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Upper quaternary evolution of the dune field of the Bolsón de Fiambalá, Catamarca: Sand dispersal at the Andes piedmonts

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ABSTRACT

The South American Arid Diagonal extends in Argentina from Puna to Patagonia regions. Several dune fields are scattered between the Andes and Pampas ranges, covering plains and plateaus. One of the northernmost dune fields is occupying the tectonic valley known as Bolsón de Fiambalá (27°S; 67°W) White transverse dunes extend from west to east, climbing to the Fiambalá Range. Some outcrops from the surrounding area allow to understand the evolution of this dune field. At the Chaschuil valley, a profile composed of 4 m of stratified sands and gravels were sampled at Las Lozas site. Epiphytes and benthic diatom assemblages suggest a shallow lake located at 3700 m altitude. Many of these brackish/freshwater aerophilous taxa tolerate desiccation periods and salt concentration. The assemblages were dominated by *Nitzschia frustulum*, *Nitzschia linearis*, *Achnanthes thermalis* var. *rumrichorum*, *Epithemia adnata*, *Pinnularia viridis* y *Nitzschia capitellata*. Limestones from this outcrop were dated on 32,000 ± 520 and 29,380 ± 410 ^{14}C years BP (Garleff et al., 1993), suggesting the Marine Isotopic Stage 3. The Holocene Interglacial is recorded either at the Chaschuil and Abaucán rivers valleys. Lake deposits at 3000 m altitude gave ages between 6175 ± 70 and 2990 ± 70 ^{14}C years BP (Garleff et al., 1993). The sand of this dune field at the northern part of the Bolsón de Fiambalá was supplied by the fanglomerates located to the west, at Medanitos. There is also a significant supply of pumicite, derived from the Cerro Blanco volcanic dome. An aridity increase have been previously recorded from archaeological data and confirmed by the discharge records of the Abaucán River during the 1919–1957 interval. Although these sand dunes with a high content in volcanic glass clearly derived from the Andes, other sand dunes of central Argentina derived from the deactivation of the Desaguadero-Curacó system.

1. Introduction

Fiambalá is a word of the original inhabitants of this region of Catamarca which means *"house of the wind"*. In the valley called "Bolsón de Fiambalá" (27°S; 67°W) there is an extended dune field located attached to the eastern flank (Fig. 1) and composed of white transverse dunes. As this partially closed valley is protected by very high mountains, the dunes migrate specially towards the NE, climbing the Fiambalá Range up to Tatón River valley. The northern area of Medanitos is affected by an intense process of desertification (Rivero and Rivero, 2010) that is enhancing in modern times (Navone, 1998). The region is subject to westerly winds with significant changes from west to east, locally causing episodic changes in air temperature (Puliafito et al., 2015). ENSO effects increased in frequency and magnitude in the 80s and 90s compared to the previous three decades (Garreaud et al., 2009).

Another issue from this region is the climatic changes that originated ancient lakes at altitudes above 3000 m (Clapperton et al., 1997). These facts increase the importance to analyse climate and morphology changes in this area. These changes conditioned the occupation of the region by humans during the Holocene (Mondini et al., 2013; Tchilinguirian et al., 2013; Yacobaccio, 2013).

The purpose of this paper is to analyse the changes in this high-altitude area recorded on sediments, either by the facies sequence as by the diatom-assemblages. The mineralogical composition of these dunes were compared to other dune fields within the South American Arid Diagonal, an area that was suggested as the provenance for eolian deposits (Gili, 2014), particularly those related to the deactivation of the Desaguadero-Colorado watershed.

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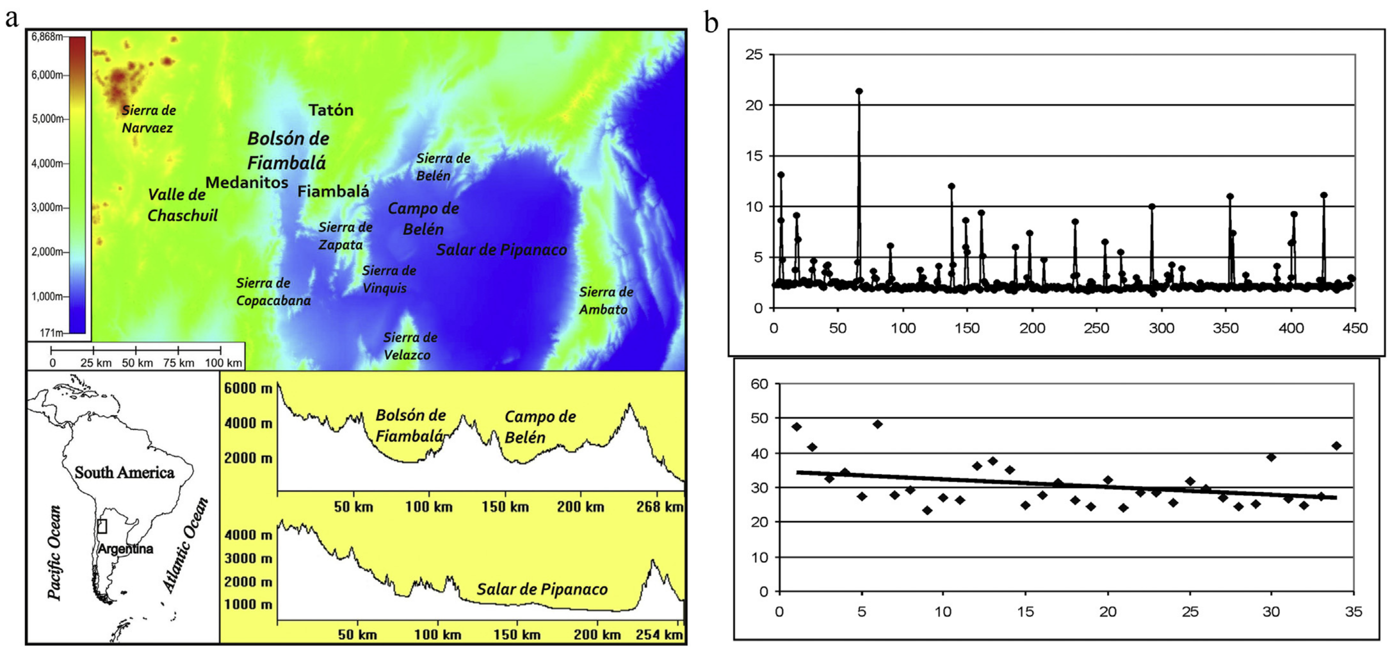

Fig. 1. a. Location and DEM of the Bolsón de Fiambalá. b. Discharges of the Abaucán River during the interval 1920–1957 (in m^3/s).

2. Regional setting

The Bolsón de Fiambalá is a tectonic basin open to the south, surrounded by several ranges over 4000 m height: Sierra de Fiambalá to the East and Sierra de Narváez to the west. The Abaucán River (also called Salado, Colorado or Bermejo) flows from north to south, within this asymmetric tectonic valley (Navone, 1998; Paoli et al., 2011), receiving the Chaschuil and De la Troya rivers from its western side. The watershed is of approximately 28,300 km^2. According to records estimated at Tinogasta, the mean flow of the Abaucán River is 2.54 m^3/s (www.hidricosargentina.gov.ar/93.pdf) with maximum discharges of 84.7 m^3/s (1948–49) and minimum records of 0.96 m^3/s (1941–42; Fig. 1b). The decrease of the discharge in the last years is in accordance with the desertification processes reported (Ratto et al., 2013), although an increase in the vegetation covers was measured (Niz, 2003). Precipitations are extremely low (50–160 mm/yr) and they are exclusively concentrated during the summer. Winds dominate from SSE with velocities between 20 and 70 km/h. The region is characterised by a typical Westerly wind that flow down the Andes called Zonda (Puliafito et al., 2015); this wind loads the atmosphere with dust entrained from the arid soils. The Andes acts as a climatic wall with dry conditions to the west and moist conditions to the east at tropical/subtropical latitudes (Garreaud et al., 2009). Between 15°S and 30°S the filtering topography effect of the Andes is maximum.

2.1. Geology

The ranges surrounding the Bolsón de Fiambalá are composed of different rocks: granites (Sierra de Fiambalá, Sierra de Zapata), high-degree metamorphic rocks (Sierra de Copacabana, Sierra de Zapata), and sedimentary and volcanic rocks (Cerro Negro de Rodríguez, Sierra de Narváez; Carrapa et al., 2006; Castro, 2007; Montero López et al., 2009). The region is characterized by low angle thrusts with earthquakes between 3 and 5 magnitudes (Nóbile, 2013).

Several volcanic and volcaniclastic deposits of Quaternary age were reported from the Laguna Blanca region (Turner, 1973). The lowermost is composed of dacitic tuffs (Laguna Blanca Formation), overlain by andesitic sediments (Negro Carachi Formation), and basalts of Los Rastrojitos Formation (Turner, 1973). Notwithstanding that, the pumicite clasts from the dune field of Medanito-Tatón area are assigned to the Cerro Blanco caldera, Sierra de Buenaventura. This small dome located north of Bolsón de Fiambalá has provided white pumicites with inclusions of biotite, quartz and less percentages of volcanic glass and lithics (Montero López et al., 2005). The last pumicite rain occurred after 5500 years BP (Montero López et al., 2010; Ratto et al., 2013).

At the western side of the tectonic valley, fluvial and gravity-dominated deposits were composed of reddish sands with gravel (Las Cumbres Formation in the sense of Sosic, 1972). Another fan is emplaced attached to Sierra de Fiambalá (Eastern side of the valley) where the thermal springs of Fiambalá are located. The region is subject to frequent earthquakes recorded as convolutions in shallow-lake deposits (Ratto et al., 2013). At the area of Tinogasta, the reddish sediments were reported of Pleistocene age. Another sand field (68 × 15 km) of aeolian origin is attached to the ranges of the East of the valley and extended in a north-south direction. Several papers focus on the wind transport of sediment at this region (Gaiero et al., 2013; Gili, 2014).

3. Materials and methods

A Digital Elevation Model (DEM) was downloaded with a spatial resolution of 90 m from http://srtm.csi.cgiar.com. Altitude information was handled with the Global Mapper v.7.04 program (www.globalmapper.com). Historic Google Earth images were handled to analyse the migration rate of the isolated barchan close to Fiambalá village.

Sand dunes were sampled from the road extending between Medanitos and Tatón (Fig. 1). Sands were sieved every 0.5 phi units and analysed in regard to the ordinary statistical parameters (Folk and Ward, 1957). Grain mineral composition was analyzed under a petrographic microscope. Results were included in a data base in order to manage those using Geographic Information Systems (Arc View) procedures.

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Samples collected from Quaternary sequences were prepared for diatom analysis by oxidation in hot 30% H_2O_2 and 35% HCl to remove organic matter and carbonates, and then rinsed with distilled water. Diluted aliquots of cleaned slurries were evaporated onto coverslips, and mounted onto slides with Naphrax®. Diatoms frustules were studied and estimated in relative abundance values because there was a very low abundance and sometimes it was impossible to count 300 diatom valves necessary to calculate percentages. All counts were performed under oil immersion (1000×), using a Zeiss microscope equipped with phase contrast optics. The identification of species was based on the local and standard diatom taxonomic literature.

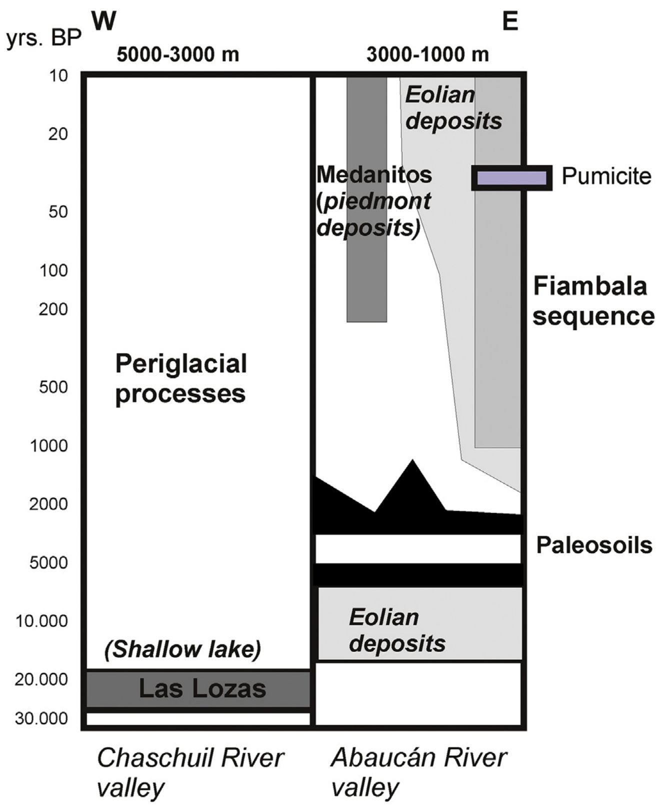

Fig. 2. Sketch of the sequences sampled at the Chaschuil and Abaucán valleys (modified from Garleff et al., 1993).

Radiocarbon datings were calibrated according to Calib 5.0.1 model (Stuiver et al., 2005).

4. Results

4.1. Quaternary deposits

4.1.1. The Las Lozas OIS 3 sequence

At the Chaschuil Valley, in a place called Las Lozas (27°12′58″ S, 68°06′31″ W), a lacustrine sequence was sampled and dated (bulk samples; Garleff et al., 1993). Two samples of lacustrine limestone, located at heights of 30 and 40 m above basin lake-terrace, gave ages of 32,000 ± 520 ^{14}C years BP and 29,380 ± 410 ^{14}C years BP (Table 1; Hv 10,233, and Hv 13,609). Another sample of carbonate-cemented pumice at the bottom of the lake terrace basin gave an age of 15,365 ± 100 ^{14}C years BP (Garleff et al., 1993). Considering these ages, the lacustrine sequence has been deposited during the OIS3 interstadial (Fig. 2). The sequence was described in details (Fig. 3a) and sampled in order to analyze the diatom assemblages corresponding to this OIS3.

The stratigraphic section is mainly composed of coarse gravels and fanglomerates, interbedded by fine sands layers with diatoms. Six samples were analyzed but only four contained diatom frustules. A total of 25 taxa were identified (Fig. 4). The assemblages are dominated by freshwater/brackish species, benthic, aerophilous and epiphytes. *Navicula cryptotenella*, *Nitzschia amphibia* fa. *umbrosa*, *Pseudostaurosira brevistriata* and *Planothidium lanceolatum* are the most important taxa characterizing a shallow environment with the presence of salt. Pleistocene diatom taxa from Las Lozas basin were also found in modern assemblages from high altitude aquatic environments of the Catamarca province (Maidana and Seeligmann, 2006).

4.1.2. The Fiambalá OIS 1 sequence

At Fiambalá village, the Abaucán River cuts Holocene deposits composed of fluvial and aeolian deposits. The 5 m sequence is composed of light-coloured fine sands with many bioturbations interleaved by gravel levels. A pumicite level was detected towards the top of the sequence (Fig. 3b).

Several organic layers were sampled and dated from this alluvial plain (Table 1). At the southern margin of Fiambalá, charcoal form a

Table 1
Radiocarbon dates and calibrated ages, location and references. Calibration was performed using CALIB 5.0.1 (Stuiver et al., 2005).

Location	Localities	Age yrs. BP	Cal. yrs. BP	Lab code-n°	References
27°08′S–68°10′W	Las Lozas	32,000 ± 520	34710–37145	Hv10233	Garleff et al., 1993
	3800 m asl	29,380 ± 410	32405-34269	Hv13609	Garleff et al., 1993
		15,365 ± 100	18352–18798	Hv16410	Garleff et al., 1993
27°44′S–68°11′W	Chaschuil	6175 ± 70	6843–7179	Hv16409	Garleff et al., 1993
	3000m asl	2990 ± 70	2921–3269	Hv10232	Garleff et al., 1993
27°35′S–67°37′W	Fiambalá	430 ± 60	317–520	Hv13606	Garleff et al., 1993
	1620m asl	765 ± 80	549–775	Hv17699	Garleff et al., 1993
	1400m asl	410 ± 55	315–506	Hv17698	Garleff et al., 1993
26°50′54″S–67°47′18″ W	La Hoyada	8830 ± 60	9582–9958	Beta- N1	Montero López et al., 2009
	3646 m asl	8410 ± 50	9252–9503	Beta- N2	Montero López et al., 2009
		8230 ± 60	9005–9310	Beta- N4	Montero López et al., 2009
		5480 ± 40	6175–6296	Beta- N5	Montero López et al., 2009
27°20′09″S–67°51′51″ W	Ojo de Agua	5960 ± 100	6485–7001	AA-OAB02	Montero López et al., 2009
	2400 m asl	5387 ± 45	5994–6221	AA-60922	Montero López et al., 2009
		5040 ± 110	5578–5950	AA-OAB022	Montero López et al., 2009
27°19′57″S–67° 50′57″W	Agua de la	4040 ± 80	4233–4710	LP-LCñ67	Ratto et al., 2013
	Cañada	3810 ± 80	3956–4410	LP-LCñ71	Ratto et al., 2013
	2370 m asl				

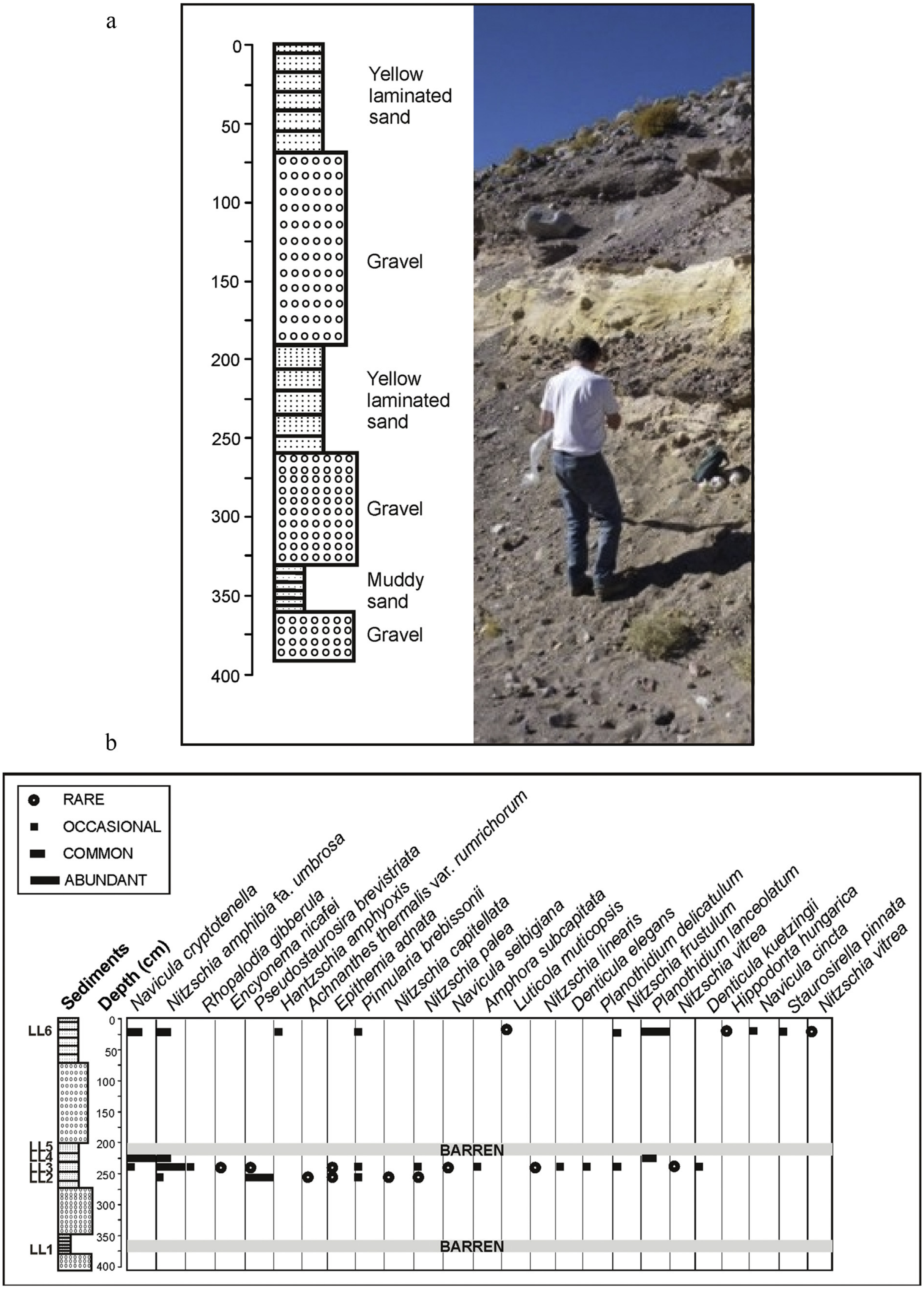

Fig. 3. A. Stratigraphic sketch of the Las Lozas profile.B. Diatom relative abundances from the Las Lozas section.

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soil layer and gave an age of 430 ± 60 ^{14}C years BP (Hv 13,606). At Morteros, two organic layers from the fluvial terrace gave ages of 765 ± 80 (Hv 17,699) and 410 ± 55 (Hv 17,698) ^{14}C years BP (Garleff et al., 1993).

Other Holocene deposits were described from the same tectonic valley separated 55 km each and approximately 100 km from Fiambalá. La Hoyada profile (26°50′54″ S; 67°47′18″ W) is composed of several ash layers about 15–45 cm each, reworked by fluvial processes and interleaved by five peat layers. Four radiocarbon dates indicate that this deposit was originated during the early Holocene: 8830 ± 60, 8410 ± 50, 8230 ± 60 and 5410 ± 40 ^{14}C years BP (Montero López et al., 2009, 2010; Ratto et al., 2013). The Ojo de Agua profile (27°20′09″ S; 67°51′51″ W, 2400 m asl) is located 10 km at west of Palo Blanco. Basal layers are of fluvial origin with a volcaniclastic origin of the sandy layers. Interleaved peats vary between 3.5 and 30 cm width. Radiocarbon ages of these peats gave ages of 5960 ± 100, 5387 ± 45 and 5040 ± 110 ^{14}C years BP (Montero López et al., 2009; Ratto et al., 2013). Agua de la Cañada profile (27° 19′ 57″S; 67° 50′57″W, 2370 m asl) is very close to the Ojo de Agua profile. Pumice and peat layers were dated at younger dates (4040 ± 80 and 3810 ± 80 ^{14}C years BP, Table 1).

At the Chaschuil valley (Fig. 1) -another valley located to the west and about 1500 m over the Fiambalá valley-, layers with molluscs and a paleosoil were dated on 6175 ± 70 and 5960 ± 60 ^{14}C years BP, respectively (Garleff et al., 1993).

4.2. The dune fields

The dune fields of Fiambalá are more extended between the villages of Medanitos and Tatón (Fig. 1). At Tatón, there is a sand ramp of longitudinal and transverse dunes climbing to the hills, and falling towards the valley where the Tatón River sweeps the base of this ramp (Fig. 5). The transverse dunes are asymmetric indicating a sand transport towards N 70 (NE and E).

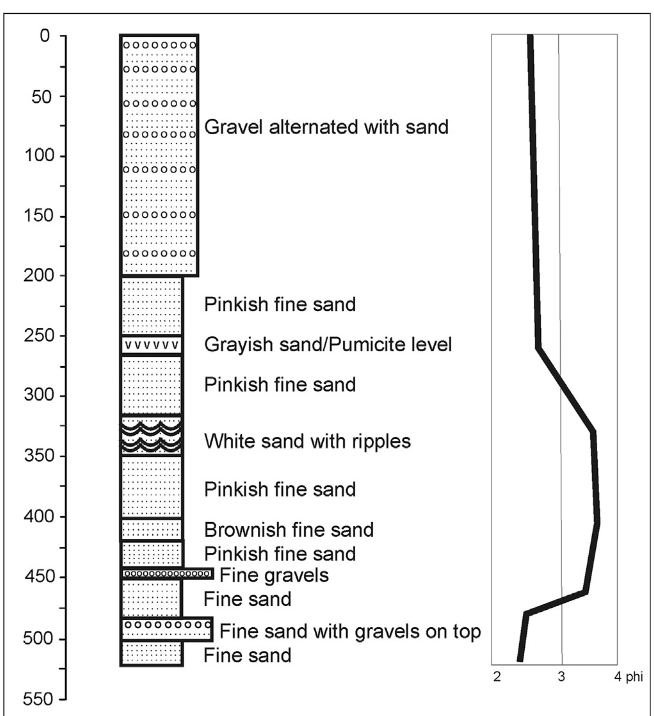

Fig. 4. Stratigraphic sketch of the fluvial deposit at Fiambalá village.

The isolated barchan of Fiambalá is located close to the village, way to the thermal baths of the Fiambalá Mountains (27°41′19″ S; 67°36′09″ W). It is an asymmetric barchan moving towards the NNE at a migration rate of 3.5 m/yr (Fig. 6).

4.3. Mineralogical composition

The dune field of Bolsón de Fiambalá has its maximum extension between Medanitos and Tatón. Although their white colours suggest a high content of quartz, there are significant amounts of pumicite clasts. These volcanic shards were supplied from a volcano located at the Sierra de Buenaventura. Quartz is the dominant mineral of the dune field at the northern end of the valley (44–65%) while volcanic glass (pumicite clasts) comprises 12–28%. Both minerals explain why this dune field is so bright when analysed from satellite images (Fig. 5). Subordinated, there are grains of lithic fragments (8–11%), feldspar (3–6%) and opaques (2–5%). Lamporobolite clasts comprise only 0.6–4%.

At the southern end of the valley, close to Tinogasta village, there is another dune field that does not content volcanic shards of pumicite. The sand grains are dominated by quartz (38%), lithic fragments (37%) and opaques (20%).

5. Discussion

Different diatom records from lacustrine deposits from Patagonia and Pampa regions were used to interpret the lake-level histories and correlate with climatic changes during Marine Isotope Stage 3 (MIS3) in the South Hemisphere (e.g. Blasi et al., 2010; Recasens et al., 2015). Bolsón de Fiambalá is located to the eastern side of the so-called South American Arid Diagonal and Late Quaternary climatic changes are of special interest because this is a transitional zone between tropical westerlies and the tropical monsoonal system (Garleff et al., 1993; Garreaud et al., 2009). Lake deposits with diatoms at 3830–3820 m asl revealed the presence of a shallow freshwater/brackish environments between *ca.* 32,000 and 29,000 ^{14}C years BP. The influx of non-diatomaceous materials (gravel) probably reflects stream activity. The similarity in species composition of Pleistocene diatom assemblages of Las Lozas basin with modern sets of high altitude aquatic environments of Catamarca province (Maidana and Seeligmann, 2006) suggest that the lacustrine section was deposited during a relatively short time interval under a environmental regime that resembled modern environments from the region. The limnic sedimentation studied in Bolsón de Fiambalá sequence represents humid phases with milder climate during MIS3.

Several papers reported the composition of the western dune fields of Argentina (Tripaldi, 2002; Szelagowki et al., 2004; Tripaldi et al., 2010; Ojeda et al., 2012; Zárate and Tripaldi, 2012). Some of these fields were built by the action of westerly winds from materials composing glacial moraines left at the foot of the Andes. Several megafans characterised the western boundaries of these tectonic valleys (Suvires, 2014) and would imprint the mineralogical signature of the dune composition. Some of these sand fields have been rebuilt after the deactivation of the Bermejo-Colorado watershed with a N–S direction. Several rivers belonged to this ancient watershed: Bermejo (Colorado) – Desaguadero - Salado - Curacó system (Zárate and Tripaldi, 2012). These sand fields, located between 27 and 40°S, comprised six provinces: Catamarca (Fiambalá), La Rioja (Médanos Negros), San Juan (Médanos Grandes), San Luis (Sayape, Justo Daract, Nueva Galia), La Pampa (La Pastoril, General Acha, Toay) and Buenos Aires (Ombucta, Mayor Buratovich; Fig. 7).

The Médanos Negros dune field (31°33′44″ S, 66°52′26″ W) is located in southern La Rioja Province (Fig. 7). They are composed

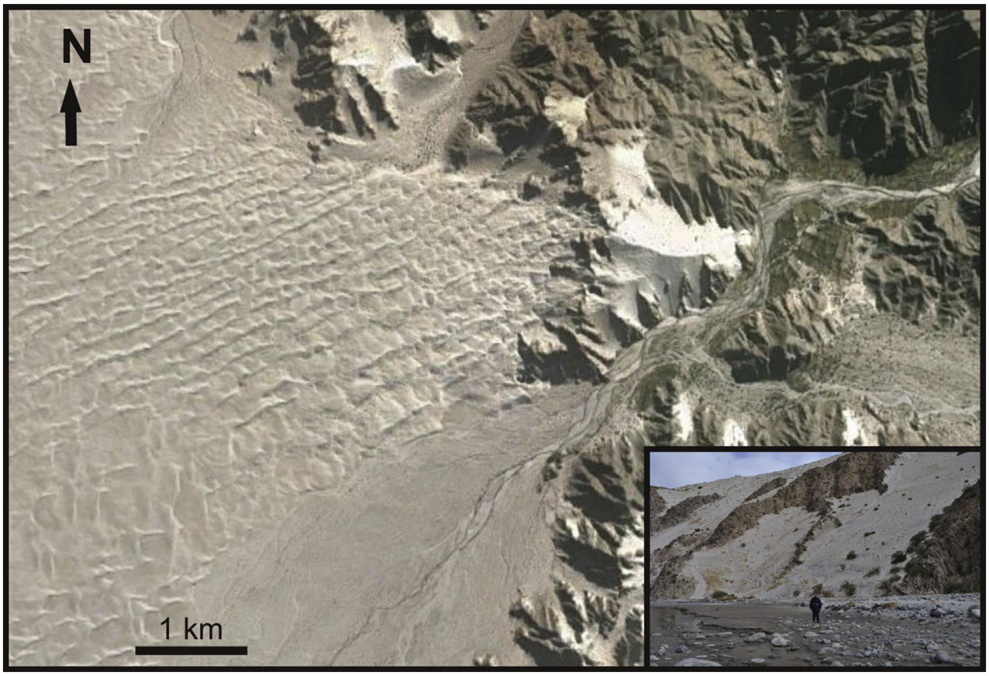

Fig. 5. Longitudinal dune field close to Tatón. Inset: sand ramp.

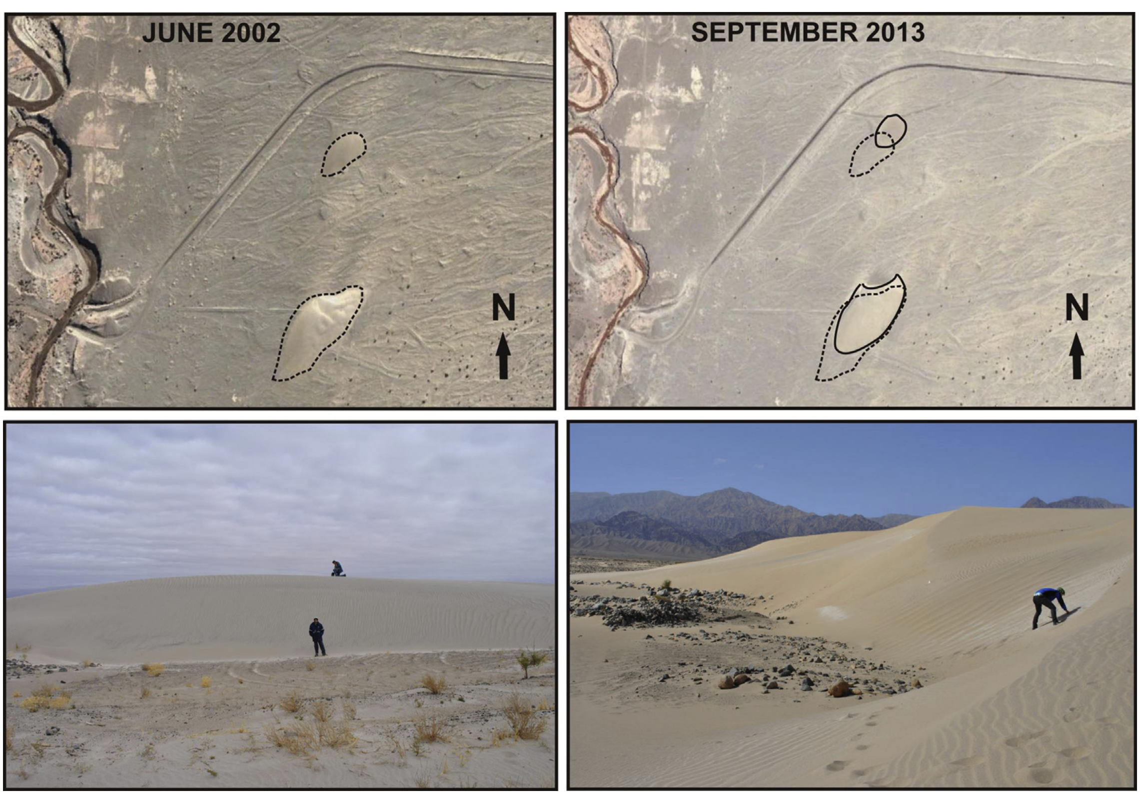

Fig. 6. Migration of the isolated barchan of Fiambalá.

mainly by feldspar (46–53%), quartz (29–36%) and lithic fragments (17–18%).Volcanic glass is less than 3% of the whole sand fraction (Tripaldi et al., 2010).

The sand field of Médanos Grandes of San Juan Province (32° S and 68° W; Fig. 7) occupies an area of about 50 × 35 km. This polycyclic sand field that was assumed to be minimised from an extended one is related to the alluvial plain of the Bermejo River. Five morphologic units were discriminated (Tripaldi, 2002). The first unit includes *draas* composed of transverse crests transported by winds from the SW. The second unit should have been originated by winds coming from the SE. The third unit is assumed to be formed by the interference of units 1 and 2, and therefore

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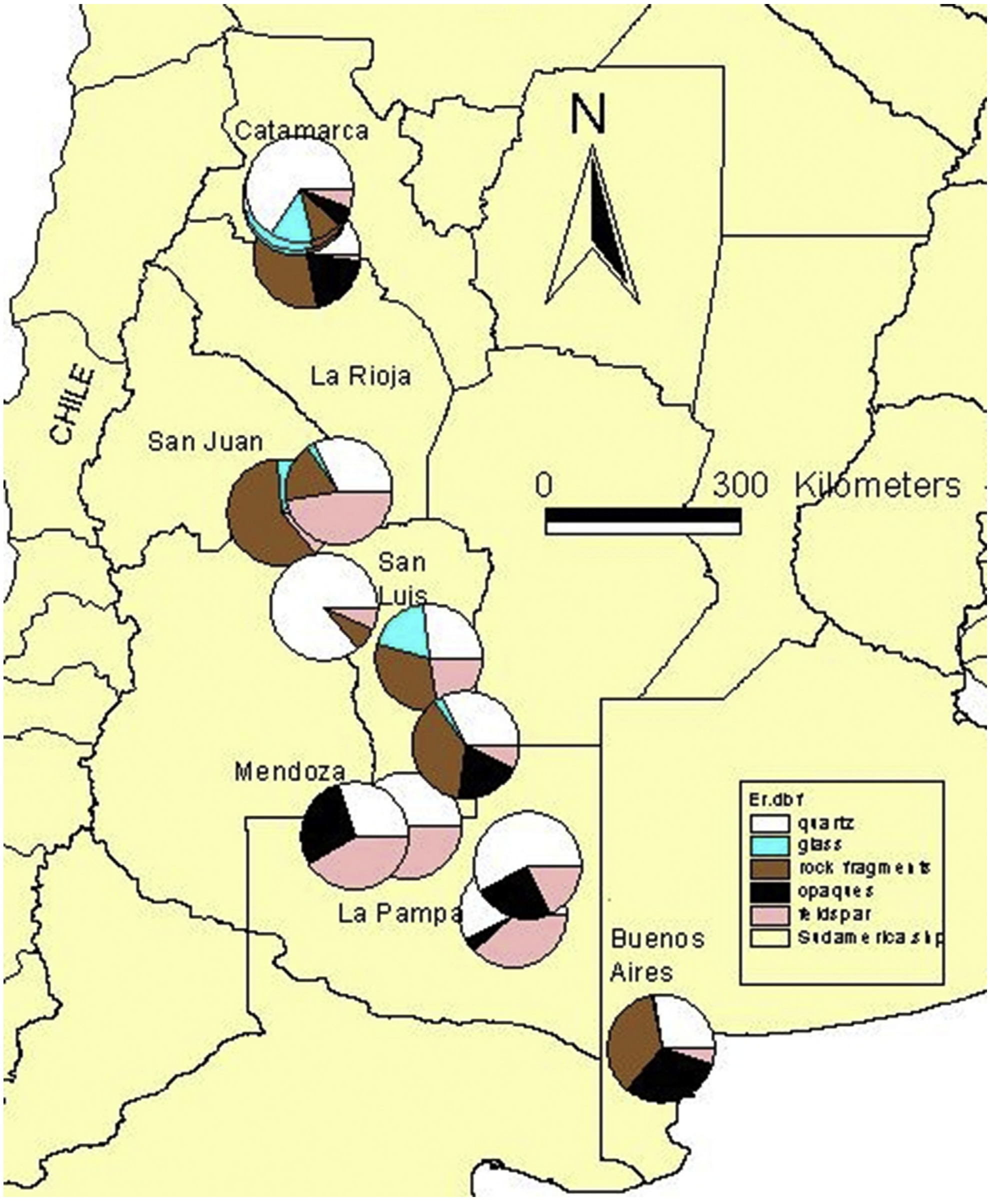

Fig. 7. Mineral composition of the dune fields of Central Argentina between 27 and 40°S.

composed of deflation ponds of 1000 m of diameter and 50 m of altitude difference. Units 4 and 5 were formed by winds coming from the SSE. Unit 4 is a bunch of linear dunes with heights of 30–50 m spaced 150 m. Transverse dunes of less heights (10 m) and spacings (70 m) are superimposed obliquely indicating a migration transport towards the NW (Tripaldi, 2002). The unit 5 occupies the south and southeastern tips of the Médanos Grandes sand field. It is formed simply by modern transverse dunes, with barchans and linear dunes in some patches. The composition of these dunes is dominated by lithic fragments (>7%) of different provenance rocks (volcanic, metamorphic and sedimentary rocks), moderated proportions of feldspar (approximately 15%), and less percentages of quartz (about 13%) and accesory minerals.

In Eastern Mendoza, lunette dunes laid to the north side of National Route 7 (Fig. 7), close to the limit with San Luis Province (33°06′ S, 67°12′ W). They are composed of sand (78%), silt (20%), and small proportions of clay (2%; Ojeda et al., 2012). Quartz was the dominant mineral (60%), with small proportions of lithic fragments and feldspar (10%), and calcareous clasts (10%). There are minor proportions of mollusc fragments (5%), gypsum (5%), calcite (5%), tourmaline (3%) and mica (2%; Ojeda et al., 2012).

The sand field located 5 km to the north of Nueva Galia, San Luis (35°04′15″ S, 65°15′ 08″W) is composed by low altitude (only few meters) transverse dunes separated 160–180 m that are fixed although it is clear they formed by westerly winds. These sands are composed mainly of rock fragments (35.6%), quartz (30%), opaques (18%), feldspar (6.85%), with 3% of pumicite grains.

The western sand field of La Pampa extends from southern San Luis to Limay Mahuida, and is attached to the Salado River (Fig. 7). A corridor of about 70 km composed of vegetated transverse dunes (in some parts barchanoids) is interfingered to deflation ponds and shallow lakes (Szelagowki et al., 2004). These sands are composed of altered rock fragments (25–48%), feldspar (2–34%), quartz (9–32%), volcanic glass (4–19%) and opaques (1–12%); lithic fragments were less than 1% (Fig. 7; Szelagowki et al., 2004). Close to Toay 36° 40′ 45″ S, 62° 35′ 06″W, deflation ponds with simple dunes within them were also sampled. Sand grains are composed altered fragments of rocks (32–49%), quartz (14–21%), feldspar

(6–13%) and volcanic glass (4–19%). Less quantities of opaques (1–14%) and lithic fragments (1–6%) were recognised (Szelagowki et al., 2004). In General Acha (37° 020′ 36″ S, 64° 35′ 06″W), within the Argentino-Utracán Valley, an elongated corridor is composed of several longitudinal dunes, associated to barchanoid and star dunes, are showing a transport towards the ENE (Szelagowki et al., 2004). These dunes are composed of grains of altered rocks (31–50%), quartz (11–22%), feldspar (14–20%) and volcanic glass (3–16%); opaques percentages are between 1 and 9% (Fig. 7; Szelagowki et al., 2004).

Two aeolian corridors merge from the valley of the Colorado River. Both corridors were composed of transverse dunes that migrated to the east. Today, these dunes were almost completely fixed by vegetation. The northern corridor, Ombucta Corridor (Spalletti and Isla, 2003), was sampled and analysed in relation to the mineralogical composition. The southern corridor, Buratovich Corridor (Fig. 7), was also studied in its composition. The sample of Mayor Buratovich was dominated by rock fragments (34%), opaques (29%) and quartz (26%) with less percentages of feldspar (4.5%). These lithic fragments are dominated by volcanic rocks.

6. Conclusions

1. Bolsón de Fiambalá is a tectonic valley where aeolian and fluvial processes dominate in response to climate changes during the Quaternary. Two sequences corresponding to intervals during OIS 3 and OIS1 were reported. The Holocene deposits were older at the north (Mid-Holocene) and related to pulses in piroclastic supply.
2. Transverse dunes are composed of different rocks from the tectonic valley. However, acidic volcanic glass deposited during Late Holocene from a volcano from the Andes dominates.
3. Lake deposits with diatoms at 3830-3820 m asl revealed the presence of shallow freshwater/brackish environments between *ca.* 32,000 and 29,000 ^{14}C years BP. The lacustrine section was deposited during a relatively short time interval under an environmental regime that resembled modern environments of the region.
4. The isolated barchan of Fiambalá is migrating 3.5 m/yr.
5. Several dune fields were reported from the piedmonts of the Andes, with significant differences in their mineralogical composition. Other dune fields originated by the deactivation of the Desaguadero-Curacó-Colorado fluvial system.

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