks windward. The inverted morphology and longitudinal profiles are explained by the action of very strong winds in relation to typical sand dunes.

Milana (2009) describes a minor MR field (giant megaripples

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field; ca. 8 km^2; 3900 m a.s.l., Fig. 1b) located immediately to the northeast of the Purulla Basin and formed by giant MR covering the Late Pleistocene Purulla and Campo de Piedra Pomez ignimbrites. This MR field is flanked upwind and downwind by linear yardangs with a mean spacing of 180 m and 20–40 m relief. These MR are the only giant-scale MR observed in the region and worldwide, reaching up to 43 m in maximum wavelength and 2.3 m in amplitude, while the entire field shows 24 m average wavelength. They show mixtures of two main clast types: dark-colored varnished volcanic clasts and pumice clasts. Conditions of formation and models of the origin of these MR are discussed in Milana (2009), de Silva (2010), de Silva et al. (2010, 2013) and Milana et al. (2010a).

3. Materials and methods

While there is an established concept that sand and dust move permanently across the Puna Plateau, defining if the Puna is only a *bypass* area or an *exporting* area is a totally different issue to solve. If it were a bypass area, the volume entering and exiting the plateau would be roughly averaged. In the bypass option, the sediment created by the erosion of the impressive yardangs mentioned above would be deposited within the same system, preferably on lowlands or at wind protected areas. However, if there is a net export of material, it will be of interest to search for the location of the areas that export more material, in order to understand their long-term dynamics and also to try linking this net export with a receiving area.

Therefore, to understand how aeolian processes work here, different types of measurements in this area were started about 8 years ago. The landscape characteristics already described, suggests there was a net export of fine materials, but as indicated, it is difficult to prove. We followed two main lines of actions at the places where it was hypothesized to be one of the largest sediment-producers, due to the huge amount of loose sediment aeolian landforms observed. The first line was to select a place to actually define a physical time baseline, in order to balance the volume that could be lost from that initial time (preferably very recently) until today. This could be a difficult task since most aeolian erosive features (mainly yardangs) are located on bedrock, so deflation rates would be difficult if not impossible to determine. However, in the Purulla Basin it was possible to define aeolian corridors that break down through a pre-existing alluvial terrace and deflation progressed into a semi-consolidated Purulla/Médano ignimbrite that is reasonably well-dated. For understanding the true distribution of Quaternary units to generate a proper volume balance, the area was studied from ground penetrating radar (GPR SIR 2000 with 200-Mhz antennas, facilitated by the Dirección de Recursos Naturales, province of Salta, Argentina). Complete GPR results are part of a different contribution although a line is included in this contribution. The 3D GPR study helped to define what has been eroded, and what has been redeposited in the time interval selected.

The second line of study focused on defining the type of sediment that is placed in transport locally by the wind. The study of the grain distribution transported by the wind flow was carried mainly to understand if the gravelly bedforms present here are active, which rank among the coarsest and largest in the world (Milana, 2009; Milana et al., 2010a). Nevertheless, the study also helps understanding if the place is actually sourcing material to the air, as if the coarse sediment collected in the installed samplers is similar to the sediment composing the aeolian bedforms, it can be assumed that the finer grained fraction would be placed in suspension at higher levels. Finally, a third line of study was the search for a meteorological phenomena that could show that this region is providing dust to high atmospheric levels, enough to reach as far as the Chaco-Pampa region.

With the objective of checking the active transport of coarse grained sediment related to the gravel-bearing wind bedforms of the Purulla Basin, sampling devices were specifically designed to be emplaced in this area taking into account the following facts: 1) Winds are very strong, and there are many reports they can move heavy material, and destroy many man-made structures (Milana, 2009), 2) Due to the widespread presence of light weight pumice grains and clasts (density of ca. 0.9 g/cm^3) resulting from the extensive outcrops of large Quaternary low-cohesive ignimbrite units, the wind is loaded with large amounts of sediment. There are many records of large boxes filled in a few minutes as testimony. Therefore, the design had to be robust, and selective of the coarsest material, in order to be able to evaluate the true competence and strength of the energy peaks of the wind in this region. The true capacity of the transport system would be quite difficult to evaluate given the verbal reports collected suggesting an overfilled transport layer, thus this parameter was not under investigation.

To create a robust design, we planned to build samplers with metallic plates placed together with continuous welding joints. With the aim of understanding the structure of the traction and saltation carpet as well, they were designed to trap the coarsest grains transported by the wind using the sampler as an aerodynamic trap. Samplers were designed to catch therefore the coarsest and heaviest grain sizes lagged behind the fine grained population that would be removed by the wind turbulence in the sampler. In order to understand the vertical structure of the wind flow, 10 samplers were built one over the other with 12 cm of separation, taking into account the normal saltating curtain is 50–60 cm thick (Sharp, 1964). Each sampling level has an entrance that doubles the size of the exit, so the flow speed should be rapidly reduced forcing deposition of the coarsest particles that need more energy to be kept in suspension. The design was quite unique due to the very exceptional conditions expected to occur in the Purulla area.

It is logical that, due to the design of the sampling tower it would alter the wind structure around it. However, as the intention was to trap the largest saltating grains up to 1.4 m high, we inferred that the inertia of the grain once in the hop would be enough to overcome the effect of flow lines deformation around the trap. Also, in several high-speed photos taken where sand-sized tephra trajectories were visible, they tended to be non-coherent in spite of the unidirectionality of the wind. This large degree of turbulence would help to randomly send the grains in different trajectories, so those with larger mass would not have problems to reach the samplers. The trap indeed affected flow lines as those placed over movable ground were always showing sideway erosion in spite of the medium gravel (clast 3 cm large) of the ground, and in some cases the tower was left entirely over the ground as it was held by 4 long metallic bars introduced deep into the ground. As the intention was a qualitative sampling we evaluated that the effect of the tower on flow lines would not affect the grain trajectories significantly, and the recover material demonstrated we were not wrong.

All samplers were emptied after the first season of winds (usually spanning from May to October) so the results presented here are from the first year of sampling, having located two sampler towers in the named Dune I, at the crest, almost the summit and 100 m downwind over the ridge (Purulla field), and one tower at the giant MR field (Fig. 1b). Particle size analyses of collected samples were carried out by sieving for fractions >31 μm (for half Phi intervals) following standard procedures. A second part of the sample was separated to analyze the proportion of light weight tephra grains and heavier grains/clasts.

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4. Results

Three sources of information are considered in the analysis. These are explained below.

4.1. Modern dust production in the Puna-Altiplano Plateau observed by meteorological tools

We want to draw the attention here of an informally reported meteorological phenomenon in the central Pampean region related to an abnormal rainfall with a brownish-reddish dust, on 19th July 2010. This phenomenon was so unusual in the environmental history of Buenos Aires that the government of the city of Buenos Aires produced an official report about it. Their findings indicated that according to their measurements of atmospheric PM10 particle mass concentrations (particles < 10 μm diameter), the amount would have reached up to 65% of the maximum level allowed (ca. 98 $\mu g/m^3$) thereby, confirming its inorganic origin as supplied from the erosion of a fine grained soil. Saldivar (2010), in a short unpublished report inferred the origin of this dust in Buenos Aires city, concluding it was sourced from the Altiplano Plateau, mainly from the Bolivian Salar de Uyuni (ca. 12,000 km^2; Fig. 1a, being the largest salt flat on the Earth). A particularly strong wind storm affected the Puna-Altiplano Plateau during the day July 17th, which was perfectly recorded by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor on the EOS-Terra satellite, showing impressive dust streaks originated out of most salt pans and playas of the plateau (Fig. 2). Conversely, during the following days, the aerosol mapping tool from the Ozone Monitoring Instrument (OMI) on the EOS-Aura satellite showed a moving cloud of aerosols from the Puna area towards the Pampean region, where the dust cloud interacted with normal clouds enhancing precipitation, as dust particles would help precursor droplets to form (Saldivar, 2010).

Gaiero et al. (2013) presented data of two dust storms, tracing it to the Uyuni Salar (3650 m a.s.l; Bolivia) and the Salinas Grandes Salar (3500 m a.s.l; Argentina; Fig. 1a) in the Altiplano-Puna Plateau and corresponding to July 2009 and 2010 events. These are the first published data related to this intense dust activity generated during an extended drought associated with La Niña (ENSO cycle) conditions over the plateau. Dust monitoring stations located downwind recorded both events, and chemical and textural data were generated by the authors, suggesting a major role for the plateau as a dust supplier. Gaiero et al. (2013) observed that the fine grained population was dispersed over a wide altitudinal band and transported in upper level air masses. The dust cloud mixed with a strong convective system in the Pampean region, and the associated precipitation favored significant deposition of the fine dust, provoking the "red rain" observed over the Pampas and reported earlier by Saldivar (2010). Dust particle size analysis for both events indicated that near the sources, dust samples showed median modes of 12–14 μm, similar to modes observed 1300 km away (Gaiero et al., 2013).

An analysis of meteorological data combined with satellite observations conducted by those authors lead to the estimation of an upper limit of the dust emission rate (25–31 t km^{-2}) produced at the plateau during a single dust storm. Evidence indicates that the dust plume on July 2010 traveled a minimum of 2000 km in less than 24 h with observed wet dust deposition in the Pampas (e.g. in Buenos Aires). Their results indicated that dust deposited by rain over the central Pampas had a mixed chemical composition, with an estimated 60% northern Puna component and 40% southern Altiplano component. This suggests that there was dust activity from additional sources non-active at the time of the satellite pass (Gaiero et al., 2013). Following the authors, satellite data showed the highest concentration of the plume reached heights of ~2.1 km above the Puna-Altiplano surface, at approximately 260 km away from the main dust sources. Once aloft, dust plumes were transported by the westerly subtropical jet streams at a mean height of 7000 m a.s.l., and in about 24 h they reached the central Pampas. Surface analysis showed that particles had a mean grain size of 16 μm when they reached this area. Surface data also showed that when injected at the core of the jet stream, dust particles of up to 70 μm could be transported over long distances (>2000 km) from the source.

Gaiero et al. (2013) also modeled the dust plumes from the 18th July 2010 event. The simulated deposition indicated that more than half of the total emitted dust mass was deposited near the source, while over one-third of the remaining fell over Uruguay and about another third fell over Buenos Aires province; recording the highest deposition rates according to the model. The model predicts significant depositions over most of Paraguay and Uruguay, the southern tip of Brazil, and northwest Buenos Aires, southern Santa Fe and Entre Rios provinces (Argentina), which represents about one-third of the total emitted dust. Also, model outputs for the 2009 event show that the simulated dust plume was mostly advected over Paraguay and southern Brazil.

Accordingly, this registered evidence dispels any doubts that the Puna-Altiplano Plateau is a present-day dust producer instead of a bypass area, and that the dust production is actually centered in the salt-pans or low-level, endorheic basins, comprising alluvial fans containing high proportion of fine sediments. Besides explaining the presence of deep hollows in the plateau that could be well-eroded by wind action, this information supports searching better the wind-erosion intensity of these basins.

4.2. Sampling of the sediment transported by wind in the Puna

Two of the previously described sampler boxes were installed in the Purulla MR field, while another sampler was installed in the Giant MR field near Purulla (Figs. 1b and 3). This contribution reports data corresponding to the first windy season sampled (from 17th March 2010 to 12th December 2010). After collecting the material trapped in the samplers, they were all relocated in order to check possible differences in the transport layer across the basin, and over bedforms and landforms. Subsequent sampling seasons showed that there are years when an enormous amount of sediment is transported (e.g. years 2012 and 2016) whereas in other years (e.g.2013 and 2015), samplers were found almost empty, suggesting transport events are uncommon and a complete year might elapse without a significant reactivation of the transport system. Accordingly, we have observed that in certain areas, our own truck tracks became completely erased over MR crests, while over other areas inside both fields, there was no reworking observed as years passed. In general, we have visited the area at least once a year since 2009.

Results of the grain size analysis are shown by way of compositional triangles (Fig. 4) and a table of basic textural parameters (Table 1). Samplers were set up to collect the creeping population at the lowest sampler, but the effect of the wind at the foot of the structure eroded the bed surrounding the tower. The wind created an erosional hollow ca. 20 cm deep around and below the sampling tower, but thanks to the fixing system, the tower did not collapse downwards nor sideways, but remained elevated from the re-leveled ground (Fig. 3). Thus, the first sampler was unable to sample the creep population but rather is considered to sample the saltating grains lower level population. A graphical view of the coarsest elements of the saltating curtain is shown in Fig. 4. Data collected show two main facts about the local saltation curtain: 1) there is an abnormal structure of the saltation curtain in this area, as there is a quite similar grain size distribution between the

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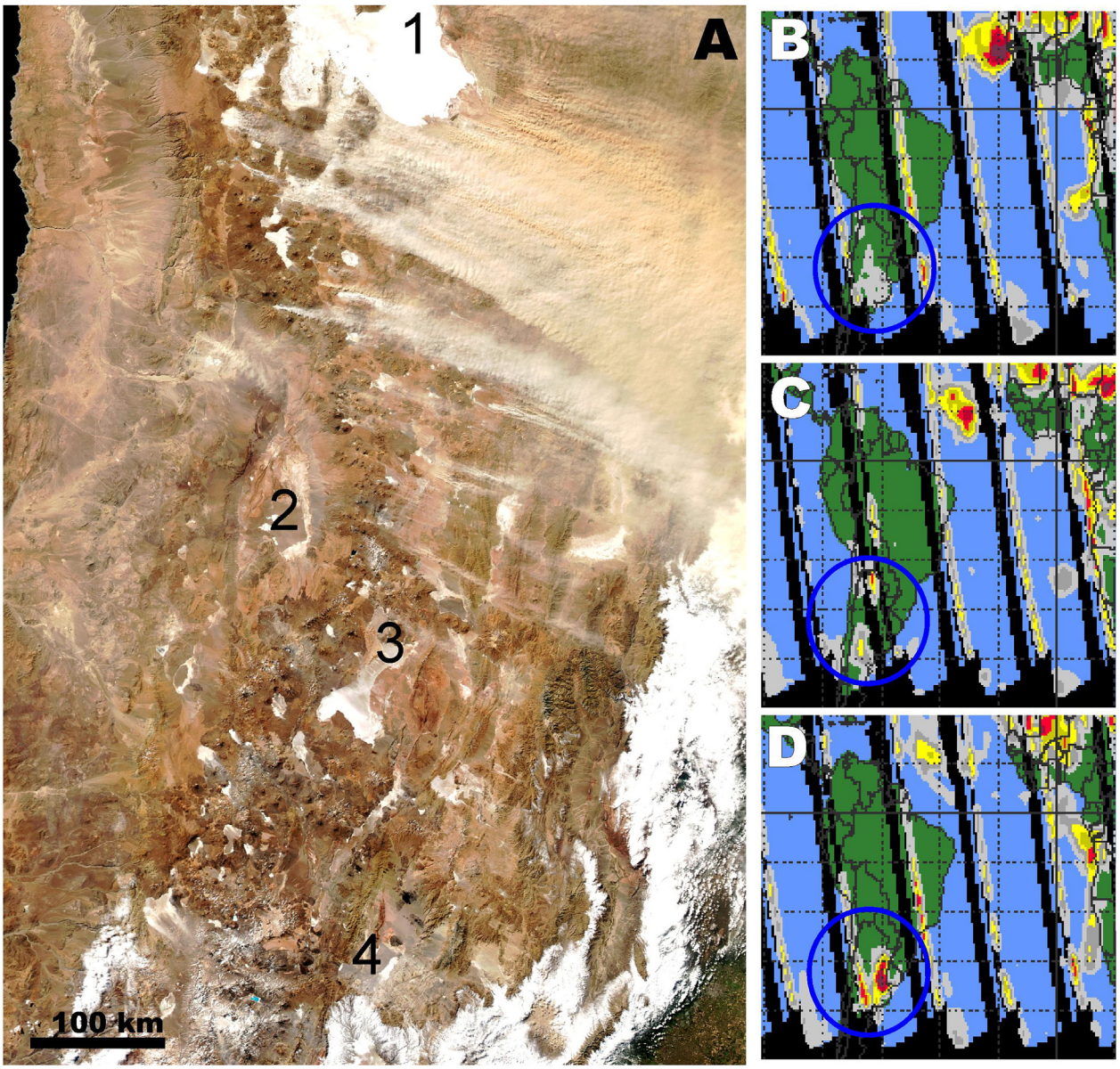


Fig. 2. A) Satellite MODIS image of the wind event producing the dust streaks that were meteorologically linked to the dusty rain recorded in Buenos Aires city and across the Pampas. Note: this wind is produced by fronts that move northward, so in all likelihood, the dust streaks were in the southern area in hours previous to the event. Numbers refer to locations cited in the text: 1: Uyuni Basin in Bolivia, 2: Atacama Basin in Chile, 3: Arizaro Basin in Argentina, 4: Purulla Basin. **B, C, D)** Aerosol index from OMI (Ozone Mapping Instrument) showing average conditions for South America the days 17, 18 and 19 of July 2010. Circle refers to the area of dust lift up at the Puna and deposition at the pampas. On the 17th July the aerosol anomaly at NW Argentina and Bolivia is absent, on the 18th, day of the wind storm develops (see also a dust cloud formed in Northern Patagonia), and on the 19 th the dust anomaly is located over the Pampas where the rain settled it down.

different sampling levels over the 1.40 m vertical sampling; 2) the saltating curtain is basically sandy gravel and gravelly sand. Of course, the last observation is biased to the heaviest part of the population and does not represent the entire population transported by the wind since lighter grains were more favored for moving through the sampler (see above). Yet, results are quite similar to the grain size of the sediment composing the interior of MR and gravel dunes of the Purulla Basin. Thus, results suggest that punctual present transport conditions are quite comparable to the conditions needed to shape the observed bedforms and landforms. Based on these data, it can be concluded that megaripples and gravel dunes are actively evolving today, although probably at slow rates due to the scarce events of coarse-grained wind transport activation as suggested by entire years without collected samples in the towers.

The quite regular composition of the samples at different heights, suggests that the distribution of the kinetic energy in this saltation curtain is very unique. In most saltation curtains the peak of kinetic energy is located at the average height of grains travelling in the transport layer, and is usually between 4 and 12.5 cm (Lian-You et al., 2003). In our case sometimes the lowest drawer (ca. 10 cm high), which should have collected the coarsest material did not show that, while the upper drawer (ca. 1.40 m high) was sometimes gathering the coarsest material. This inversion of maximum grain size with respect to height was better seen for the places where higher wind speed would be expected: at the dune top and at the giant megaripple top. At the dune tail, the structure of the saltating curtain seems to have become quite homogeneous.

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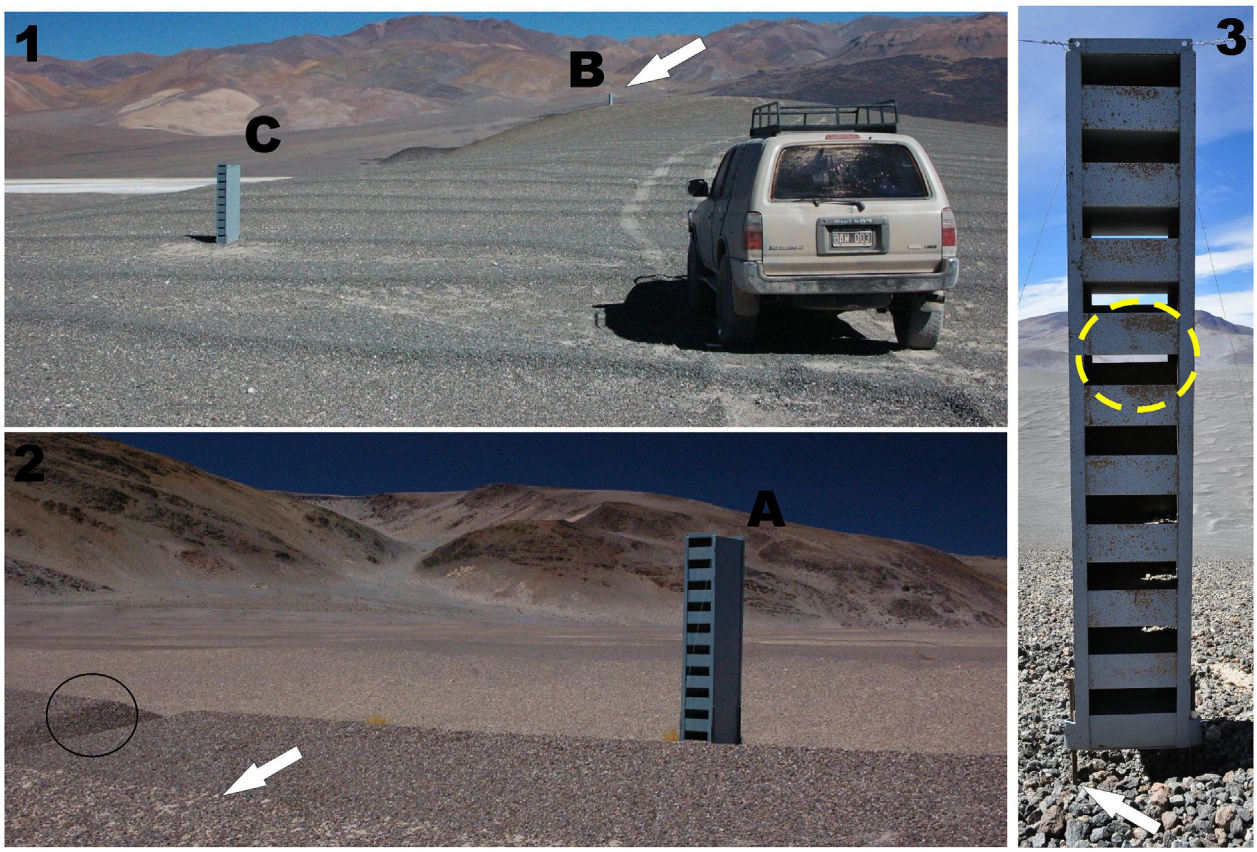


Fig. 3. Samplers deployed at the Purulla Basin, letters correspond to analysis shown in Fig. 4. 1) View of the two samplers deployed at the gravel dune front (arrow, B) and dune tail (foreground, C). 2) View of the third sampler deployed at the top of one giant megaripple, the trench (arrowed) marks the position of the OSL sample published for these megaripples (see Milana et al., 2010a). 3) View of the more intensely abraded paint at ca. 70 cm high (circle) from the ground of sampler B. It was installed to level the opening of the lower cage with the ground but wind eroded the gravelly ground, leaving the heavy tower supported only by the iron poles and wires.

The abnormal structure of this transport system is also indicated by the 'wearing-out' of the sampling tower. The towers were freshly-painted to prevent rust when first time placed at the field. After one season the painted surface became quite worn out, but irregularly. In general, we could document that the painting was more abraded at the height of 60–80 cm above the ground (Fig. 3). Kinetic wind energy in traditional saltating curtains is concentrated when sand transport is active and it is usually estimated measuring the height of maximum abrasion that was estimated as 10–25 cm by some field studies (Sharp, 1964, 1980; Wilshire et al., 1981) while experimental studies report this peak to be three times less (cf. Lian-You et al., 2003; Bridges et al., 2005). By considering that maximum abrasion should occur at the level of peaking kinetic energy, it is clear that the observed maximum abrasion height at Purulla is about ten times the normal height reported both from experiments and in a lesser degree by field studies.

The conclusions of this study, with respect to the sediment wind transport are: 1) wind transport is active and capable to place gravel-sized grains in saltation, 2) the composition of the coarsest tail of the saltating curtain is in complete accordance with the composition of the average internal sediment observed in the gravel dunes which differs from surface sediments. The gravel dunes are covered by an overall protective veneer of pebbles (volcanic and metasedimentary lithics of 2.5–2.6 g/cm^3 specific weight) that becomes dislodged during strong winds and frees material to be transported by the wind. While finer grained material could escape as long as wind energy is strong enough to maintain it at higher levels in turbulent suspension, the coarse grained fraction stays in the basin contributing the macrobedforms as MR and dunes. Meanwhile, the middle fraction (sand) seems to progress episodically towards the East, until reaching the edge of the plateau, where sand is massively deposited and actually drowning entire valleys today (Milana and Peralta, 2012).

4.3. Volumetric balance of a small portion of the Purulla Basin

As previously mentioned, the main problem of balancing the exported material from one region is to define the position of a well-known "Time = 0" surface, and then to define its age. Both issues are complicated if one is investigating a volume loss, as the Time = 0 surface usually disappears as the erosive process proceeds. Therefore, the first attribute of this surface should be that erosion is so irregular that it does not disappear completely, leaving patches to reconstruct the position of that surface. Fortunately, wind erosion tends to be irregular and we fortunately found a suitable surface to work in the basin to perform this experiment. As mentioned before, wind erodes the ground but is not capable of exporting all the material out of the basin: while the dust is sent to upper atmospheric levels, the sand may continue its travel into the next basin, but the gravel fraction is only moved limited distances. In the unique case of Purulla Basin, the gravel has been piled out generating gravelly dunes, whose external and internal geometry is synthetized in Milana et al. (2010b, 2011). These wind-generated gravelly dunes are built by MR as the main building block. There are also micro-scale bedforms as ripples, but they are scarce as

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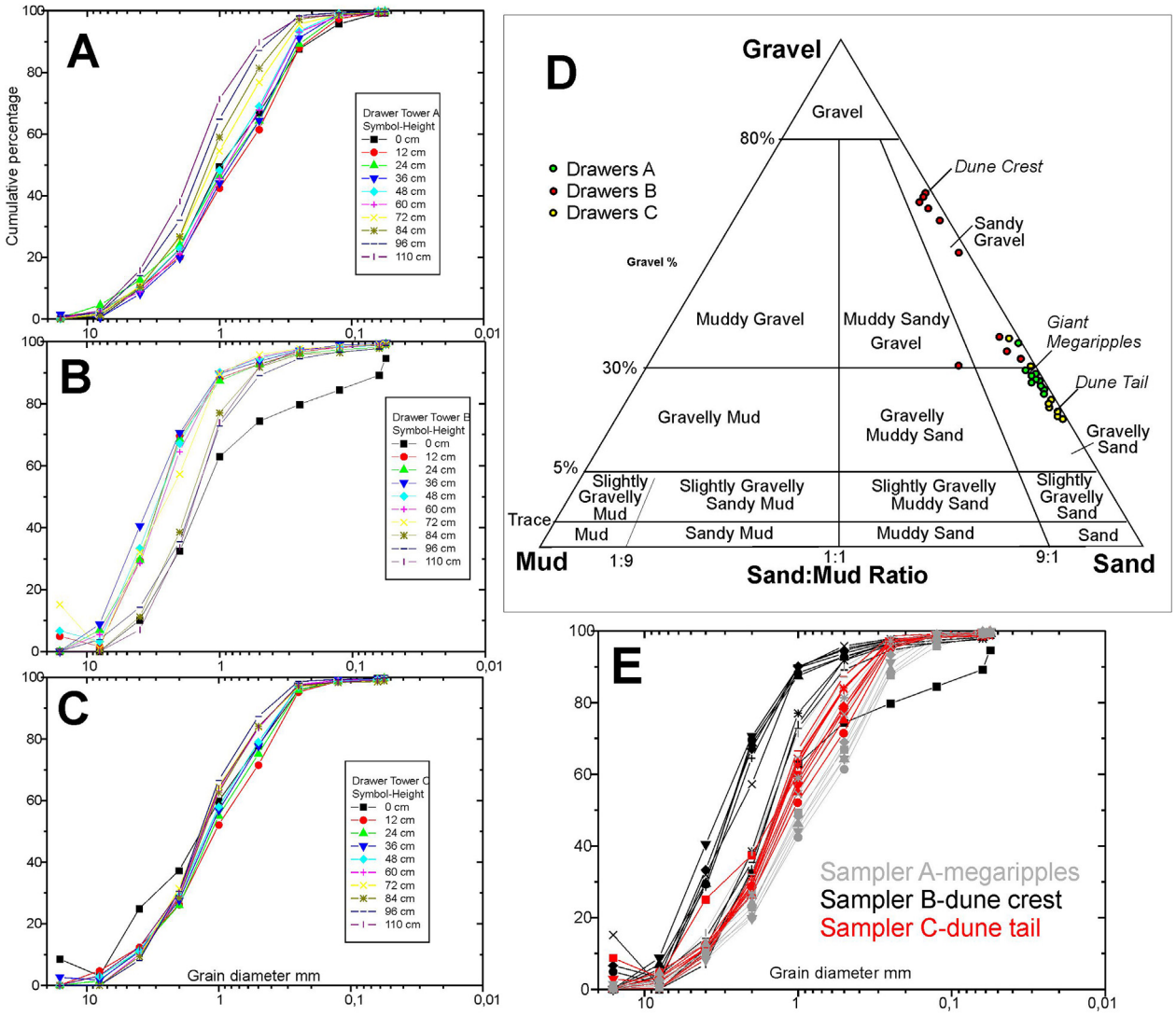


Fig. 4. Grain size results of sediment recovered from the three samplers deployed over the gravelly dune and the giant megaripple, showing that coarsest grain size fraction is gravelly sand to sandy gravel, in coincidence with the internal grain-size composition of the Purulla dunes. A, B, C insets are the accumulation curve of each drawer that refer to the giant megaripple crest (A) the dune front (B) and dune tail (C). D) Plot of all the samples in a triangular diagram defining the name of the sediment. E) Plot of all the grain-size accumulation curves in only one graph.

there is not much free sand, and hence they were not preserved as we observed in the many trenches dug all over the basin to control the depositional modes.

A) The *Time = 0* surface: In our GPR study of the gravelly dunes (showing a steep wind-face and a gently sloping lee face), we could define the existence of a disrupted and very visible surface under the ground that showed also some surface evidence. This surface formed when the basin was more alluvial dominated and hence, the local alluvial systems formed a clear surface over the pre-existing Purulla/Médano ignimbrite at a time that, at least at the margins of the basin, alluvial processes were dominant over the aeolian processes. This surface defines a time at which, at least in marginal parts of the basin, alluvial process were capable to generate a continuous sheet of alluvial gravels. These gravels were sourced directly from the mountain-side bordering the basin, and in addition to reworking pre-existing gravels (of alluvial, aeolian or pyroclastic origin), they brought clast sizes into the basin that cannot be moved by the wind (e.g. over 5–6 cm in diameter). This characteristic, the presence of clasts too large to be moved by the wind, is the best characteristic to recognize the surface but also could led to mistakes due to the potential deflation of the surface and creation of a lag at a lower topographic level. The surface can be recognized by the presence of oversized clasts as the wind locally seems limited to transport sizes up to 3–4 cm in diameter, but alluvial flows show they were losing their competence to the basin interior. Consequently at merely 500–800 m from the mountain side, this surface loses its identity as it maximum grain size becomes of the same range as those moved by wind or freed from the Purulla ignimbrite. This alluvial surface (Fig. 5) lies directly over the top of the Purulla/Médano ignimbrite, or a unit that is the result of the ignimbrite reworking. The pre-Purulla/Médano ignimbrite history is unknown and probably buried at the basin center. The unit reworking the ignimbrite suggest there was a wind-dominated epoch between the ignimbrite deposition and the alluvial surface, but in many sites we observed the alluvial surface lying directly on top of the Purulla ignimbrite. The age of our Time = 0 surface was not available, but the uppermost levels dated on the Purulla/Medano ignimbrite yielded ages between 12 and 15 ka. BP (Arnosio et al., 2008).

During the LGM and the Late glacial the Altiplano-Puna Plateau

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Table 1
Values and descriptions of the statistical data of each sample according to two different methods indicated in the table.

Sampler Tower A (A1 lower, A10 upper)											
METHOD	PARAMETER	A1 - Puna (s/muestra total)	A2 - Puna	A3 - Puna	A4 - Puna	A5 - Puna	A6 - Puna	A7 - Puna	A8 - Puna	A9 - Puna	A10 - Puna
METHOD OF MOMENTS Logarithmic (f)	MEAN	0,41	0,52	0,35	0,47	0,33	0,37	0,09	−0,01	−0,25	−0,41
	SORTING	1,65	1,64	1,68	1,50	1,55	1,52	1,46	1,38	1,37	1,41
	SKEWNESS	0,08	−0,30	−0,31	−0,34	−0,13	−0,23	−0,03	0,05	−0,01	0,44
	KURTOSIS	2,60	2,68	2,45	2,66	2,86	2,88	2,86	3,14	3,05	3,99
FOLK AND WARD METHOD (f)	MEAN	0,39	0,47	0,38	0,46	0,37	0,40	0,09	0,04	−0,25	−0,33
	SORTING	1,63	1,63	1,69	1,55	1,58	1,56	1,46	1,41	1,30	1,29
	SKEWNESS	−0,11	−0,22	−0,22	−0,20	−0,19	−0,20	0,03	0,05	−0,07	−0,04
	KURTOSIS	1,04	1,07	1,08	1,02	1,05	1,05	0,94	0,97	0,99	1,01
FOLK AND WARD METHOD (Description)	MEAN:	Coarse Sand	Coarse Sand	Coarse Sand	Coarse Sand	Coarse Sand	Coarse Sand	Coarse Sand	Coarse Sand	Very Coarse Sand	Very Coarse Sand
	SORTING:	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted
	SKEWNESS:	Coarse Skewed	Coarse Skewed	Coarse Skewed	Coarse Skewed	Coarse Skewed	Coarse Skewed	Symmetrical	Symmetrical	Symmetrical	Symmetrical
	KURTOSIS:	Mesokurtic	Mesokurtic	Mesokurtic	Mesokurtic	Mesokurtic	Mesokurtic	Mesokurtic	Mesokurtic	Mesokurtic	Mesokurtic
Sampler Tower B (B1 lower, B10 upper)											
METHOD	PARAMETER	B1 - Puna	B2 - Puna	B3 - Puna	B4 - Puna	B5 - Puna	B6 - Puna	B7 - Puna	B8 - Puna	B9 - Puna	B10 - Puna
METHOD OF MOMENTS Logarithmic (f)	MEAN	0,44	−1,04	−1,01	−1,23	−1,14	−1,02	−1,10	−0,33	−0,29	−0,25
	SORTING	2,10	1,41	1,49	1,40	1,42	1,33	1,46	1,35	1,51	1,19
	SKEWNESS	0,87	1,42	1,51	1,27	1,29	1,36	0,73	1,42	0,85	1,16
	KURTOSIS	2,65	6,28	6,52	5,54	6,36	6,79	4,85	6,41	4,88	6,10
FOLK AND WARD METHOD (f)	MEAN	0,64	−1,21	−1,20	−1,28	−1,24	−1,19	−1,41	−0,34	−0,30	−0,28
	SORTING	2,27	1,29	1,30	1,30	1,29	1,15	1,38	1,16	1,33	1,12
	SKEWNESS	0,47	0,14	0,14	0,15	0,09	0,05	−0,15	0,04	0,07	0,04
	KURTOSIS	1,04	1,15	1,14	1,08	1,06	0,93	0,88	1,40	1,14	0,96
FOLK AND WARD METHOD (Description)	MEAN:	Coarse Sand	Very Fine Gravel	Very Fine Gravel	Very Fine Gravel	Very Fine Gravel	Very Fine Gravel	Very Fine Gravel	Very Coarse Sand	Very Coarse Sand	Very Coarse Sand
	SORTING:	Very Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted
	SKEWNESS:	Very Fine Skewed	Fine Skewed	Fine Skewed	Fine Skewed	Symmetrical	Symmetrical	Coarse Skewed	Symmetrical	Symmetrical	Symmetrical
	KURTOSIS:	Mesokurtic	Leptokurtic	Leptokurtic	Mesokurtic	Mesokurtic	Mesokurtic	Platykurtic	Leptokurtic	Leptokurtic	Mesokurtic
Sampler Tower C (C1 lower, C10 upper)											
METHOD	PARAMETER	C1 - Puna	C2 - Puna	C3 - Puna	C4 - Puna	C5 - Puna	C6 - Puna	C7 - Puna	C8 - Puna	C9 - Puna	C10 - Puna
METHOD OF MOMENTS Logarithmic (f)	MEAN	−0,30	0,15	0,13	0,02	0,01	−0,06	−0,07	−0,03	−0,14	−0,13
	SORTING	1,75	1,56	1,45	1,44	1,44	1,29	1,34	1,33	1,19	1,41
	SKEWNESS	−0,08	−0,18	0,07	−0,14	0,08	0,39	0,68	0,63	0,47	0,26
	KURTOSIS	2,23	2,84	2,93	3,03	3,18	3,40	4,04	4,18	3,78	3,72
FOLK AND WARD METHOD (f)	MEAN	−0,29	0,12	0,10	0,07	0,05	0,00	−0,02	−0,17	−0,21	−0,03
	SORTING	1,79	1,46	1,41	1,41	1,40	1,34	1,34	1,21	1,17	1,37
	SKEWNESS	−0,11	0,03	0,07	0,06	0,07	0,10	0,12	0,01	0,02	0,08
	KURTOSIS	0,90	0,70	0,87	0,89	0,88	0,90	0,89	0,91	0,91	0,92
FOLK AND WARD METHOD (Description)	MEAN:	Very Coarse Sand	Coarse Sand	Coarse Sand	Coarse Sand	Coarse Sand	Very Coarse Sand	Very Coarse Sand	Very Coarse Sand	Very Coarse Sand	Very Coarse Sand
	SORTING:	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted
	SKEWNESS:	Coarse Skewed	Symmetrical	Symmetrical	Symmetrical	Symmetrical	Fine Skewed	Fine Skewed	Symmetrical	Symmetrical	Symmetrical
	KURTOSIS:	Platykurtic	Platykurtic	Platykurtic	Platykurtic	Platykurtic	Mesokurtic	Platykurtic	Mesokurtic	Mesokurtic	Mesokurtic

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		B1 - Puna	B2 - Puna	B3 - Puna	B4 - Puna	B5 - Puna	B6 - Puna	B7 - Puna	B8 - Puna	B9 - Puna	B10 - Puna
METHOD OF MOMENTS (ϕ)	Logarithmic MEAN	0,444	−1044	−1010	−1226	−1136	−1024	−1105	−0,333	−0,290	−0,253
	SORTING	2102	1414	1489	1401	1417	1328	1463	1352	1507	1190
	SKEWNESS	0,868	1419	1513	1270	1288	1356	0,729	1420	0,849	1160
	KURTOSIS	2651	6282	6525	5543	6365	6790	4852	6408	4876	6101
FOLK AND WARD METHOD (ϕ)	MEAN	0,643	−1210	−1202	−1283	−1245	−1191	−1410	−0,336	−0,300	−0,278
	SORTING	2272	1286	1303	1299	1286	1150	1377	1163	1331	1119
	SKEWNESS	0,470	0136	0,136	0149	0,086	0046	−0,153	0040	0,071	0037
	KURTOSIS	1040	1148	1145	1076	1063	0,927	0877	1403	1142	0,957
FOLK AND WARD METHOD (Description)	MEAN:	Coarse Sand	Very Fine Gravel	Very Fine Gravel	Very Fine Gravel	Very Fine Gravel	Very Fine Gravel	Very Fine Gravel	Very Coarse Sand	Very Coarse Sand	Very Coarse Sand
	SORTING:	Very Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted	Poorly Sorted
	SKEWNESS:	Very Fine Skewed	Fine Skewed	Fine Skewed	Fine Skewed	Symmetrical	Symmetrical	Coarse Skewed	Symmetrical	Symmetrical	Symmetrical
	KURTOSIS:	Mesokurtic	Leptokurtic	Leptokurtic	Mesokurtic	Mesokurtic	Mesokurtic	Platykurtic	Leptokurtic	Leptokurtic	Mesokurtic

was more humid; in that sense many salt pans were lakes and many present day lakes were reaching high stands at 11–15 ka. BP (Clapperton, 1993; Godfrey et al., 2003; Tchilinguirian and Olivera, 2014, among others). Hence, we are confident our Time = 0 alluvial surface, was formed by the hydrological surplus related to the end of the Pleistocene time. As aforementioned by Milana et al. (2010a) the ages of the two samples taken across the dune crest are around the 3 ka. BP. These data imply that the main constructive phase of the gravel dunes took place sometime before now, while evolution may still continues at present, but in a different mode.

B) The surveyed area: Detecting the Time = 0 surface was not an easy task and involved the excavation of many trenches in order to check if the original alluvial surface was present, or if it was a deflation relict of it, and hence located at a lower level. Some preliminary GPR surveys helped to track this surface as it is quite reflective to the radar (Fig. 6) due to the large concentration of extra-basinal clasts contrasting with the almost transparent Purulla ignimbrite and the well bedded and undulating wind MR overlying it, in the cases of aeolian gravel accumulation over the alluvial surface. Therefore, our test was carried at a limited place of 900 × 800 m where, at the marginal basin area the alluvial terrace was still connected with the alluvial fans and colluvial talus of the mountain front (Fig. 5). Further into the basin we could detect the same alluvial surface in several places well distributed across the surveying area. To carry out the survey, a topographic instrument was deployed (a total station with laser rangefinder). Unfortunately, the ground would not reflect the laser beam, so it was necessary to manually transport the mirror all over the entire zone; an arduous task due to altitudinal and climatic conditions of the study region.

The information was then post-processed, gridded and then modeled using two basic different methods: linear interpolation and kriging, producing two irregular surfaces with each modeling method. To evaluate volume losses the first surface was the true topographic surface and the second was a theoretical surface containing all the points surveyed over the alluvial terrace/surface, that would be representing the intersection of it (the Time = 0 surface) and the elaborated present-day aeolian surface. After obtaining surfaces that reasonably represented the field observations, we operated between both surfaces in order to find the negative volume representing the eroded material that disappeared below the alluvial surface and the positive volume (Fig. 7) in cases of accumulated eolian material over the alluvial surface. The positive volume would represent the sediment that could not be exported out of the survey area, but rather remain here to form the conspicuous gravel dunes.

The results of the surface operations show that the modeling of the ca. 72 Ha surveyed indicate a net negative volume loss and therefore of eroded material below the alluvial surface of 3.386 hm^3 using linear interpolation or 4.083 hm^3 using a kriging model. Contrariwise, the positive volume, meaning the sediment that was brought over the alluvial surface, due to a lack of competence, was 0.963 hm^3 using linear interpolation and 1.083 hm^3 using kriging. The resulting volume (cut minus fill) is the net exported material out of this area and yields 2.423 hm^3 using linear interpolation or 3.178 hm^3 using a kriging model. When averaged over the 72 Ha of the survey, these numbers suggest an impressive value of a net loss of ca. 4 m of loose sediment and ignimbrite in the Purulla Basin (ca. 42,000 m^3/Ha).

We have qualitatively surveyed other salt pans to the North; in particular the Arizaro Salar (Province of Salta; Fig. 1a) shows large evidences of impressive recent deflation process. Arizaro is the largest salt pan in northwestern Argentina only ranking behind Uyuni and Atacama salt pans. Although we cannot still quantify the rate of deflation there, our preliminary estimation is an

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approximated loss of about 2 m of ground during the Holocene. This situation is repeatedly observed in many of the salt pans of this plateau; although wind erosion is only possible to discern at the basin margins were the fringing alluvial fan toes enter the salt pans and delineate a reference surface to define the presence of this widespread deflational process. It is clear that an intensive dating plan is needed in order to truly quantify this deflation process, as the deflation evidence is widespread and there is a virtual lack of data on this end.

5. Discussion

The three different types of data presented in this contribution reinforce the fact the Puna-Altiplano Plateau is a real contributor of fine materials to the buildup of soils in the Chaco-Pampa plains and therefore it probably contributed large amounts of material during the formation of the typical Pampean loess units. While nowadays it is not considered an epoch of loessic formation, there is a Holocene loessic unit in the Pampas described by Iriondo and Kröhling

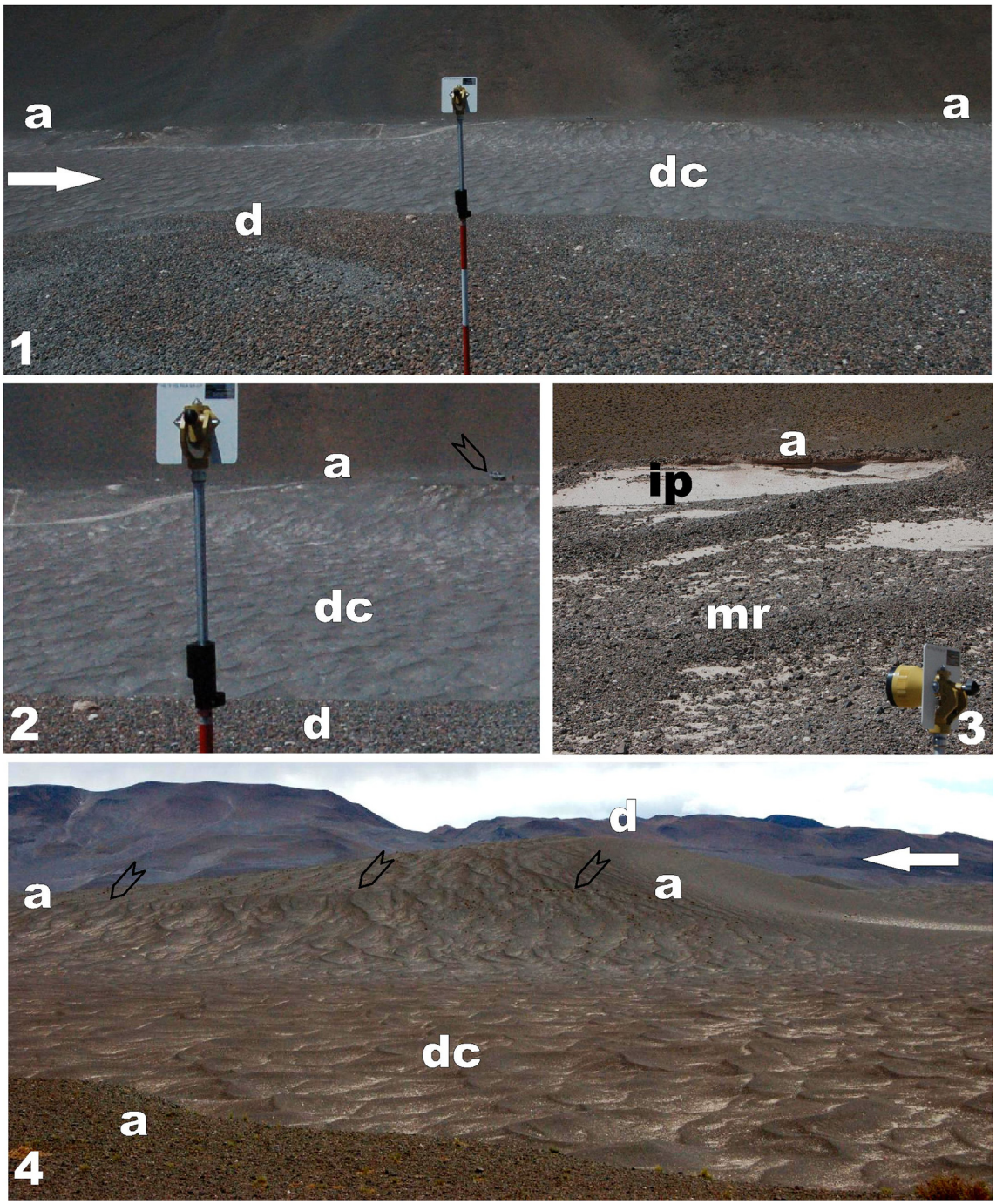


Fig. 5. Photographs of the topographic survey. 1) View to North from the dune (d) of the main station of the Total Topographic Station at the edge of the alluvial terrace (a) eroded to the South by a deep deflation corridor (dc). White arrow indicates dominant wind direction. 2) Enlargement of (1) showing car and instrument measuring pointed by arrow. 3) The alluvial terrace (a) cut showing the Purulla Ignimbrite (ip) and development of megaripples (mr). 4) View to South from the alluvial terrace to the dune of photo 1, where a line can be seen, which is the morphological expression of the same alluvial surface (arrows). All the sediment topographically above that surface was accumulated by the wind as many trenches and GPR profiling proved.

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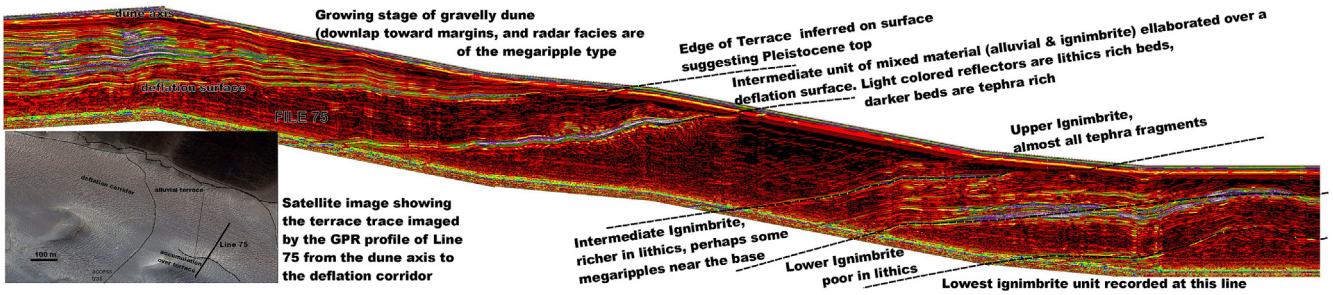


Fig. 6. An example of a GPR line (line 75, showing 150 ns of record, Two Way Travel Time) corrected topographically, showing well defined reflections from the buried alluvial surface elaborated at the end of the Pleistocene over the Purulla Ignimbrite. The ignimbrite shows at least 4 different units, while the upper unit was produced by the reworking of the ignimbrite. The uppermost unit was entirely sectioned in a trench, and it is interpreted as formed by megaripple superposition over the alluvial terrace.

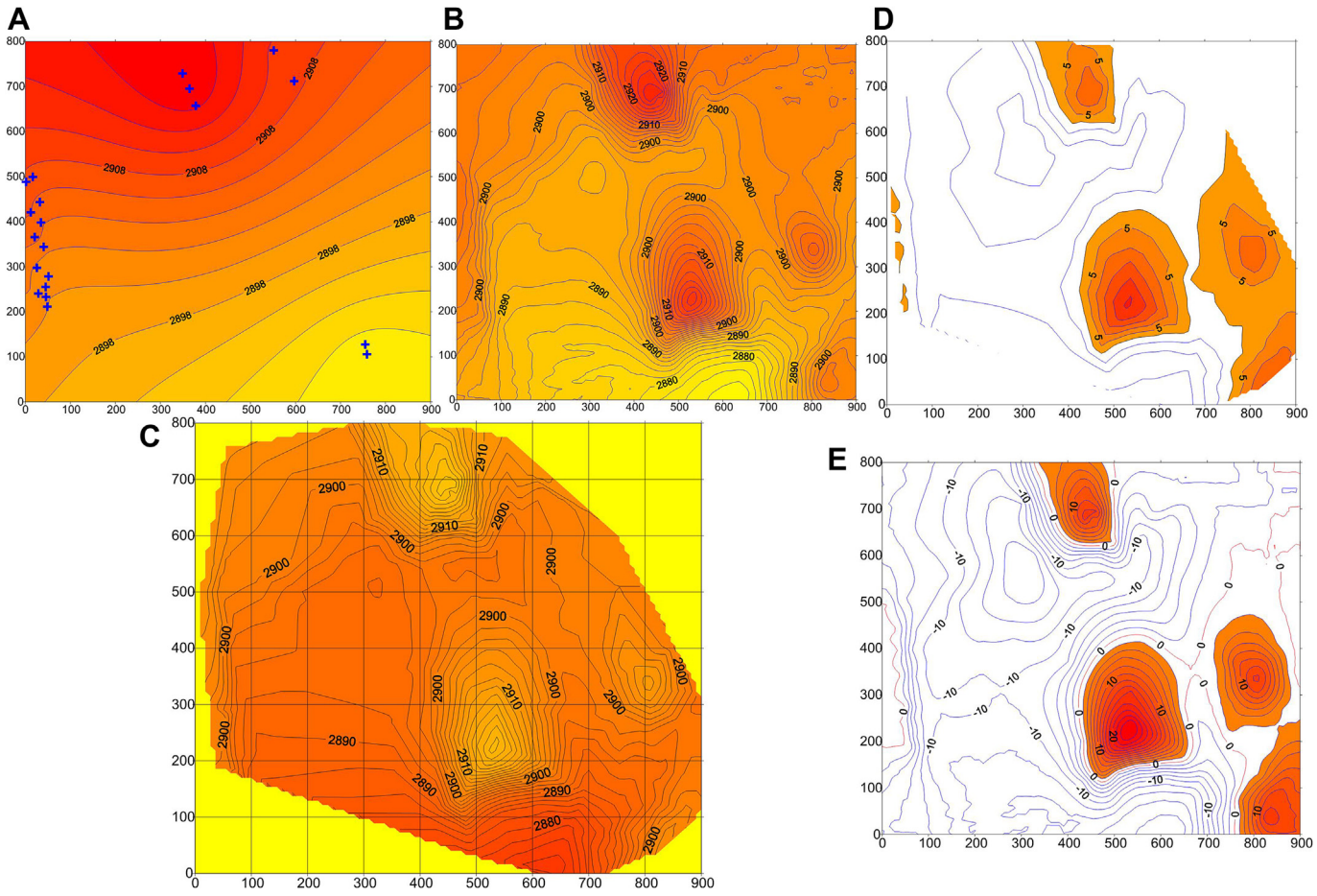


Fig. 7. Results of the topographic modeling of the survey area. A) Map of the old alluvial surface modeled (Time = 0). B) True topographic surface modeled by kriging. C) True surface modeled by linear interpolation. D) Map resulting from subtracting Map C (alluvial Time = 0 surface) and A (actual surface modeled by linear interpolation). E) Map resulting from subtracting Map C (alluvial Time = 0 surface) and A (actual surface modeled by linear interpolation). On maps D and E, accumulative areas are colored (areas located above de alluvial terrace). A tolerance of ±2 m above and below the Time = 0 surface has not been colored, but numbers calculated in the text are more precise. Notice the larger values of kriging may correspond to the fact this procedure interpolates within a rectangular area, while linear interpolation does so only at the surveyed boundary points.

(1996, 2007). This unit implies that during the Late Holocene (ca. 3.5 to 1 ka. BP), loess deposition was more active. Iriondo et al. (2009) also refer an extensive sheet of aeolian silt spreading across the Chaco plains of Bolivia, Paraguay and Argentina, as well as surrounding regions of Brazil and Uruguay. Those authors reconstructed the climatic conditions and proposed the paleo-wind pattern explaining the generation of this loessic unit in a large region that also comprises the Puna Plateau. Given the data presented here, it is not difficult to imagine all the exported dust out from the plateau is continuously adding material to the aforementioned regions.

Accordingly, although the transport system at the Puna Plateau is active, first OSL datings obtained in the Purulla Basin (Milana et al., 2010a) suggest this aeolian megaform defined as gravel dunes, should have been evolved more rapidly at some moment of the Holocene, given the fact they were growing with stronger winds than those recorded today over the uppermost Pleistocene alluvial surface (our Time = 0 surface). Perhaps the main growth of

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these gravel dunes is related to the truncation of the A-horizon of the buried soil by deflation (Holocene *Optimum Climaticum* soil; cf. Iriondo and Kröhling, 1996, 2007) underlying the Holocene loess of the Pampa region. This Holocene loess unit overlying the truncated soil reaches up to 80 cm thick in some places, although in general it shows an average thickness of 40 cm, indicating there was a considerable dust fallout since the 3.5 ka. These data fit very well with the continued deflation observed in the Puna Plateau since that time.

In spite of these findings, the added influence of dust coming from northern Patagonia cannot be denied. In the recent eruption of Puyehue-Cordon Caulle volcanic complex (Chile), and depending on the wind patterns, the ash plume could be observed crossing the humid Pampas all the way, and being visible until the areas of the Buenos Aires city (Collini et al., 2013). This fact proves that both sources are not mutually excluding, as they change according to the dominant wind pattern, a process that occurs intra weekly. In present times, during fair-weather conditions the dust would be supplied from the northern Patagonian areas, while during synoptic phenomena forced by the expanding polar cell (polar fronts), that are usually more active during the Southern Hemisphere winter and spring (May through October), the dust would be supplied from the Puna-Altiplano Plateau to the same area. The present-day main dust activity sources discriminated by Prospero et al. (2002) from TOMS data comprises both major source areas (Southern Puna/Altiplano Plateau and Western Andes/North Patagonia). The observable processes nowadays do not necessarily imply these conditions will remain similar over different epochs, or under different scenarios. As suggested by many elements, dominant wind patterns may have changed significantly over time. A clear example of this is observed at the Paraná Delta, that changes from wave to fluvial-dominated only ca. 2 ka. BP (Milana and Kröhling, 2015). New research along the coasts of Southern Brazil suggests a complete reversal of the longshore currents that would imply a drastic change in the dominant wind direction (Milana et al., this volume). At the same time, in the Purulla Basin itself, it was possible to observe that these Holocene gravel dunes were undergoing a period where dominant winds changed their pattern, producing an accumulation unit over the previous stoss-face, suggesting epochs of complete wind reversal at the Puna Plateau (Milana et al., 2011).

All this evidence indicates that the Holocene history of Southern South America is more complicated than previously thought, and revealing an urgent need for increasing dating numbers of recent units, in order to start reconstructing the puzzle that is the climatic evolution of this region. In this sense, authors believe that these gravelly dunes may store important environmental and paleoclimate information in their depositional history that is only in the early stages of being depicted by detailed geophysical studies.

6. Conclusions

Three different sources of information prove that the Altiplano-Puna Plateau is an effective supplier of fine-grained sediment to the Chaco-Pampa plains, being perhaps the main responsible agent of its fertility due to the large provision of non-weathered, first cycle minerals, supplied mainly from the extensive pyroclastic units present in the plateaus formed among northwestern Argentina, northern Chile and southwestern Bolivia. This contribution does not deny, however, the supply produced from the Northern Patagonia area, as they operate under different climate conditions; the Northern Patagonia supply is brought by normal-weather winds, while the Puna contribution is brought by seasonal synoptic polar fronts, characteristically high-energy wind events. The relative contribution needs to be studied in the light of the known differences in sedimentological and geochemical data aforementioned in the cited references, and studies of volumetric balance. In this sense, this research produced two types of studies to analyze the dynamics and the type of material that wind place in suspension and saltation in the Southern Puna Plateau.

The first study defined the grain size of the sediment transported in order to compare it with the grain size observed in the coarse-grained wind bedforms observed in the Purulla Basin, and to decide whether they are relic or active. The three sampling towers showed that a unique saltation curtain composed of sandy gravel to gravelly sand develops locally, which is the result of the combined effect of very strong winds and widespread presence of light weight grains of tephra (0.9 g/cm^3). This saltating curtain coincides very well with the sediment type found at the interior of the gravelly dunes, though it is finer grained than the gravel veneer that protects gravel dunes and megaripples from being deflated away by low-energy winds. Under strong wind conditions the coarser gravel veneer is dislodged and material is today deflated out from the ground as observed in a few episodes of strong wind. This finding suggests the area is actively exporting fine grained material as was indicated by recent meteorological reports using satellite imagery.

The second study evaluated the volumetric contribution of a basin area to the build up of dunes and to the general sediment export. The most conservative numbers produced by the linear interpolation gridding method, indicated total wind erosion since ca. 12 ka. of 3.386 hm^3 of sediment in 72 Ha. From this volume, 0.963 hm^3 of sediment were deposited locally over the selected reference surface (Time = 0), in the way of dunes, implying that about the 28% of the sediment eroded could not escape from the area. Contrarily, the net sedimentary loss of the area would be 2.423 hm^3. This last figure corresponds to a net loss of a continuous sheet of ca. 4 m thick of ground in the area.

While this is the first attempt to characterize the relation between the aeolian erosion in the Puna Plateau and the deposition in the Chaco-Pampean region, it is clear more data are needed in order to reconstruct the complete regional climate story as well as this deflation and dust export process that is crucially important for the soil recycling in the lowlands. In particular, the lack of chronometric data makes all correlations quite tentative in spite of the important changes that occurred in this region. While authors believe this information is valuable, more research is needed in the area in order to better understand the complicated teleconnections between the Altiplano-Puna Plateau, the Northern Patagonia, and the Chaco-Pampa plain in terms of aeolian processes.

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