Aeolian Research 2 (2010) 33–48

Contents lists available at ScienceDirect

Aeolian Research

journal homepage: www.elsevier.com/locate/aeolia

Petrography and geochemistry of late Quaternary dune fields of western Argentina: Provenance of aeolian materials in southern South America

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A R T I C L E I N F O

Article history:
Received 27 July 2009
Revised 2 January 2010
Accepted 4 January 2010

Keywords:
Petrography
Geochemistry
Sediment source
Late Quaternary
Dune field
South America

A B S T R A C T

Landscapes of western Argentina are dominated by aeolian sand of diverse composition, reflecting multiple sediment sources. This study focuses on determining the petrography and geochemical composition of sand from three western Argentina dune fields, Médanos Grandes, Médanos Negros and San Luis, to better constrain the provenance of aeolian sand and its relation to Pampean loess. Médanos Grandes sands are litharenites to feldspathic litharenites, with metamorphic and volcanic rock fragments and lesser amounts of quartz and feldspar. Trace elements (U, Th, Sc, V) indicate the dominance of felsic source. A mixed provenance, with contributions from Sierras Pampeanas metamorphic–igneous complex, pre-Quaternary volcanic rocks and direct input from Andean explosive volcanism, is assumed. Médanos Negros sands are lithic feldsarenites, with abundant feldspars and quartz and lesser amounts of rock fragments. Trace elements indicate a mafic source for these aeolian sands, geochemically and petrographically distinct likely due to the input of ultramafic-mafic lithologies of the Sierra Pampeanas. The San Luis sand has substantial petrographic variability with lithic feldsarenites, feldspathic litharenites and lithic arenite. Trace element composition indicates a felsic source. A diagnostic attribute is the dominance of fresh pumice and volcanic glass shards. Contributions from Andean volcanic sources and local metamorphic and igneous rocks are ascertained. Pampean loess and western Argentina dune field sand show broad petrographic and geochemical similarities indicating aeolian sand, silt particles and, eventually, far travelled dust may have a relatively common source. Another viable source for loess is associated with aeolian abrasion in the many dune fields in western Argentina.

1. Introduction

Quaternary dune fields and other aeolian landforms are common surficial features of central-western Argentina (e.g. Iriondo and Kröhling, 1996; Carignano, 1999; Muhs and Zárate, 2001; Tripaldi, 2002a,b; Zárate, 2003; Tripaldi and Forman, 2007). These extensive aeolian deposits (Fig. 1) are principally related to uplift and enhanced glaciation of the Andes since the Miocene, augmented in the Quaternary with volcanic ash input (Clapperton, 1993; Zárate, 2003). The central and western Pampas are covered by an extensive aeolian cover ("Pampean Sand Sea", Iriondo and Kröhling, 1996; Iriondo, 1990, 1999), grading to the northeast and east to loess and loessoid sand (Zárate and Blasi, 1991; Bidart, 1992; Kröhling, 1999a). Loess deposition also extended into mountainous western Argentina with loess-paleosol sequences in Tucumán province spanning the past ca. 1.15 million years (Kemp et al., 2003, 2004a,b; Schellenberger and Veit, 2006). In central Argentina (Córdoba province) discrete intervals of loess deposition were recently recognized during glacial and potentially interglacial intervals (Kemp et al., 2006). Large ergs also occur to the west (Tripaldi, 2002a,b) in intermontane areas of the Sierras Pampeanas, Precordillera and the Andean Cordillera (Fig. 1), which have been episodically active in the late Pleistocene to late Holocene (Tripaldi and Forman, 2007).

Teruggi (1957) seminal contribution outlined granulometric and mineralogic composition of the Pampean loess and showed that the coarse fraction is mainly composed of an assemblage of volcanic minerals. Subsequent studies revealed a loess composition dominated by volcanic elements (as lithic fragments and glass) and with variable proportions of bedrock lithic components, characteristic of specific regions of Argentina (Tricart, 1973; González Bonorino, 1965; Zárate and Blasi, 1991; Kröhling, 1999b; Morrás, 1999; Zárate, 2003). Case in point, the modal sand fraction of the typical loess (southern Santa Fé province) has abundant polycrystalline quartz-tridimite, frequent glass shards derived from acid rocks, scarce plagioclase and lithic fragments and low percentages (1%) of heavy minerals (Kröhling, 1999a). Whereas, in northern Buenos Aires, loess and loessoid sediments show variable amounts of quartz (6–13%),

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doi:10.1016/j.aeolia.2010.01.001

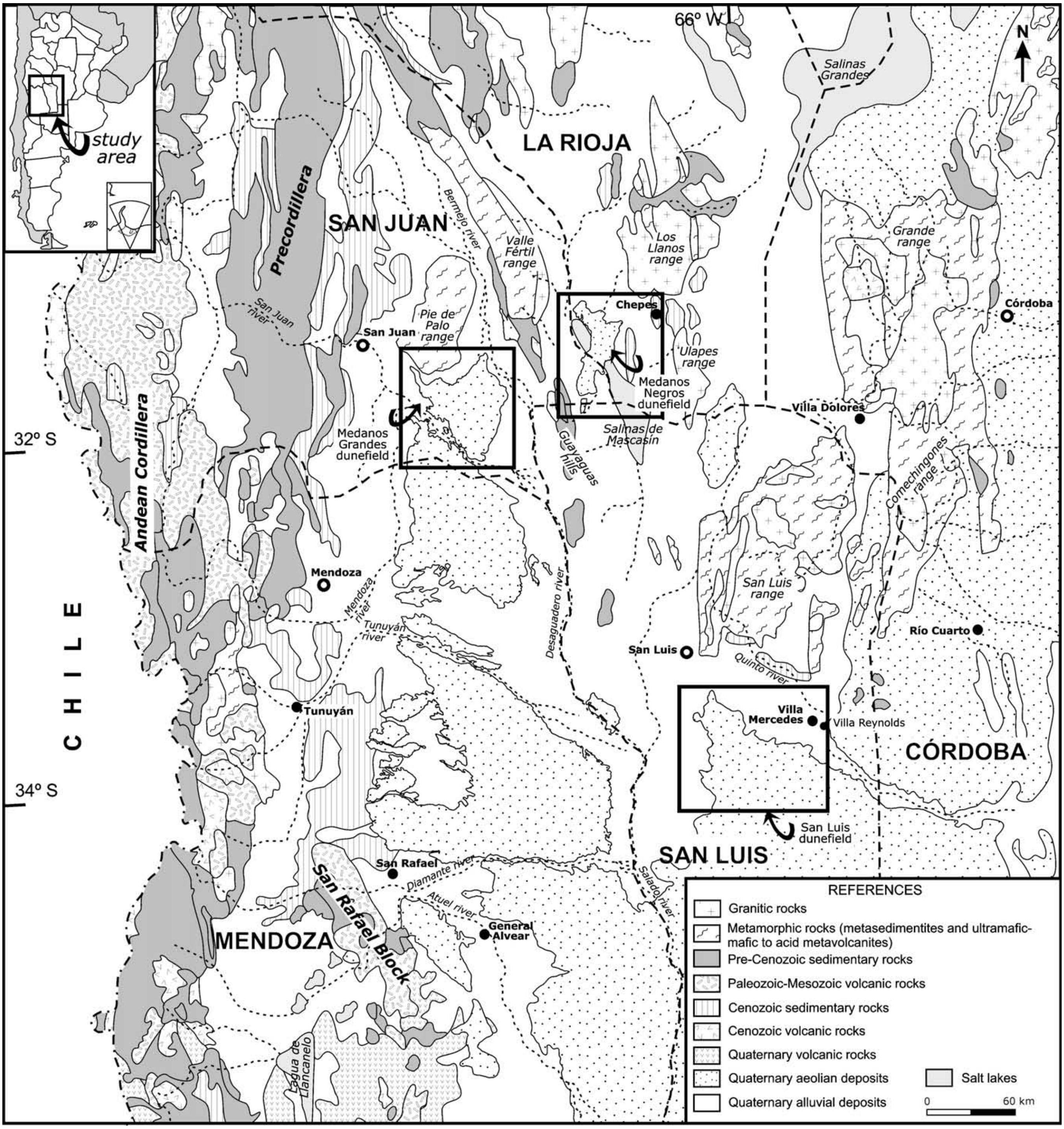

Fig. 1. Geologic setting and location of the studied dune fields.

feldspars (33–49%), lithic fragments (2–23%) and glass (19–39%) (Tonni et al., 1999; Orgeira et al., 2002; Tófalo et al., 2008). Recent studies have focused on defining the geochemical fingerprint for Pampean loess (Morrás, 2003; Schellenberger and Veit, 2006) to evaluate sources for dust from Antarctic ice cores (Gallet et al., 1998; Smith et al., 2003; Gaiero et al., 2004, 2007).

Comparatively little attention has been paid to the mineralogical and geochemical composition of the Quaternary aeolian sand from western Argentina and the associated provenance. Initially, González (1981) described aeolian sand rich in quartz, mica and pumice clasts in Pleistocene deposits related to Bebedero salt marsh (Salinas del Bebedero, Fig. 1). Sánchez and Blasarín (1987) reported that the aeolian sand in Córdoba province, near Río Cuarto city (Fig. 1), is composed principally of K-feldspar (47–64%), volcanic glass shards (13–28%), quartz (11–27%) and plagioclase (4–13%), with principal heavy minerals of amphiboles, tourmaline, micas, apatite, zircon, garnet and opaque minerals. Mineralogical studies for aeolian sand in southern San Luis province (Fig. 1) show a similar sand composition with high proportion of K-feldspar (53%), quartz (14%), volcanic glass shards (10%), plagioclase (9%), alterites (6%), ferromagnetic minerals (4%) and 3% of heavy minerals (Strasser, 1982). Iriondo and Ramonell (1983) also found in southern San Luis Province aeolian sand rich in K-feldspar (42%), quartz (27%), alterites (12%), volcanic glass shards (7%) and plagioclase (4%). Aeolian sand exposed along Mar Chiquita lake are composed of volcanic glass shards (1–54%), quartz (18–50%), plagioclase (9–34%), altered feldspar (6–24%), K-feldspar (1–7%), lithic fragments (0–19%), alterites (4–22%) and 4% of heavy minerals (Iriondo and Kröhling, 1999). Mineralogic signature of Pampean loess and dune fields indicate a source from the Salado–Desaguadero-Curacó River (Iriondo, 1990).

The diverse mineralogy of sand and loess across central Argentina indicates potentially multiple sources of the aeolian material and more quantitative studies are needed to better assess provenance. In this study, we examine the petrography and geochemistry of aeolian sand from three representative dune fields of western Argentina (WADF, Fig. 1) in an attempt to constrain the sources of these sediments and to compare them with the published loess and aeolian sand composition. The three studied dune fields are: Médanos Grandes (MG), Médanos Negros (MN) and San Luis (SL). The petrographic composition of the WADF sands is used to infer possible sources for aeolian sediments (Dickinson, 1985; Le Pera and Critelli, 1997; Critelli et al., 1997). Elemental analysis is employed to discern distinct geochemical signatures (McLennan, 1989; Kasper-Zubillaga et al., 1999; Pease and Tchakerian, 2003). This data together with previously presented geomorphic and chronostratigraphic assessment (Tripaldi and Forman, 2007) yield new insights on the provenance and paleoclimatic implications for dune fields in western Argentina.

2. Geologic and climatologic context

The three studied dune fields have distinct geologic and climatic attributes. The Médanos Grandes (MG) and Médanos Negros (MN) dune fields occur in intermountain valleys of western Argentina related to the Andean orogen where hills are composed of a variety of lithologies. In contrast, San Luis (SL) dune field is located in the western margin of the Pampean plain with high relief hills to the north, composed mostly of metamorphic–igneous rocks (Fig. 1).

The Médanos Grandes dune field (San Juan Province) is bounded by the Sierra de Pie de Palo to the north, a 3100-m high massif mainly composed of Precambrian-Lower Paleozoic metasedimentary and metavolcanic rocks, the latter ones from ultramafic-mafic to acid compositions (Vujovich and Kay, 1996, 1998) and is truncated or partially buried by colluvial and fluvial deposits along its east, west and southern margins (Fig. 2a). The Sierra de Valle Fértil rises up to 2800 m to the northeast and is mostly composed of Precambrian-Lower Paleozoic metasedimentary rocks and non- to strongly metamorphosed, mafic to acid igneous rocks (Dalla Salda et al., 1999; Otamendi et al., 2009). Mesozoic sedimentary rocks appear in the Sierra de Valle Fértil as well, and outcrop to the south forming the lower relief Sierra de Guayaguas (Fig. 1). Pie de Palo and Valle Fértil are included in the Sierras Pampeanas geologic province. Other important sources of sediments, located to the west of MG dune field are the Andes and the Precordillera. The Andes, which rise up to 6000 m, are composed principally of Upper Paleozoic granitic and volcanic successions and of Upper Paleozoic, Mesozoic and Cenozoic sedimentary and volcanic rocks (Fig. 1). Adjacent to the east of the Andes, and separated by a long valley, is the Precordillera that constitute a series of hills, rising up to 3000 m, composed of mainly Paleozoic and Cenozoic sedimentary rocks together with minor Upper Paleozoic volcanites (Fig. 1).

The Médanos Negros dune field (La Rioja province) is located in an endorheic basin limited to the east by Sierra de los Llanos and Sierra de Ulapes and to west by the Sierra de Valle Fértil and the Sierra de Guayaguas (Fig. 1). Los Llanos and Ulapes chains are formed by rocks of the same composition of the previously described the Sierra de Valle Fértil, together with subordinate

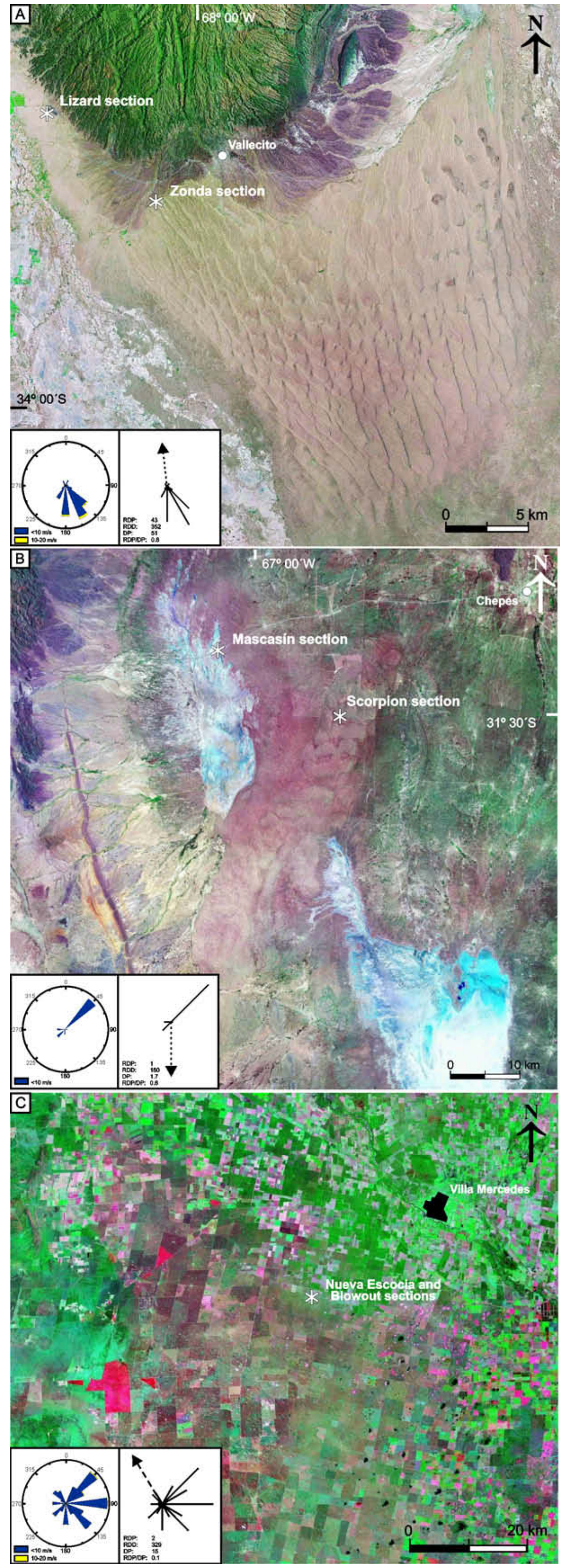

Fig. 2. Landsat ETM images and wind data of studied dune fields: (a) Médanos Grandes; (b) Médanos Negros; (c) San Luis.

Upper Paleozoic and Cenozoic sedimentary successions. Aeolian sand for this dune field is principally sourced from related alluvial and lacustrine deposits, the latter associated with the Mascasín Salt Pan (Salinas de Mascasín), which is encroached partially by dunes (Fig. 2b). Mascasín Lake is feed by episodic runoff from the Valle Fértil, Guayaguas, and the Los Llanos and Ulapes hills (Fig. 1).

The San Luis dune field (San Luis Province) is immediately south of the 2000 m high Sierra de San Luis and Sierra de los Comechingones (Sierras Pampeanas geologic province), which are mainly composed of Precambrian-Lower Paleozoic metamorphic–igneous complexes, with minor amounts of Cenozoic volcanic and Mesozoic sedimentary rocks (Fig. 1). The aeolian cover of San Luis grades laterally into fine-grained fluvial deposits, and constitutes the western margin of a large erg developed across the Pampas and referred to as the "Pampean Sand Sea" (Iriondo and Kröhling, 1996; Iriondo, 1999; Kröhling, 1999a,b). San Luis dune field is limited to the northeast by the Quinto River, having its headwaters in the Sierra de San Luis, and to the east by the Desaguadero River.

The studied dune fields, San Luis, Médanos Negros and Médanos Grandes, lie on a precipitation gradient with mean annual values decreasing east to west from ~700 mm near Villa Mercedes, to ~370 mm at Chepes, and to ~91 mm in San Juan (Compagnucci et al., 2002). A striking characteristic is the seasonal precipitation distribution, with over 70% of precipitation occurring in austral spring and summer months of October through March associated with the southward expansion of the South American Convergence Zone (e.g. Barros and Silvestri, 2002). Mean maximum summer temperatures during this rainy season can often exceed 35 °C, enhancing evaporative losses.

3. Geomorphology of WADF

Médanos Grandes (MG) dune field has a variety of dune forms. The dominant landforms are 50-m high parallel ridges, spaced between 0.25 and >1.5 km, exceeding 5 km in length and with a preferred NNW to SSE orientation (Fig. 2a). Most of these ridges are asymmetric (transverse dunes), with steeper sides facing NNE in the northern area and SSW to the southern region, indicating opposing wind directions. Smaller, linear dunes and orientated NW to SE are superimposed on these ridges. Large blowout dunes also occur in the central area of MG dune field. This complex pattern of dune forms is surrounded by a lower relief, rolling surface formed mainly by linear dunes, orientated from N–S to NW–SW.

Médanos Negros dune field is dominated by transverse forms at two distinct scales and orientation (Fig. 2b). Larger forms are west-to-east oriented ridges with troughs spaced ~2-to-4 km apart, and with about 50 m of relief and steeper sides facing south. Superimposed on this undulating topography are 5-to-10 m high, transverse dunes facing SSW to SW. Moreover, these transverse dunes extend beyond the host landforms, to the west and to the south, showing sinuous crests that are often highly modified by coppice dunes. Linear dunes (3–5 m high, 20–30 m wide and 100's m long) commonly occur to the northeast, associated with subjacent salt-rich lake deposits, whereas sand sheet deposits occurs farther to the southwest, associated with alluvial fans emanating from the Sierra de Guayaguas.

San Luis dune field is characterized by a mantle of aeolian sands that show different degrees of deflation and aeolian reworking in the form of simple and compound parabolic dunes and blowouts (Fig. 2c). Single parabolic dunes are about 900 m in length and 250 m in width, with compound forms averaging 2000 m in length and 1130 m in width, in all cases with orientation indicating paleowinds mostly from the southeast. To the eastern area of the dune field active, irregular blowouts dominate, showing large and irregular surfaces of loose sand spreading out over their southwestern margins. Many blowout depressions are often filled with water forming perennial lakes.

Analysis of wind data from San Juan (hourly), Chepes (three times daily) and Villa Reynolds (hourly) weather stations near MG, MN and SL dune fields, respectively, illustrates the main wind directions (data from Servicio Meteorológico Nacional, Buenos Aries, Argentina). In MG dune field winds are mostly from the south to southwest; in MN dune field there is a strong northeasterly wind component, whereas SL dune field shows dispersed components from the northeast to the southeast (Fig. 2).

The studied dune fields show a dispersed vegetation cover mostly dominated by shrubs and short grasses but with variable amounts of trees (scattered in MG but more significant in MN and SL), that hinder the wind transport of sand.

4. Methodology

To characterize the petrography and geochemistry of aeolian sand from WADF sediments were collected from stratigraphic sections in the three dune fields from east to west: San Luis, Médanos Negros and Médanos Grandes (Figs. 1 and 2). In each locality two sections were logged and sampled: Lizard and Zonda sections in MG, Mascasín and Scorpion in MN and New Scotia and Blowout in SL (Fig. 3). Detailed descriptions of these sections are in Tripaldi and Forman (2007). The granulometry of the aeolian sediments was determined for the sand to coarse silt grain size by sieving at 0.25 phi intervals using Tyler meshes and a Ro-Tap. The concentration of sediments finer than 64 mμ is <7% in all samples. Log-normal populations mean and standard deviation were calculated from granulometry by the moment method whereas median, skewness and kurtosis were determined by graphic formulas after Folk and Ward (1957).

The medium to fine sand fractions were separated to determine petrographically mineral composition. Grains were mounted in epoxy resin and subjected to standard petrographic analysis (Potter et al., 2001; Garzanti et al., 2005). In each sample, 300 grains were counted by the Gazzi–Dickinson method (Gazzi, 1966; Dickinson, 1970). Roundness was estimated by visual comparison in thin sections after Powers's (1953) table.

The recognized components of aeolian sand of WADF are shown in Table 1. Quartz (Q) grains were separated in monocrystalline (Qm) and polycrystalline (Qp) types, whereas among feldspar (F), K-feldspar (FK), plagioclase (P) and microcline (M) were recognized. Rock fragments (L) include volcanic (Lv), metamorphic (Lm) and sedimentary (Ls) lithics. Volcanic sand grains were subdivided into paleovolcanic (Paleo-V) and neovolcanic (Neo-V) grains following Critelli and Ingersoll (1995). The paleovolcanic grain category includes fresh or faintly altered volcanic fragments of acid composition (Lva); fairly altered volcanic fragments of basic composition (Lvb) and rounded and metamorphosed volcanic fragments of intermediate to basic compositions (Lvbm). Neovolcanic grains, derived from active volcanism during sedimentation, comprise fresh glass shards and pumices (Glass). Metamorphic fragments (Lm) include phylite, schist and amphibolite types. Whereas, siliciclastic and carbonate lithic fragments were categorized as sedimentary rock fragments (Ls). Accessory minerals include micas, both biotite and muscovite, and amphiboles, pyroxenes, zircons and opaques.

Petrographic data for sand grains are the basis for classification of aeolian sands and to infer provenance for the studied dune fields. Sands are classified according to the Q:F:L (quartz, feldspars and rock fragments) ratio following Folk et al. (1970). The relation among quartz, feldspars and rock fragments, the presence of different kinds of feldspars, the relative amounts of volcanic, sedimentary and metamorphic rock fragments and the discriminations between different types of volcanic lithics, among other features are the basis for inferring sediment source (Dickinson, 1985; Ingersoll, 1990; Le Pera and Critelli, 1997; Critelli et al., 1997; Kasper-Zubillaga et al., 1999; Kasper-Zubillaga and Dickinson, 2001). The composition of sand may not depend exclusively on the source rocks but may be affected by the physiography and chemical weathering in the source

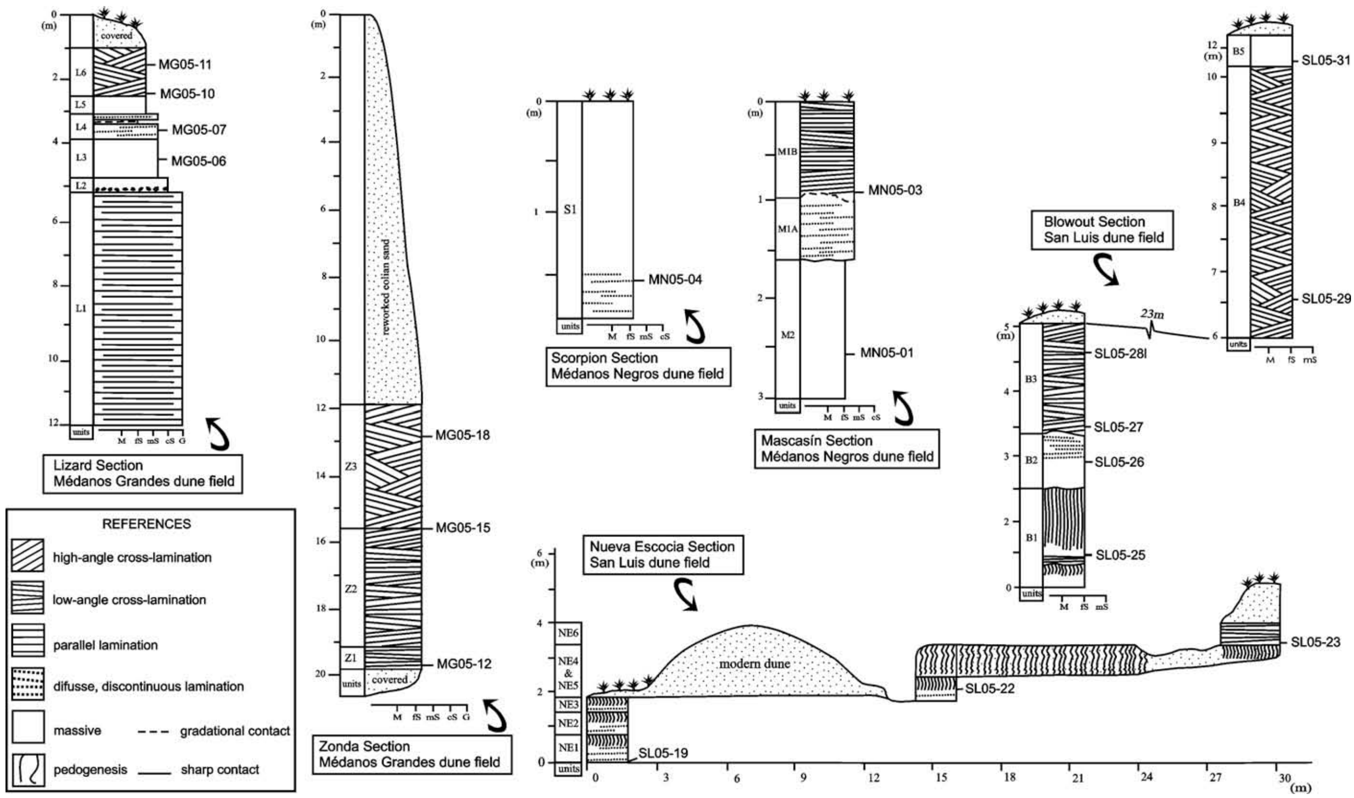

Fig. 3. Logged sections in MG, MN and SL dune fields with location of samples.

area of the sediment (Basu, 1985). However, the studied sediments showed no evidence of chemical weathering, nor appreciable pedogenesis, thus the petrographic composition was analyzed in terms of sediment source and geomorphic context of the dune fields.

Concentrations of SiO_2, Al_2O_3, $Fe_2O_3(T)$, MnO, MgO, CaO, Na_2O, K_2O, TiO_2, P_2O_5, Ba, Sr, Zr, Y, Sc, Be, V, Th, U were determined on total sediment aliquots by inductively coupled plasma mass spectrometry by Activations Laboratory Inc., Canada (Table 2). The elemental analysis is used to evaluate the presence of distinct geochemical signatures in the studied dune fields (McLennan, 1989; Rollinson, 1993; Kasper-Zubillaga et al., 1999; Pease and Tchakerian, 2003), to examine the mineralogic maturity of the sands and to compare with published geochemical data of Pampean loess and sand.

5. Petrographic composition of aeolian sand from WADF

WADF are composed of well to moderately well sorted, fine to very fine sands with unimodal, symmetrical and mesokurtic granulometric distribution and <7% of material finer than 62 mμ (Table 3). These features are consistent with the typical grain texture of aeolian sand (Ahlbrandt, 1979). Aeolian sand from MN dune field is somewhat less sorted than sand from MG and SL dune fields, whereas sediments from SL dune field show the finer grained sand. Sand grains show subrounded to subangular forms according to visual comparison (Powers, 1953).

5.1. Médanos Grandes dune field

Aeolian sands from MG dune field are litharenite to feldspathic litharenites (Fig. 4a) showing a varied composition of lithic fragments (Fig. 4b). Rock fragments are by far the most abundant component (~70% of whole sand), followed by feldspars (~15% of whole sand), quartz (~13% of whole sand) and accessory minerals (~9% of whole sand). The two studied sections in this dune field showed slight differences in their modal composition (Table 1). The Lizard section is dominated by rock fragments of high grade metamorphic rock types (~89% of total lithics), including gneissic, amphibolitic and schistose grains (Fig. 5a). Accessory minerals are remarkably abundant (~14% of whole sand) with micas (biotite and muscovite), amphiboles with green pleocroism, pyroxenes, opaque minerals and zircon. Volcanic lithics are recognized also, with both paleo- and neo-types. Paleovolcanic rock fragments are mostly highly altered basic volcanic grains with microlithic and intergranular textures. Whereas, neovolcanic species are dominated by fresh glass shards and pumice (2–10% of whole sand). Quartz and feldspars are also present in this sand, but as minor amounts (~16% and 14% of whole sand, respectively), with K-feldspar being more abundant than plagioclase.

Aeolian sands from Zonda section in MG dune field show a different modal composition with little variation between samples of different stratigraphic position (Table 1). In general, volcanic fragments are more abundant than metamorphic and sedimentary grains. Sand from the lower part of the section has a Q:F:L ratio of 8:11:81, where lithics are dominated by volcanic grains (~90% of total lithics). Surprisingly there is a significant amount of glass shards and fresh and altered pumice (41% of whole sand), and acid and basic volcanic fragments are also common (36% of total lithics, Fig. 5b). There are also minor amounts of methamorphic (slate and micacite; ~7%) and sedimentary lithics (~3% of total lithics). The upper most sand from Zonda section yielded sand with Q:F:L ratio of 19:29:52 and with a low amount of glass (1% of whole sand, Table 1). The lithic fraction in this sand is dominated by volcanic and metamorphic rock fragments (51% and 47% of total lithics, respectively). Among the volcanic lithics, the acid and basic types are dominant (49% of total lithics). Metamorphic lithics (Lm) include gneissic, amphibolitic and schistose grains. Polycrystalline and monocrystalline quartz is 8–18% of the whole sand. Feldspars are dominated by K-feldspars (~75%) that include low altered

Table 1
Petrographic composition of aeolian sand of WADF. References: Qm, monocrystalline quartz; Qp, polycrystalline quartz; Qt, total quartz; FK, K-feldspar; Plag, plagioclase; M, microcline; Ft, total feldspar; Neo-V, neovolcanic lithics; Paleo-V, paleovolcanic lithics; Glass, glass shards and pumices; Lva, acid volcanic lithics; Lvb, basic volcanic lithics; Lvbm, metamorphosed intermediate to basic volcanic lithics; LvT, total volcanic lithics; Ls, sedimentary lithics; Lm, metamorphic lithics; Lt, total lithics; acc. accessory minerals; Q, quartz; F, feldspar; L, lithics; SD, standard deviation.

Sand grain composition (recalculated values to 100%)																	Folk et al. (1970)			Dickinson et al. (1983)					
Sample	Qm	Qp	Qt	FK	Plg	M	Ft	Neo-V Glass	Paleo-V Lva	Paleo-V Lvb	Paleo-V Lvbm	LvT	Ls	Lm	Lt	acc	Q	F	L	Q	F	L	Qm	F	Lt
MG05-07	10.1	5.5	15.6	11.7	3.6	1.0	16.2	9.7	0.6	3.2	9.7	23.4	6.5	24.7	54.5	13.6	18.0	18.8	63.2	18.0	18.8	63.2	11.7	18.8	69.5
MG05-10	5.2	6.4	11.6	3.6	2.8	0.4	6.8	2.0	0.8	0.0	1.2	4.0	3.2	59.0	66.2	15.3	13.7	8.1	78.2	13.7	8.1	78.2	6.2	8.1	85.8
MG05-12	7.2	0.5	7.7	7.2	2.7	0.5	10.4	40.7	19.0	5.4	1.8	67.0	2.7	6.3	76.0	5.9	8.2	11.1	80.8	8.2	11.1	80.8	7.7	11.1	81.3
MG05-18	8.3	10.0	18.3	20.1	5.2	1.7	27.0	1.0	1.7	10.4	12.1	25.3	0.7	23.2	49.1	5.5	19.4	28.6	52.0	19.4	28.6	52.0	8.8	28.6	62.6
Mean	7.7	5.6	13.3	10.7	3.6	0.9	15.1	13.4	5.5	4.8	6.2	29.9	3.3	28.3	61.5	10.1	14.8	16.6	68.5	14.8	16.6	68.5	8.6	16.6	74.8
SD	2.0	4.0	4.6	7.1	1.1	0.6	8.8	18.6	9.0	4.4	5.5	37.5	2.4	22.1	12.0	5.1	5.1	9.2	13.5	5.1	9.2	13.5	2.3	9.2	10.6
MN05-01	26.1	8.1	34.2	22.6	22.6	1.9	47.1	0.0	1.9	0.6	2.6	5.2	1.3	9.7	16.2	2.6	35.1	48.3	16.6	35.1	48.3	16.6	26.8	48.3	24.8
MN05-03	26.5	6.8	33.2	24.2	14.5	3.5	42.3	3.2	2.3	0.3	0.3	6.1	2.6	8.4	17.1	7.4	35.9	45.6	18.5	35.9	45.6	18.5	28.6	45.6	25.8
MN05-04	19.4	8.1	27.5	30.4	18.2	1.6	50.2	1.2	0.8	1.6	2.0	5.6	0.0	11.8	17.4	4.9	28.9	52.8	18.3	28.9	52.8	18.3	20.4	52.8	26.8
Mean	24.0	7.6	31.6	25.7	18.4	2.4	46.5	1.5	1.7	0.9	1.6	5.7	1.3	10.0	16.9	5.0	33.3	48.9	17.8	33.3	48.9	17.8	25.3	48.9	25.8
SD	4.0	0.8	3.6	4.1	4.0	1.0	4.0	1.6	0.8	0.7	1.2	4.2	1.3	1.7	0.7	2.4	3.8	3.6	1.1	3.8	3.6	1.1	4.3	3.6	1.0
SL05-19	31.9	4.3	36.2	20.0	10.2	2.6	32.8	15.7	3.4	2.1	4.7	26.0	0.0	2.6	28.5	2.6	37.1	33.6	29.3	37.1	33.6	29.3	32.8	33.6	33.6
SL05-23	28.0	7.5	35.4	9.9	5.6	3.4	18.9	23.3	2.8	3.7	3.7	33.5	1.2	4.7	39.4	6.2	37.7	20.2	42.1	37.7	20.2	42.1	29.8	20.2	50.0
SL05-25	34.6	6.9	41.6	17.3	16.5	4.3	38.1	1.3	4.3	5.2	4.3	15.2	1.3	2.6	19.1	1.3	42.1	38.6	19.3	42.1	38.6	19.3	35.1	38.6	26.3
SL05-26	12.6	3.0	15.6	8.9	4.1	0.4	13.3	51.9	3.3	3.7	2.2	61.1	0.7	3.7	65.6	5.6	16.5	14.1	69.4	16.5	14.1	69.4	13.3	14.1	72.5
Mean	26.8	5.4	32.2	14.0	9.1	2.7	25.8	23.0	3,5	3.7	3.7	33.9	0.8	3.4	38.1	3.9	33.4	26.6	40.0	33.4	26.6	40.0	27.7	26.6	45.6
SD	9.8	2.1	11.4	5.5	5.6	1.7	11.6	21.3	0.6	1.3	1.1	24.2	0.6	1.0	20.1	2.4	11.5	11.4	21.7	11.5	11.4	21.7	9.8	11.4	20.5

orthoclase in tabular perthitic grains and minor microcline. Finally, plagioclase (25% of feldspars) is present in tabular grains with polysynthetic twining.

5.2. Médanos Negros dune field

Aeolian sands from Médanos Negros dune field are lithic feldsarenites (Fig. 4a) reflected by the proportion of feldspars (46–53%), quartz (29–36%) and lithic fragments (17–18%). Accessory minerals, mostly amphiboles with green pleocroism (Fig. 5c), pyroxenes, biotite and muscovite, vary between 2% and 7%.

Monocrystalline quartz is more abundant (24% of whole sand) than polycrystalline forms (∼8%), whereas K-feldspar predominates slightly over plagioclase (∼26% and ∼18% of whole sand). Most K-feldspar is orthoclase (95%) in tabular perthitic grains, with a low degree of alteration, and, in minor proportion, microcline (2%) with the typical crosshatch structure.

MN aeolian sand shows the lowest proportion of rock fragments of the three studied dune fields. The most abundant lithics are metamorphic rock fragments (∼59% of total lithics), including slate, schist and micacite grains (Fig. 4b). Volcanic rock fragments are second in abundance (34% of total lithics), with both paleovolcanic and neovolcanic species (Fig. 4c). In this sand, volcanic glass shards are scarce (less than 3% of whole sand) and paleovolcanic fragments are composed of intermediate to mafic lithics with intergranular and lathwork textures (Fig. 5d). Occasionally, sedimentary lithics are also recognized (7% of total lithics) like siliciclastic (Fig. 5c) and carbonate lithic fragments.

5.3. San Luis dune field

Aeolian sand from San Luis dune field shows the largest variability in composition compared to sands from Médanos Grandes and Médanos Negros. In this locality, and according to Q:F:L ratios, aeolian sand are lithic feldsarenites and feldspathic litharenites, except for one sample that corresponds to a lithic arenite (Fig. 4a). These sands show variable proportions of quartz (16–42%), feldspars (13–38%) and rock fragments (19–66%), together with small amounts of accessory minerals (<5%), like amphibole, muscovite and zircon. Quartz appears mainly as monocrystalline grains (∼83% of total quartz), with slight undulatory extinction. Polycrystalline quartz is also present but in low proportion (5.4% of the whole sand). Among feldspars, K-feldspar is the most abundant variety (∼14% of the whole sand) whereas plagioclase and microcline are rare (∼9 and ∼3% of the whole sand, respectively).

Volcanic grains are by far the most common rock fragments (90% of total lithics) in San Luis aeolian sand, with both paleo- and neovolcanic types, whereas some grains are composed of low metamorphic and sedimentary fragments (Fig. 4b). In those samples with abundant rock fragments there are also high percentages of fresh pumices and glass shards (16–52% of whole sand, Table 1, Figs. 5e and f). Other volcanic lithics are acid (∼4%) and basic (∼3%) grains, showing different degrees of alteration. Paleovolcanic grains comprise highly altered intermediate to basic rock fragments (∼4.5%).

6. Geochemical composition of aeolian sand from WADF

Geochemical data for Médanos Grandes, Médanos Negros and San Luis dune fields are presented in Table 2 and graphed in Harker diagrams (Fig. 6). The SiO_2 proportion in MG and SL sands differs between 66.32% and 75.64%, whereas in MN silica is less variable, varying between 68.17% and 69.93%. In average, the SiO_2 content is slightly higher in MG sands than in the other

Table 2
Geochemical composition of aeolian sand of WADF.

Element:	SiO_2	Al_2O_3	Fe_2O_3(T)	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	LOI	Total	Ba	Sr	Y	Sc	Zr	Be	V	Th	U
Units:	%	%	%	%	%	%	%	%	%	%	%	%	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Detection limit:	0.01	0.01	0.01	0.001	0.01	0.01	0.01	0.01	0.001	0.01	0.01	0.01	2	2	1	1	2	1	5	0.1	0.1
Médanos Grandes																					
1604-MG	75.64	11.70	2.52	0.043	0.71	1.88	3.06	2.48	0.396	0.08	1.41	99.91	615	268	25	6	181	1	46	5.8	1.6
1606-MG	75.32	11.53	2.61	0.045	0.78	1.95	3.14	2.39	0.376	0.08	1.58	99.79	587	262	19	6	143	1	46	5.8	1.6
1612-MG	70.24	13.17	3.58	0.060	1.11	2.47	3.26	2.61	0.527	0.10	2.23	99.36	592	314	27	8	225	1	63	8.0	2.1
1615-MG	66.34	13.98	4.07	0.071	1.41	2.95	3.15	2.68	0.609	0.13	3.71	99.10	556	347	29	10	245	1	69	9.1	2.4
1716-MG	72.75	12.15	3.73	0.060	0.98	2.31	3.20	2.37	0.540	0.12	1.78	100.00	565	295	22	7	256	1	79	6.9	1.8
1717-MG	71.31	12.64	3.86	0.060	1.10	2.35	2.96	2.55	0.569	0.14	1.99	99.53	595	316	27	8	254	1	79	7.3	2.1
1719-MG	69.38	13.47	3.75	0.061	1.23	2.89	3.36	2.57	0.539	0.14	3.08	100.50	564	339	26	9	208	1	69	7.4	2.3
MD	71.57	12.66	3.45	0.06	1.05	2.40	3.16	2.52	0.508	0.11	2.25	99.74	582	306	25	8	216	1	64	7.2	2.0
DE	3.32	0.92	0.62	0.01	0.25	0.41	0.13	0.11	0.088	0.03	0.84	0.46	21	33	3	1	42	0	14	1.2	0.3
Médanos Negros																					
1605-MN	69.93	12.96	4.71	0.089	2.00	5.10	2.54	1.44	0.535	0.15	1.03	100.50	392	222	24	18	283	2	111	5.0	1.1
1713-MN	68.63	13.22	4.99	0.088	1.99	5.01	2.40	1.37	0.522	0.13	0.48	98.83	357	204	25	19	212	2	117	4.2	0.9
1720-MN	68.17	13.79	5.15	0.092	2.10	5.25	2.10	1.28	0.526	0.07	0.80	99.34	371	203	23	20	149	2	124	4.4	0.9
1761-MN	69.93	12.96	4.71	0.089	2.00	5.10	2.54	1.44	0.535	0.15	1.03	100.5	392	222	24	18	283	2	111	5.0	1.1
1762-MN	70.35	13.69	4.49	0.084	1.95	5.32	2.43	1.33	0.46	0.08	0.72	100.9	379	201	24	18	178	2	106	4.1	0.7
MD	69.40	13.32	4.81	0.088	2.01	5.16	2.40	1.37	0.52	0.12	0.81	100.01	378	210	24	19	221	2	114	4.5	0.9
DE	0.94	0.40	0.26	0.003	0.06	0.13	0.18	0.07	0.03	0.04	0.23	0.88	15	11	1	1	61	0	7	0.4	0.2
San Luis																					
1607-SL	67.87	14.87	3.40	0.054	1.20	2.81	3.79	2.87	0.472	0.07	2.67	100.10	680	334	23	8	172	2	56	9.0	2.5
1608-SL	67.68	14.82	3.49	0.063	1.16	2.86	3.79	2.74	0.498	0.08	2.50	99.70	661	345	23	8	168	2	63	9.4	2.3
1609-SL	66.99	15.06	3.57	0.055	1.24	3.10	3.79	2.60	0.518	0.08	2.09	99.09	698	370	22	8	180	2	65	7.5	2.1
1610-SL	67.14	14.82	3.37	0.059	1.16	2.91	3.74	2.88	0.467	0.09	2.99	99.63	660	330	24	8	183	1	59	9.4	2.5
1611-SL	66.92	15.23	3.46	0.058	1.19	2.90	3.84	2.78	0.495	0.08	2.52	99.48	693	350	23	7	169	1	58	8.2	2.2
1613-SL	66.94	15.33	3.84	0.063	1.29	3.15	3.86	2.57	0.561	0.08	2.15	99.82	700	379	22	9	178	1	70	7.9	2.1
1614-SL	68.18	14.69	3.21	0.057	1.04	2.64	3.72	2.81	0.447	0.07	2.56	99.42	711	331	24	8	174	2	56	9.2	2.5
1616-SL	66.32	15.34	3.84	0.059	1.26	2.94	3.89	2.79	0.560	0.09	2.54	99.63	672	353	24	10	202	2	76	8.9	2.4
1714-SL	70.84	13.71	3.08	0.056	1.00	2.44	3.46	2.66	0.418	0.09	2.08	99.84	656	330	23	7	175	2	55	7.9	2.3
1715-SL	69.81	14.50	3.03	0.057	1.16	2.84	3.59	2.70	0.462	0.10	2.17	100.40	687	351	20	8	149	2	63	7.6	2.2
1718-SL	69.35	14.84	3.17	0.055	1.05	2.63	3.77	2.78	0.44	0.10	2.22	100.4	725	352	21	7	168	2	58	7.9	2.3
MD	68.00	14.84	3.41	0.058	1.16	2.84	3.75	2.74	0.485	0.08	2.41	99.77	686	348	23	8	174	2	62	8.4	2.3
DE	1.42	0.46	0.28	0.003	0.09	0.21	0.12	0.10	0.05	0.01	0.29	0.40	22	16	1	1	13	0	7	0.7	0.2

Table 3
Granulometric parameters of aeolian sand of WADF. References: SD, standard deviation; ϕ 1%, first percentile; K_G, kurtosis; SK_1, asymmetry; % <62 μm, proportion of material finer than 62 μm.

Sample	Mean	SD	Mode	ϕ 1%	Median	K_G	SK_1	% <62 μm
MG05-07	3.25	0.52	3.50	1.70	3.10	1.05	0.02	4.85
MG05-10	3.30	0.54	3.50	1.70	3.20	0.94	−0.06	6.40
MG05-12	3.08	0.49	3.00	2.10	2.80	1.09	0.39	5.20
MG05-18	2.84	0.40	2.75	2.00	2.60	1.07	0.32	0.30
Mean	3.12	0.49	3.19	1.88	2.93	1.04	0.17	4.19
DE	0.21	0.06	0.38	0.21	0.28	0.07	0.22	2.68
MN05-01	2.96	0.61	3.00	1.50	2.80	1.02	0.04	3.50
MN05-02	2.99	0.61	3.00	1.50	2.90	1.02	0.04	1.20
MN05-04	2.96	0.61	3.00	1.40	2.80	1.02	0.04	3.50
Mean	2.97	0.61	3.00	1.47	2.83	1.02	0.04	2.73
DE	0.02	0.00	0.00	0.06	0.06	0.00	0.00	1.33
SL05-19	3.35	0.49	3.50	1.80	3.20	1.23	0.03	6.60
SL05-23	3.34	0.55	3.50	1.40	3.30	1.72	−0.17	3.30
SL05-25	3.31	0.51	3.50	1.30	3.20	1.23	−0.03	3.70
SL05-26	3.24	0.58	3.50	2.40	3.20	1.23	0.15	2.90
Mean	3.31	0.53	3.50	1.73	3.23	1.35	0.00	4.13
DE	0.05	0.04	0.00	0.50	0.05	0.25	0.13	1.68

two dune fields, with a mean value of 71.57%, whereas mean silica in MN and SL sand are 68.91% and 68.00%, respectively. The highest concentration of alumina appears in SL sand, with an average of 14.85% of Al_2O_3; MG dune sands have lower values (av. 12.66%, Fig. 6).

The composition of the other major oxides is somewhat similar between MG and SL sands whereas sand from MN dune field shows a distinctive geochemical signature. This geochemical similarity for MG and SL sands is particularly evident in the percentages of CaO, Fe_2O_3(T), MgO, MnO, Na_2O and K_2O (Fig. 6). In contrast for MN sands the contents of MgO (av. 2.00%) and CaO (av. 5.12%) are almost twice the amounts of these oxides in MG (av.1.05% and 2.40%) and SL (av.1.16% and 2.88%) sands. The proportion of Fe_2O_3(T) and MnO are also higher in MN sand than in MG and SL sands resulting in clear differentiation of MN sands on Harker diagrams (Fig. 6). The MN sands also have the lowest alcalis (Na_2O, K_2O) values, whereas MG and SL sands have relatively elevated values (Fig. 6)

Trace element composition of WADF sand also shows some distinctive trends for the three studied dune fields. The most distinctive tendencies are the presence of higher values of Ba, Sr, U and Th elements in MG and SL sands than in MN sand, with corresponding lower values of Sc and V elements (Table 2). Average Ba content for MG and SL sands is 582 ppm and 686 ppm, respectively, but only 373 ppm for MN sands. MG sand exhibit mean Th and U of 7.2 ppm and 2.0 ppm, whereas SL and MN have corresponding Th and U values of 8.45 and 2.31 ppm and 4.5 and 1 ppm. Sr content covaries like U and Th with averages of 306 ppm and 348 ppm for MG and SL sands, respectively, and nearly 210 ppm in MN sands. Noticeable is the high mean content of V, 117 pm, for MN sands, compared to 64 and 62 ppm for MG and SL sands, respectively.

WADF geochemical data allow discrimination of the three studied dune fields (Fig. 7) The plot of Ba versus K_2O differentiates well sand from MG, SL and MN dune fields (Fig. 7a). Various elemental ratios, including La/Sc, La/Co, Th/Sc, are appropriate geochemical discriminators, reflecting contribution from mafic and felsic source rocks. La and Th tend to concentrate in felsic igneous rocks whereas Co, Sc and Cr have higher concentrations in mafic rocks (e.g., Wronkiewicz and Condie, 1987; Osae et al., 2006). Th/Sc vs Sc plot of WADF also discriminates well MN sand from MG and SL sands (Fig. 7b). The Th/Sc ratios of 0.82–1.17 for MG and SL sands indicate a felsic source, whereas MN sand yield lower ratios of 0.22–0.28 suggesting a mafic source, according to ranges presented by Condie (1993).

Continental crust rocks are usually enriched in U, whereas elevated V reflects ultramafic–mafic rocks. Thus, sediments derived from felsic sources usually have high values of U, whereas ultramafic–mafic source rocks supply sediments with elevated V content (Bhatia and Crook, 1986). MG and SL sands have average U content of 2.0 and 2.3 ppm, respectively, and MN sand a noticeably lower average value of 1.00 ppm. In contrast, MN sand has higher V values (av. 117 ppm) than MG and SL sand, both with average V of 63–64 ppm (Table 2). U and V contents indicate that MG and SL sands are derived principally from a felsic source while MN sand shows a relatively more mafic provenance.

The more mafic signature of MN sand probably reflects the significant presence of ultramafic–mafic lithologies in the Valle Fértil, Los Llanos and Ulapes hills (Vujovich and Kay, 1996, 1998; Otamendi et al., 2009). These high relief mountains enclose MN

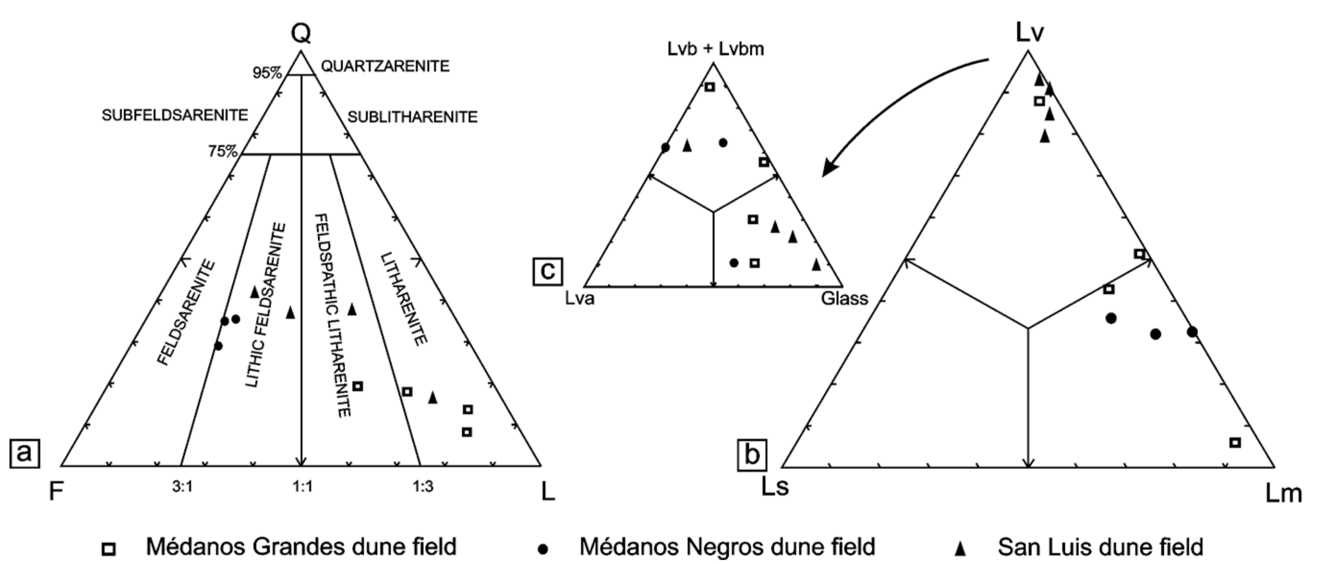

Fig. 4. Petrographic composition of WADF sand: (a) sand classification according to Folk et al. (1970); (b) distribution of sedimentary (Ls), metamorphic (Lm) and volcanic (Lv) rock fragments; c, distribution of glass, intermediate to basic paleovolcanic (Lvb + Lvbm) and acid paleovolcanic (Lva) rock fragments.

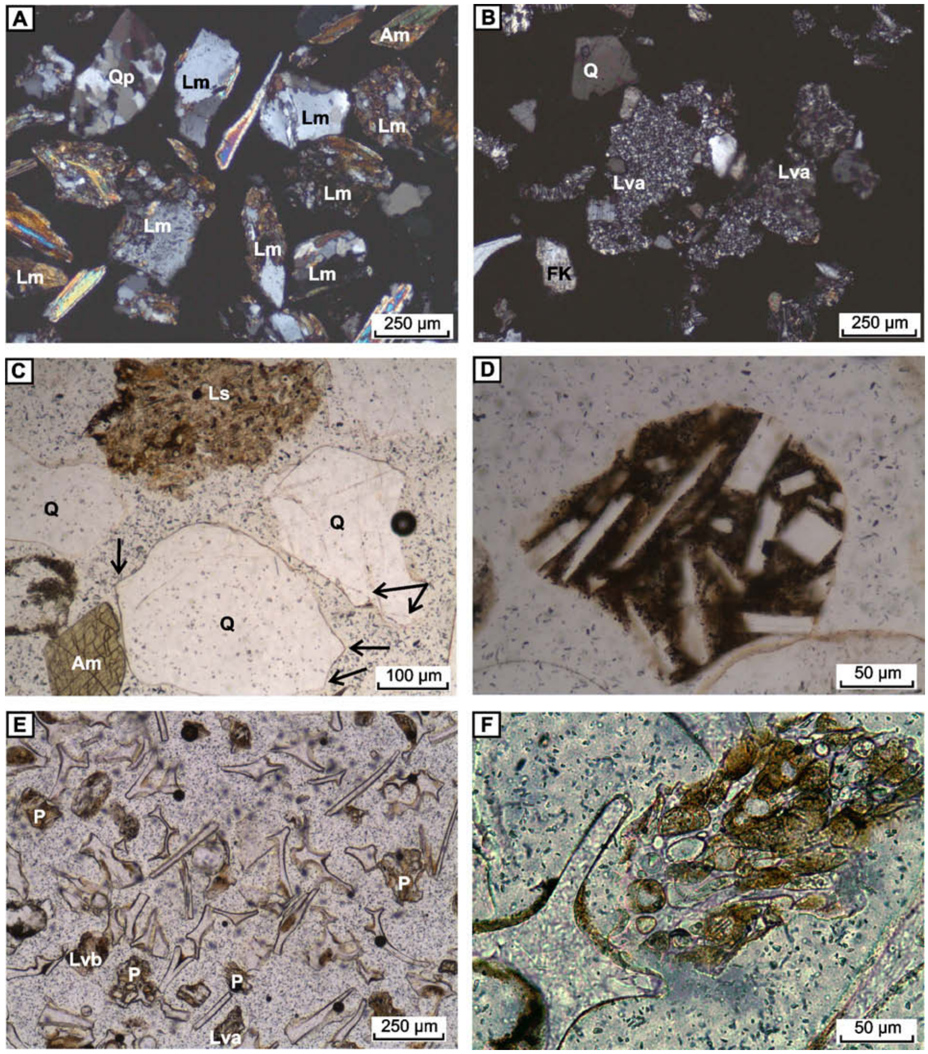

Fig. 5. Compositional variation of WADF sand: (a) metamorphic rock fragments from MG dune field; (b) acid (Lva) volcanic rock fragments, K-feldspars (FK) and quartz (Q) from MG dune field; (c) quartz grains (Q) with well preserved quartz overgrowth (arrowed), amphibole (Am) and sedimentary rock fragment (Ls) from MN dune field; (d) basic volcanic rock fragment from MN dune field; (e) glass shards, pumices (P), acid (Lva) and basic (Lvb) volcanic rock fragments from SL dune field; (f) close view of fresh glass shard and pumice from SL dune field.

dune field and was a major sediment source for the alluvial system and, subsequently, for the aeolian dunes. MG sand may be also sourced from Sierra de Valle Fértil (Fig. 1) and from Sierra de Pie de Palo that exposes numerous metasedimentary successions. An additional source area for MG dune field is the Andean Precordillera, which contains felsic volcanic lithics and glass that would dilute the mafic signature from more proximal sources in the Valle Fértil Range. The felsic signature of SL sand indicates a significant proportion of sediments derived from the Andes, though there may be local contributions from the Sierra de San Luis, which includes some igneous rock outcrops of ultramafic–mafic composition.

Th and Zr are often concentrated in more mature sands, as these elements are highly resistant to weathering (Taylor and Eggleton, 2001, p. 140, 143). The binary plot of Th/Sc vs. Zr/Sc ratios clearly discriminates MN sand from MG and SL sands (Fig. 7d). The lower Th and Zr contents in MN samples suggest that this sand is relatively mineralogically immature, with less transport and recycling than sands from MG and SL dune fields. Likewise, MN sand shows commonly grains with well preserved quartz overgrowths indicating limited sand transport (Fig. 5c). This apparent mineralogical immaturity of MN dune sand reflects the setting with the dune field developed in an endorheic basin and sand derived from local sources (Fig. 1). In contrast, MG and SL sands are relatively mature sediments probably sourced from extensive alluvial plains (Fig. 1).

7. Provenance of aeolian sand of WADF

Aeolian sand is mainly derived from the reworking of fluvial or lacustrine deposits and less commonly from direct bedrock sources (e.g. Cooke and Warren, 1973; Fryberger and Ahlbrandt, 1979; Muhs et al., 2003; Yang et al., 2007). The composition of the WADF deposits reflects the complex mixtures of mono and polycrystalline grains eroded from rocks of highly diverse composition (Fig. 1), and then transported by colluvial, fluvial and aeolian processes. The sand samples of the three studied dune fields show compositional differences reflected in the QFL and QmFL ratios, proportions of volcanic and metamorphic rock fragments and amounts of glass and accessory minerals (Table 1 and Fig. 8). These different petrographic compositions point to various sediment sources. WADF sands are related principally, via fluvial systems, to three main provenances: (1) pre-Quaternary volcanic rocks, (2), metamorphic-igneous rocks and (3) contemporary explosive volcanism. The pre-Quaternary volcanic lithics come mainly from the Andean Cordillera, but also from the Precordillera and the San Rafael Block. Sierras Pampeanas are the

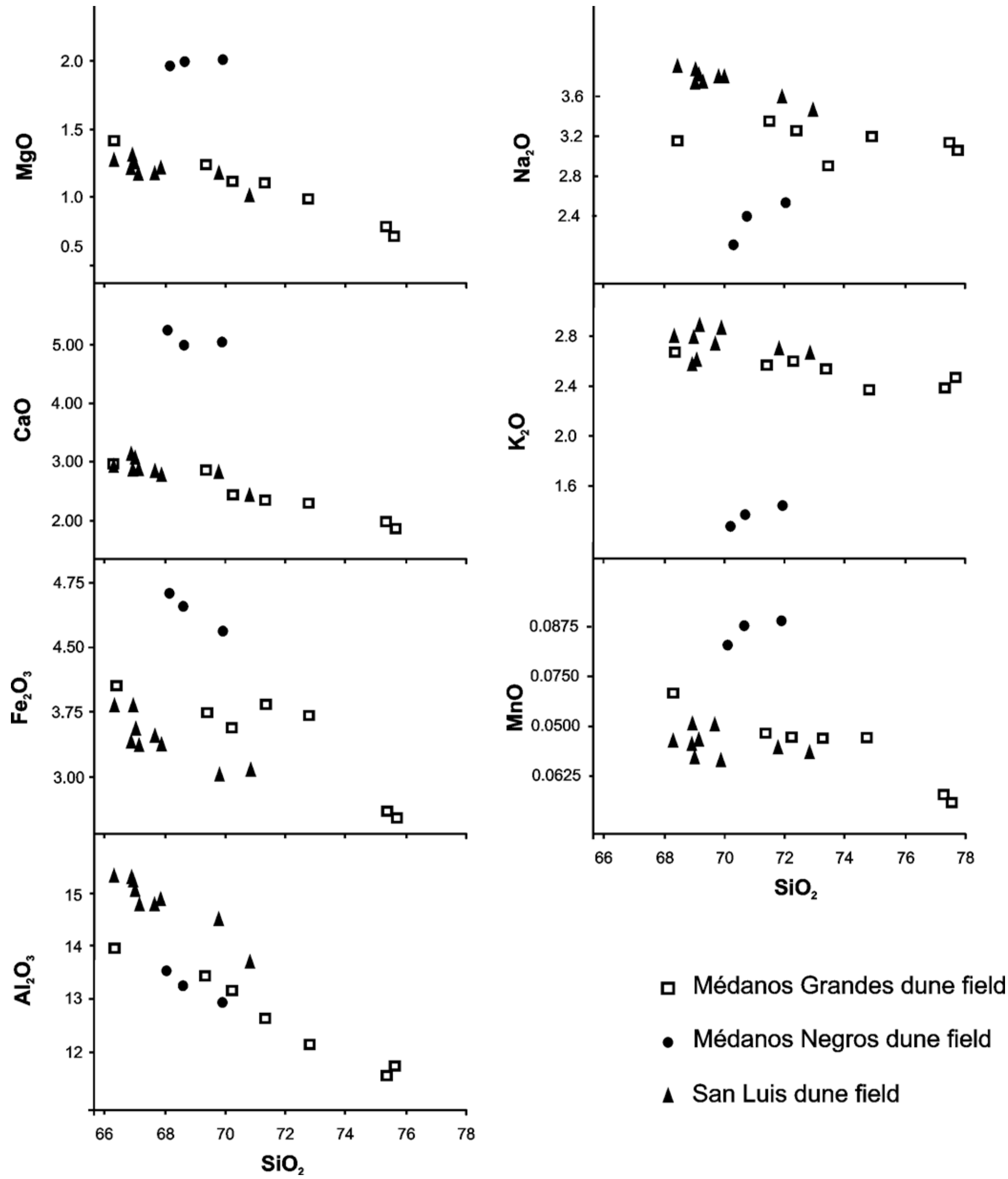

Fig. 6. Harker diagrams showing the distribution of major oxides in MG, MN and SL sands.

main supplier of metamorphic–igneous rock clasts in central-western Argentina while the fresh glass was originated from explosive volcanism of the Andes during the Quaternary. Although extended Quaternary volcanic rocks appear in southern Mendoza province (Fig. 1). Those outcrops are a secondary sediment source because basalt flows are characteristically unweathered and dissected by low order streams with limited transport capabilities.

The litharenite to feldspathic litharenites of MG dune field show greater proportion of lithic fragments than quartz and feldspar and most of the lithics are fragments of metamorphic and volcanic rocks (Fig. 4). MG sands also have variable amounts of accessory minerals (like micas, amphiboles, pyroxenes opaque minerals and zircon), much of the quartz is polycrystalline and feldspars are mainly K-feldspars. Volcanic components in MG sands are paleovolcanic and neovolcanic sources (Fig. 4). These petrographic features suggest a mixed provenance with elements from Sierras Pampeanas metamorphic–igneous complex, pre-Quaternary volcanic rock assemblages and Quaternary Andean explosive volcanism.

The lithic feldsarenites of MN dune field present the greatest proportions of feldspar grains in relation to quartz and lithics, together with high quantities of accessory minerals (mainly amphiboles and pyroxenes) and small amounts of paleovolcanic rock fragments of intermediate to mafic types. Rock fragments are dominated by metamorphic lithologies, like slate, schist and micacite grains and K-feldspars are equally abundant as plagioclases. The petrographic composition of MN sand indicates a provenance dominated by the metamorphic–igneous complexes of the Sierras Pampeanas.

The SL sand shows the greatest mineralogical variation with lithic feldsarenite, feldspathic litharenite and lithic arenite, due to variable proportions of feldspars and rock fragments and less quartz. In turn, those sands have appreciable amounts of metamorphic rock fragments and have higher amounts of accessory minerals (like amphibole, muscovite and zircon). A significant feature of SL sand is the presence of fresh pumices and glass shards (Figs. 4c and 5e). The SL sand composition reveals a mixed provenance with volcanic elements from the Andes and variable proportions of Sierras Pampeanas metamorphic–igneous rocks, similar to that portrayed by MG sand.

WADF sand petrographic analysis indicates that MG and SL share a common provenance with Andean volcanic and Sierras

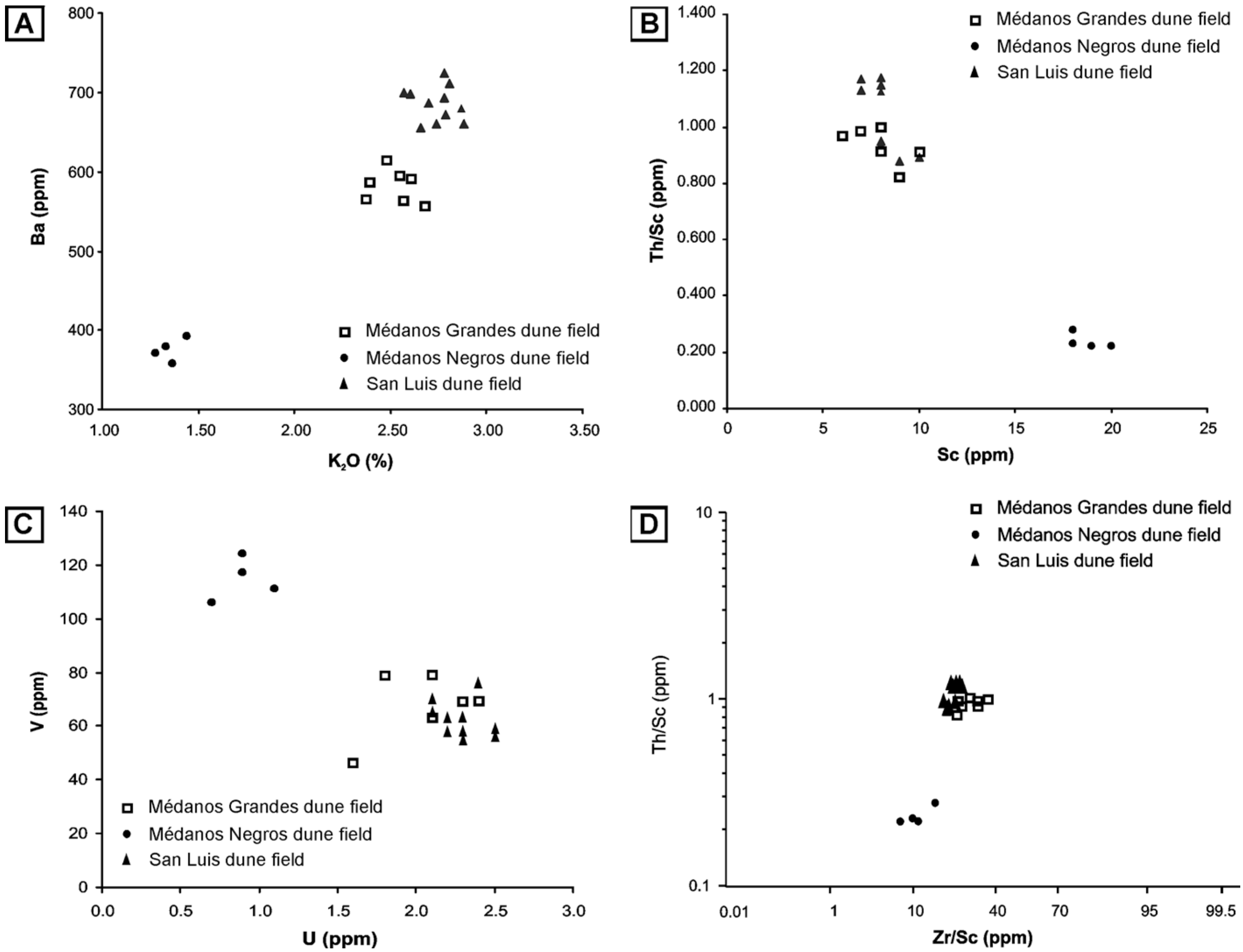

Fig. 7. Geochemical signatures of WADF sand illustrated by the relations between potassium (K_2O) and barium (Ba) (a), thorium (Th), zirconium (Zr) and scandium (Sc) (b), uranium (U) and vanadium (V) (c), thorium/scandium and zirconium/scandium (d).

Pampeanas contributions. A noticeable feature of MG and SL sands is the persistent occurrence of fresh glass indicating significant sand contributions from Quaternary explosive volcanism. Whereas MN dune sand reflects lithologies almost solely from the Sierras Pampeanas basement.

Geochemical data underscores petrographic trends with noticeable similarities between MG and SL and distinctive signature of MN sands (Fig. 6). Specifically, MN shows higher amounts of MgO, CaO, Fe_2O_3(T), MnO and lower amounts of Na_2O and K_2O than MG and SL sands. Equally diagnostic are trace elements like Ba, Sr, Th and U which are higher in MG and SL sands than in MN one, whereas on the contrary Sc and V contents in MN almost double the values in MG and SL sands. These geochemical tendencies portray a felsic signature for MG and SL sands and a relatively more mafic one for MN sand. The principal contribution of felsic elements in MG and SL sands are derived from Andean sources whereas the more mafic signature of MN sand reflects the significant presence of ultramafic–mafic lithologies in the Valle Fértil, Los Llanos and Ulapes hills that enclose this dune field (Vujovich and Kay, 1996, 1998; Otamendi et al., 2009).

Provenance petrographic studies typically employ discriminative ternary plots (see Dickinson, 1985), to evaluate the source and tectonic setting of ancient sandstones (Dickinson et al., 1983; Ingersoll, 1983; Net and Limarino, 2006). This methodology is also useful to evaluate sources and associated processes for Quaternary fluvial and aeolian terrains (Critelli et al., 1997; Le Pera and Critelli, 1997; Kasper-Zubillaga et al., 1999; Kasper-Zubillaga and Dickinson, 2001). Thus, the provenance patterns for WADF are analyzed by plotting the sand composition in the diagrams proposed by Dickinson et al. (1983). In the QFL diagram aeolian sand from SL and MN dune fields resides in the dissected arc field (Fig. 8a), except for one sample from the San Luis dune field which plots in the undissected arc field due to the very high percentage of volcanic glass (52%). Aeolian sand from MG dune field plots in the undissected to transitional arc fields (Fig. 8a). Likewise, in the QmFL scheme aeolian sand from SL and MN dune fields also mostly occupies the dissected arc field, whereas sand from MG dune fields falls into the undissected arc to lithic recycled fields (Fig. 8b). This distribution is consistent with the location of the three studied dune fields, east of the Andean orogen which has been uplifted since the early Cenozoic, resulting in several volcanic sequences (Andean orogenic cycle; Ramos, 1999). Moreover, the inmature mineralogic composition of these aeolian sands is linked to sediment sources from granitic and metamorphic rocks of the Sierras Pampeanas and of sedimentary and pre-Cenozoic volcanic successions outcropping in the Precordillera (Limarino et al., 2002; Remesal et al., 2004) and the San Rafael block (Llambías et al., 1993, 2003; López Gamundí, 2006; Bissig et al., 2002; Litvak

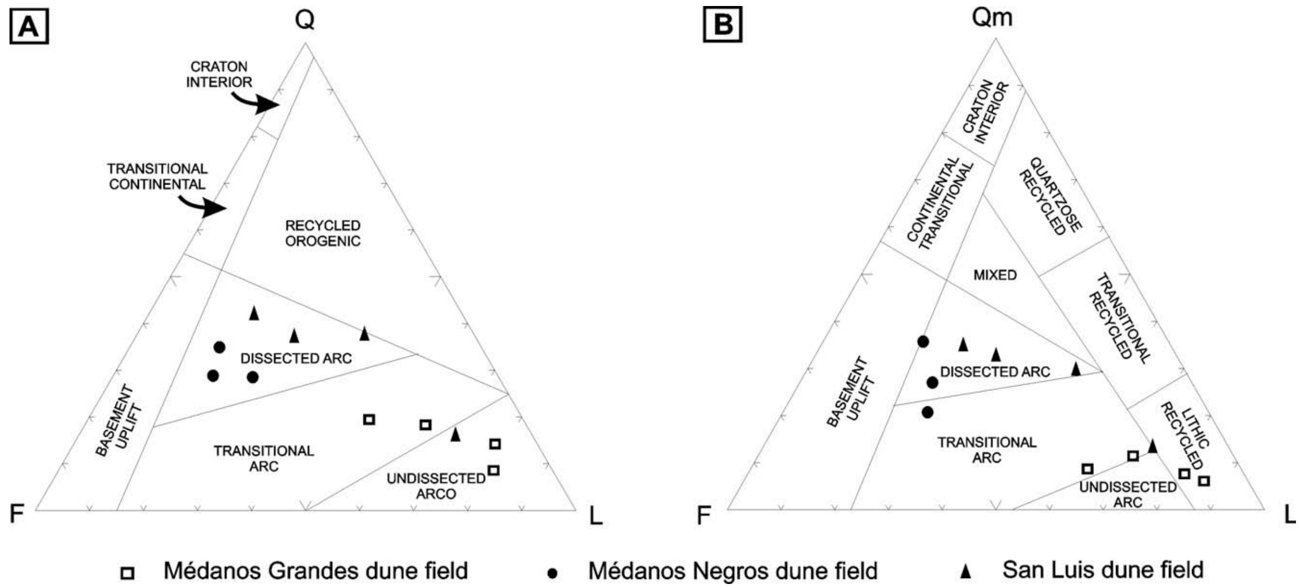

Fig. 8. QFL and QmFL relations from WADF sands. Provenance diagrams after Dickinson et al. (1983).

and Poma, 2005; Litvak et al., 2007) (Fig. 1). This high relief terrain supplied large quantities of sediments with a variable composition to alluvial fans and streams, which developed extended alluvial plains. Due to the semiarid to arid climate of western Argentina many of these alluvial systems were subsequently reworked by aeolian transport forming several dune fields.

Most of the WADF sand samples plot in the volcanic arc fields (Fig. 8), however there are some variations in composition between dune fields reflecting diverse geologic setting and associated geomorphic processes. MG aeolian sand was derived probably from the east flowing San Juan River, emanating from the Andean Cordillera and crossing the Precordillera and from the south flowing Bermejo-Desaguadero River whose tributaries emerge from the Precordillera and the Sierra de Valle Fértil (Fig. 1). These rivers deliver mostly volcanic and basement lithologies, respectively. Both rivers have significant bed infiltration and the San Juan River terminates with a large fan, another source of aeolian sand. Other potential sources for aeolian sediment are the alluvial fans, at present partially dissected, that form along the range front of the Sierra de Pie de Palo, composed of metamorphic rocks.

MN dune field is not far away from MG dune field (about 50 km apart) but its aeolian sand portrays a different tectonic setting, shifted to the transitional to dissected arc fields (Fig. 8). MN dune field is in an endorheic basin with its lower parts occupied by evaporitic–epiclastic ephemeral lakes (Salinas de Mascasín), which are proximal sources for aeolian sand. These ephemeral lakes are in turn fed by low-energy fluvial input, draining essentially the metamorphic–igneous complex of the Sierras Pampeanas (Fig. 1). This source rock would explain the presence of a larger proportion of plagioclase, feldspars and less rock fragments than those occurring in the MG and SL sands. The dominance of mafic lithologies reflects source and availability controls of aeolian sand restricted to this closed basin.

SL aeolian sand has a composition consistent mostly with the dissected arc field (Fig. 8), reflecting significant percentages of feldspar and lithic fragments, and minor amounts of quartz. One noticeable exception is one sand sample that has >50% of glass and thus plots in the undissected arc field. Likely sources of aeolian sediments are the large fluvial systems of the Quinto and Bermejo-Desaguadero rivers. The Quinto River drains from the Sierra de San Luis, which is composed mostly of metamorphic and igneous rocks. In contrast the Bermejo-Desaguadero River has sediment from a number of tributaries (San Juan, Mendoza, Tunuyán and Diamante rivers) emanating from the Andean Cordillera. This diverse source of sediments is reflected in the presence of volcanic and metamorphic–granitic lithologies in aeolian sand, as indicated on the Dickinson diagrams (Fig. 8). The high percentage of pumice and glass shards in SL sand indicates an additional sand supply from Quaternary explosive volcanism from the Andes.

8. Results and discussion

The petrographic and geochemical compositions of WADF aeolian sand indicate a mixture of sources, with a main component from the Andes, accompanied by significant proportions of basement lithologies from the Sierras Pampeanas. The volcanic component is varied, including fragments of highly altered or metamorphosed, intermediate to basic volcanic rocks and of mostly fresh acid volcanic rocks. These fragments suggest an origin from old volcanic rock outcrops (like Upper Paleozoic–Mesozoic series, e.g. Remesal et al., 2004; Llambías et al., 1993, 2003; López Gamundí, 2006) and from more recent volcanic successions, likely from the thick Andean Cenozoic volcanic series (e.g. Bissig et al., 2002; Limarino et al., 2002; Litvak and Poma, 2005; Litvak et al., 2007). There are also variable amounts of fresh pumices and glass shards in the WADF sand, with some samples showing none to <3% and others ranging from $\sim$10% up to 52%. These pristine volcanic particles may have been introduced from the deflation of pyroclastic-rich alluvial sediments, as suggested by Zárate and Blasi (1993), but also likely from direct ash fall. Significant explosive volcanism has occurred in the Andes in the late Quaternary (González Ferrán, 1994; Naranjo and Haller, 2002; Siebert and Simkin, 2002; Risso et al., 2008) with ash plumes covering central to northern Argentina due to strong high altitude westerly–southwesterly winds (Hildreth and Drake, 1992). In turn volcanic ash and pumice on the landscape may serve as a saltation catalyst by providing particles for entrainment and reduction of obstacles, enhancing aeolian transport.

Early study of the mineralogy of Pampean loess indicates that this ubiquitous deposit is maybe derived partially from an Andean volcaniclastic source (Teruggi, 1957). Zárate and Blasi (1993) assumed the explosive volcanism as the predominant process of formation for most of the particles of southern Pampas aeolian deposits. Geochemical studies show that the Neodimium isotopic composition of Pampean loess reflects an Andean volcanic source (Smith et al., 2003). However, other investigations illustrate that the Pampean loess has a heterogeneous composition. For example, Morrás (1999) presented a geochemical differentiation of Pampean sediments based on the natural phosphorus contents in soils using data obtained in the early 20th century. Three main compositional regions for phosphorous were identified in southern, northern and northeastern Pampas, which are related to different sediment sources. The lowest values of phosphorus were found in northeastern Pampas and correlated to a provenance from the Paraná River flowing from the Brazilian shield (Morrás, 1999). The highest phosphorus content occurred in northern Pampas soils reflecting a sediment supply from the Sierras Pampeanas mixed with Andean volcaniclastic sediments. Finally, loess from southern Pampas shows intermediate values and is associated with an Andean provenance (Morrás, 1999). The presence of loess with different compositions across the Pampas is also portrayed in mineralogic parameters (quartz/feldspar + glass index and percentages of heavy minerals, pyroxenes and micas) according to data provided by Morrás (2003).

This mixture of sediments from different sources in the aeolian deposits was also highlighted by Zárate (2003), pointing out the presence of several loess and loessoid domains across the Chaco-Pampean region related to different source areas. The combination of sources is also reflected in the composition of the WADF sand which is probably derived from deflation of alluvial plains emanating from the Andes and the Sierras Pampeanas, plus the direct input of volcanic ash.

The petrographic composition of aeolian sand from MG, MN and SL dune fields is somewhat similar to aeolian sand from other localities of central-western Argentina. The aeolian sand from WADF has similar proportions of quartz but less amounts of K-feldspar and plagioclase, higher amounts of lithic fragments and important and variable occurrence of fresh glass compared with sand compositions published by Sánchez and Blasarín (1987), Strasser (1982), Iriondo and Ramonell (1983), Iriondo and Kröhling (1999) (Tables 1 and 4). In relation to Pampean loess and loessoid sediments the WADF sand shows generally larger amounts of lithic fragments and smaller proportions of feldspars and glass (Tables 1 and 4). The petrographic relationships between aeolian sand and loess are shown in Fig. 9. Among the WADF sand the closest compositional similarities to loess and loessoid sediments are sands from SL dune field.

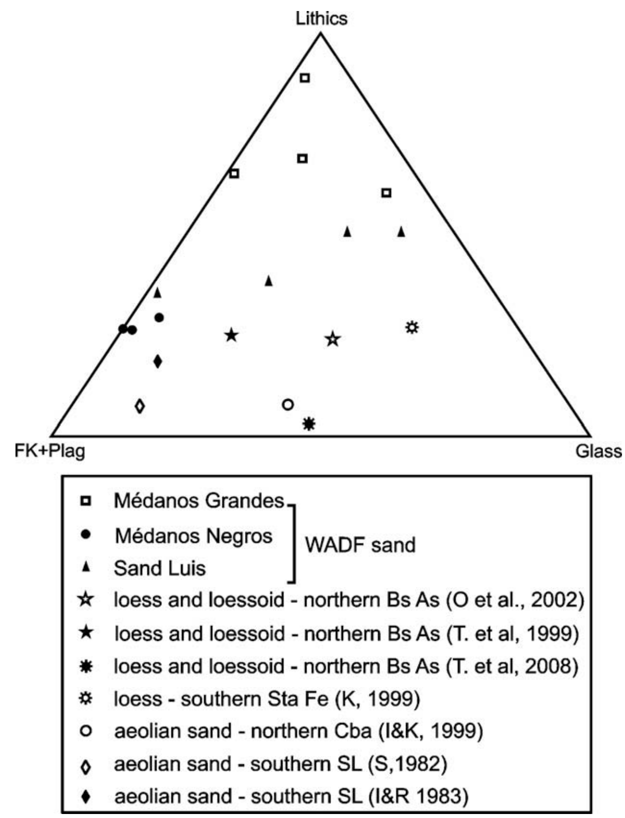

Fig. 9. Comparison of petrographic composition of loess, loessoid and aeolian sand from central Argentina. Plotted samples are from the here studied Médanos Grande, Médanos Negros and San Luis dune fields and from the following authors: Iriondo and Kröhling (1999), Strasser (1982), Iriondo and Ramonell (1983), Kröhling (1999b), Orgeira et al. (2002), Tonni et al. (1999), Tófalo et al. (2008); Bs As, Buenos Aires province; Sta Fe, Santa Fé province; Cba, Córdoba province; SL, San Luis province.

Table 4
Petrographic composition of aeolian sediments (loess, loessoid and sand) from Argentina. Qt, total quartz; FK, K-feldspar; Plag, plagioclase; A, alterites; L, lithic fragments. Data from: Sánchez and Blasarín (1987), Iriondo and Kröhling (1999), Strasser (1982), Iriondo and Ramonell (1983), Kröhling (1999b), Orgeira et al. (2002), Tonni et al. (1999) and Tófalo et al. (2008).

Locations	Qt	FK	Plag	FK + Plag	Glass	A + L
Aeolian sand						
Southern Cba (S&B)[a]	19.0	55.5	8.5	64.0	20.5	–
Northern Cba (I&K)	34.0	15.0	21.5	36.5	27.5	13.0
Southern San Luis (S)	14.0	53.0	9.0	62.0	10.0	6.0
Southern San Luis (I&R)	27.0	42.0	4.0	46.0	7.0	12.0
Loess loessoid						
Southern Sta Fe (K)	56.4	5.9	2.5	8.5	23.0	11.4
Northern Bs As (Orgeira et al.)	6.0	3.0	30.0	33.0	37.0	21.5
Northern Bs As (Tonni et al.)[b]	9.0	11.3	37.7	49.0	19.0	22.7
Northern Bs As (Tófalo et al.)[c]	10.0	–	–	43.0	39.2	1.0
WADF sand						
Médanos Grandes dune field	12.6	10.3	3.6	13.9	14.0	63.8
Médanos Negros dune field	31.6	25.7	18.4	44.1	1.50	16.9
San Luis dune field	32.2	14.0	9.1	23.1	23.0	38.1

[a] Alterites and lithic fragments not informed.
[b] Fluvially reworked loess.
[c] FK and Plag not discriminated.

The relation between alumina and silica further aids in discriminating among WADF sand with Pampean loess and aeolian sand from other regions of Argentina (Fig. 10a). There is a slight increase in the Al_2O_3/SiO_2 ratio from MG to MN to SL sand, and with loess from northern Buenos Aires province (Mercedes city; data from Gallet et al., 1998). A published geochemical data of aeolian sand near Río Cuarto city, southern Córdoba province (Schultz et al., 2004), plots close to SL sand. The relation between mafic and felsic mineralogic components, represented by the sum of iron, manganese, magnesium and calcium versus the amount of potassium plus sodium (Fig. 10b), shows that the northern Buenos Aires loess presents a variable composition (cf. Gallet et al., 1998). Comparing with WADF sand some loess samples are similar to MG and SL sands while other loess are more comparable to MN sand. Southern Córdoba aeolian sand mirrors the Al_2O_3/SiO_2 relationship of MG and SL sands (Fig. 10b).

Westerly Zonda (foehn) winds and other westerly winds (related to incursions of cold fronts and to extratropical cyclones) (cf. Prohaska, 1976; Norte, 1988; Garreaud et al., 2008) can affect the western and central Argentina by carrying particles from the alluvial plains that emerge from the Andes and the Sierras Pampeanas to the Pampean plains. The dominance of west-to-east transport of clastic sediments and the petrographic–geochemical similarity between WADF sands and some Pampean loess indicate a potential provenance for silt particles from

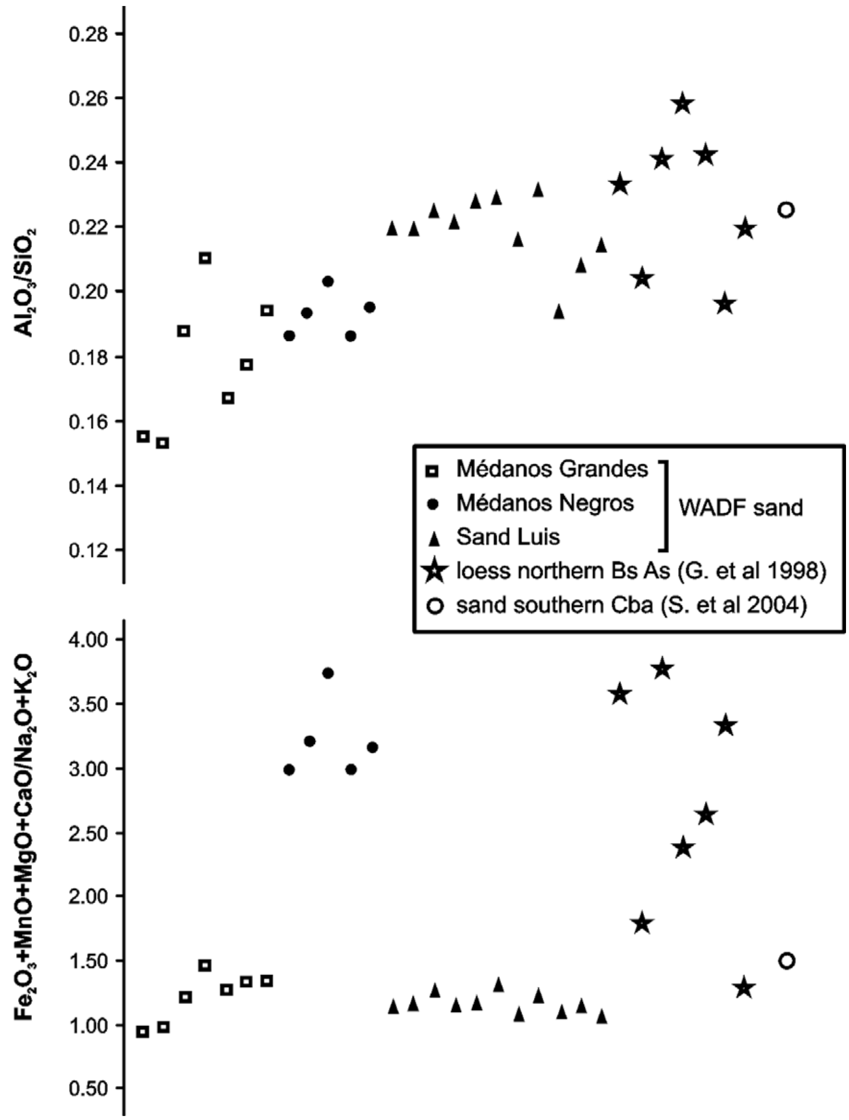

Fig. 10. Comparison of geochemical composition of loess, loessoid and aeolian sand from central Argentina. Plotted samples are from the here studied Médanos Grande, Médanos Negros and San Luis dune fields, loess from northern BsAs (Buenos Aires province) from Gallet et al. (1998) and sand from southern Cba (Córdoba province) from Schultz et al. (2004).

western and central Argentina. The Pampean loess was analyzed to evaluate it as a source material for the dust found in Antarctic ice cores. Provenance analyses of Antarctic dust use principally Sr and Nd isotopes and remote sensing to infer two main South America sources areas: the Patagonia and the Puna-Altiplano plateau (a 4000 m high elevated basin principally covered by volcanic-ignimbrite deposits) (Basile et al., 1997; Prospero et al., 2002; Delmonte et al., 2004; Gaiero et al., 2004, 2007; Gaiero, 2007). Both regions account for the contribution of volcanic materials to the Antarctic dust. This study indicates that WADF sand also contains a significant component of volcanic lithologies, likely derived from the extensive volcanic successions of the Andean Cordillera, the San Rafael Block and from more restricted outcrops of the Precordillera. The extensive alluvial plains and dune fields emerging from these high relief areas cannot be ruled out as one of the source of volcanic-rich aeolian sediments in southern South America. Aeolian abrasion within the many dune fields in western Argentina may be another source of silt and finer particles (cf. Pye, 1987; 16–18). In that sense, future Antarctic dust provenance studies should include the central-western Argentina as a potential source area.

9. Summary and conclusions

Aeolian sands from western Argentina dune fields of Médanos Grandes, Médanos Negros and San Luis have distinctive petrographic and geochemical composition. Provenance analyses indicate lithologic components from the Andes, the Precordillera and the Sierras Pampeanas, with significant volcanic component from bedrock and direct airfall ash sources.

Médanos Grandes dune sands are litharenites to feldspathic litharenites and have a higher proportion of metamorphic and volcanic rock fragments than quartz and feldspar. Trace element geochemistry (U, Th, Sc and V content) indicates the dominance of felsic source rocks. In total the geochemical and petrographic properties indicate a mixed provenance with contributions from the Sierras Pampeanas metamorphic–igneous complex, from pre-Quaternary volcanic rock assemblages and significant input from Quaternary Andean explosive volcanisms. This association indicates that aeolian sand is probably derived from San Juan and Bermejo-Desaguadero rivers that mostly transport volcanic and basement lithologies.

Médanos Negros aeolian sands are lithic feldsarenites with abundant feldspars and quartz and lesser amounts of lithics.

K-feldspar abundance is similar to plagioclase whereas rock fragments are mainly of slate, schist and micacite. Th, Sc, U and V content indicates a mostly mafic source lithology. These aeolian sands are geochemically and petrographically distinctive, derived probably from nearby metamorphic–igneous complexes of the Sierras Pampeanas, particularly the Valle Fértil Range. MN dune field reflects source and availability controls restricted to this closed basin.

The San Luis dune field shows substantial petrographic variability with lithic feldsarenites, feldspathic litharenites and lithic arenite reflecting variable proportions of feldspar and rock fragments. Trace element geochemistry suggests a more felsic source, similar to Médanos Grandes. A diagnostic feature is the presence of fresh pumices and volcanic glass shards. The composition of SL aeolian sand reflects variable contributions from Andean volcanic sources and metamorphic–igneous rocks from the Sierras Pampeanas, like Médanos Grandes.

The broad petrographic and geochemical similarities among Médanos Grandes and San Luis dune fields and Pampean loess denote that aeolian sand, silt particles and, eventually, far travelled dust may share a relatively common source, for instance the numerous west-to-east draining fluvial systems and dune fields of western Argentina.

Acknowledgements

This study was partially supported by a Cooperative Agreement between the Univ. of Illinois and Dept. of Interior, National Park Service to forward a comparative analysis between North and South American dune fields. Additional funding was provided by UBACyT X866 Grant. Satellite images and meteorological data supplied by CONAE and Servicio Meteorológico Nacional (Argentina), respectively. Support for field logistics was provided by University of Buenos Aires. We gratefully acknowledge the critical reading of an early version of the manuscript by S. Marenssi and P. Leal and their helpful suggestions. The comments of the anonymous reviewers help to improve the paper.

References

Ahlbrandt, T.S., 1979. Textural parameters of eolian deposits. In: McKee, E.D. (Ed.), A Study of Global Sand Seas, Professional Paper 1052. U.S. Geological Survey, pp. 187–238.
Barros, V.R., Silvestri, G.E., 2002. The relation between sea surface temperature at the subtropical south-central Pacific and precipitation in southeastern South American. Journal of Climate 15, 251–267.
Basile, I., Grousset, F.E., Revel, M., Petit, J.R., Biscaye, P.E., Barkov, N.I., 1997. Patagonian origin of glacial dust deposited in East Antarctica (Vostok and Dome C) during glacial stages 2, 4 and 6. Earth Planetary Science Letters 146, 573–589.
Basu, A., 1985. Influence of climate and relief on compositions of sands released at source areas. In: Zuffa, G.G. (Ed.), Provenance of Arenites, 148. NATO Science Series C, pp. 1–18.
Bhatia, M.R., Crook, K.A.W., 1986. Trace element characteristics of greywackes and tectonic discrimination of sedimentary basins. Contributions to Mineralogical Petrology 92, 181–192.
Bidart, S., 1992. Clasificación de los sedimentos eólicos del Pleistoceno tardío – Holoceno del sur de la provincia de Bs. As., Argentina: Una propuesta. IV Reunion Argentina de sedimentología. Actas 2, 159–166.
Bissig, T., Clark, A.H., Lee, J.K.W., 2002. Cerro de Vidrio rhyolitic dome: evidence for Late Pliocene volcanism in the Central Andean flat-slab region, Lama-Veladero district, 29o20′S., San Juan Province, Argentina. Journal of South American Earth Sciences 15 (5), 571–576.
Carignano, C.A., 1999. Late Pleistocene to recent climate change in Córdoba Province, Argentina: Geomorphological evidence. Quaternary International 57–58, 117–134.
Clapperton, Ch.M., 1993. Nature of environmental changes in South America at the last glacial maximum. Palaeogeography, Palaeoclimatology, Palaeoecology 101, 189–208.
Compagnucci, R.H., Agosta, E.A., Vargas, W.M., 2002. Climatic change and quasi-oscillations in central-west Argentina summer precipitation: main features and coherent behaviour with southern African region. Climate Dynamics 18 (5), 421–435.
Condie, K.C., 1993. Chemical composition and evolution of the upper continental crust: contrasting results from surface samples and shales. Chemical Geology 104, 1–37.
Cooke, R., Warren, A., 1973. In: Geomorphology in Deserts. B.T. Batsford Ltd., London, p. 394.
Critelli, S., Ingersoll, R.V., 1995. Interpretation of neovolcanic versus palaeovolcanic sand grains: an example from Miocene deep-marine sandstone of the Topanga Group (Southern California). Sedimentology 42, 783–804.
Critelli, S., Le Pera, E., Ingersoll, R.V., 1997. The effects of source lithology, transport, deposition and sampling scale on the composition of southern California sand. Sedimentology 44, 653–671.
Dalla Salda, L., Toselli, A., Caminos, R., Gardini, C., 1999. Proterozoico y Paleozoico inferior de las Sierras Pampeanas Occidentales. In: Caminos, R. (Ed.), Geología Argentina. Servicio Geológico Minero Argentino, pp. 159–167.
Delmonte, B., Basile-Doelsch, I., Petit, J.R., Maggi, V., Revel-Rolland, M., Michard, A., Jagoutz, E., Grousset, F., 2004. Comparing the Epica and Vostok dust records during the last 220, 000 years: stratigraphical correlation and provenance in glacial periods. Earth Science Reviews 66 (1–2), 63–87.
Dickinson, W.R., 1970. Interpreting detrital modes of graywacke and arkose. Journal of Sedimentary Petrology 40, 695–707.
Dickinson, W.R., 1985. Interpreting provenance relations from detrital modes of sandstones. In: Zuffa, G.G. (Ed.), Provenance of Arenites, 148. NATO Science Series C, pp. 333–361.
Dickinson, W.R., Beard, L.S., Brakenridge, G.R., Erjavec, J.L., Ferguson, R.C., Inman, K.F., Knepp, R.A., Lindberg, F.A., Ryberg, P.T., 1983. Provenance of North American phanerozoic sandstones in relation to tectonic setting: geological Society of America. Bulletin 94, 222–235.
Folk, R.L., Ward, W.C., 1957. Brazos River bar – a study in the significance of grain-size parameters. Journal of Sedimentary Petrology 27 (1), 3–27.
Folk, R.L., Andrews, P.B., Lewis, D.W., 1970. Detrital sedimentary rock classification and nomenclature for use in New Zealand. New Zealand Journal of Geology and Geophysics 13, 937–968.
Fryberger, S.G., Ahlbrandt, T.S., 1979. Mechanisms for the formation of eolian sand seas. Zeitschrift für Geomorphologie 23, 440–460.
Gaiero, D.M., 2007. Dust provenance in antarctic ice during glacial periods: from where in the southern hemisphere? Geophysical Research Letters 34, L17707.
Gaiero, D.M., Depetris, P.J., Probst, J.L., Bidart, S.M., Leleyter, L., 2004. The signature of river- and wind-borne materials exported from Patagonia to the southern latitudes: a view from REEs and implications for paleoclimatic interpretations. Earth and Planetary Science Letters 219, 357–376.
Gaiero, D.M., Brunet, F., Probst, J.-L., Depetris, P.J., 2007. A uniform isotopic and chemical signature of dust exported from Patagonia: rock sources and occurrence in southern environments. Chemical Geology 238, 107–120.
Gallet, S., Jahn, B., van Vliet-Lanoe, B., Dia, A., Rosello, E., 1998. Loess geochemistry and its implication for particle on composition of the upper continental crust. Earth and Planetary Science Letters 156, 157–172.
Garreaud, R.D., Vuille, M., Compagnucci, R., Marengo, J., 2008. Present-day South American climate. Palaeogeography, Palaeoclimatology, Palaeoecology. doi:10.1016/j.palaeo.2007.10.032.
Garzanti, E., Vezzoli, G., Andò, S., Paparella, P., Clift, P.D., 2005. Petrology of Indus River sands: a key to interpret erosion history of the Western Himalayan Syntaxis. Earth Planetary Science Letters 229, 287–302.
Gazzi, P., 1966. Le arenarie del flysch sopracretaceo dell'Appennino modenese; Correlatzioni con il flysch di Monghidoro: Mineralogiez e Petrografica. Acta 12, 69–97.
González, M., 1981. Evidencias paleoclimáticas en la salina del Bebedero. VIII Congreso Geológico Argentino. Actas 3, 411–438 (San Luis).
González Bonorino, F., 1965. Mineralogía de las fracciones arcilla y limo del pampeano en el área de la ciudad de Buenos Aires y su significado estratigráfico y sedimentológico. Revista Asociación Geológica Argentina 20 (1), 67–148.
González Ferrán O., 1994. Volcanes de Chile. Ed. Inst. Geográfico Militar. Santiago de Chile, 640 pp.
Hildreth, W., Drake, R.E., 1992. Volcán Quizapu, Chilean Andes. Bulletin of Volcanology 54, 93–125.
Ingersoll, R.V., 1983. Petrofacies and provenance of late Mesozoic forearc basin. Northern and Central California: American Association of Petroleum Geologists Bulletin 67, 1125–1142.
Ingersoll, R.V., 1990. Actualistic sandstone petrofacies: discriminating modern and ancient source rocks. Geology 18, 733–736.
Iriondo, M., 1990. Map of the South American plains—its present state. Quaternary of South America and Antarctic Peninsula, vol. 6. Balkema, The Netherlands. pp. 297–308.
Iriondo, M., 1999. Climatic changes in the South American plains: records of a continent-scale oscillation. Quaternary International 57–58, 93–112.
Iriondo, M., Ramonell, C., 1983. San Luis. In: Iriondo, M. (Ed.), El Holoceno en la Argentina, vol. 2. CADINQUA, Paraná, pp. 131–162.
Iriondo, M., Kröhling, D., 1996. El Sistema Eólico Pampeano. Com. Museo Provincial Ciencias Naturales "Florentino Ameghino" (N.S.), 5 (1), 68 pp.
Iriondo, M., Kröhling, D., 1999. Upper Quaternary Palaeoclimates of the Mar Chiquita area, North Pampa, Argentina. Quaternary International 57 (58), 149–163.
Kasper-Zubillaga, J.J., Dickinson, W.W., 2001. Discriminating depositional environments of sands from modern source terranes using modal analysis. Sedimentary Geology 143, 149–167.
Kasper-Zubillaga, J.J., Carranza-Edwards, A., Rosales-Hoz, L., 1999. Petrography and geochemistry of Holocene sands in the western Gulf of Mexico: implications for

provenance and tectonic setting. Journal of Sedimentary Research 69 (5), 1003–1010.
Kemp, R.A., Toms, P.S., Sayago, J.M., Derbyshire, E., King, M., Wagoner, L., 2003. Micromorphology and OSL dating of the basal part of the loess-paleosol sequence at La Mesada in Tucumán province, northwest Argentina. Quaternary International 106–107, 111–117.
Kemp, R.A., Toms, P.S., King, M., Kröhling, D.M., 2004a. The pedosedimentary evolution and chronology of Tortugas, a Late Quaternary type-site of the northern Pampa, Argentina. Quaternary International 114 (1), 101–112.
Kemp, R.A., King, M., Toms, P., Derbyshire, E., Sayago, J.M., Collantes, M.M., 2004b. Pedosedimentary development of part of a Late Quaternary loess-palaeosol sequence in Northwest Argentina. Journal of Quaternary Science 19, 567–576.
Kemp, R.A., Zárate, M., Toms, P., King, M., Sanabria, J., Argüello, G., 2006. Late Quaternary paleosols, stratigraphy and landscape evolution in the Northern Pampa, Argentina. Quaternary Research 66 (1), 119–132.
Kröhling, D.M., 1999a. Sedimentological maps of the typical loessic units in North Pampa, Argentina. Quaternary International 62 (1), 49–55.
Kröhling, D.M., 1999b. Upper Quaternary geology of the lower Carcarana Basin, North Pampa, Argentina. Quaternary International 57–8, 135–148.
Le Pera, E., Critelli, S., 1997. Sourceland controls on the composition of beach and fluvial sand of the northern Tyrrhenian coast of Calabria, Italy: Implications for actualistic petrofacies. Sedimentary Geology 110, 81–97.
Limarino, C., Fauqué, L., Cardo, R., Gagliardo, M.L., Escosteguy, L., 2002. La faja volcánica miocena de la Precordillera septentrional. Revista Asociación Geológica Argentina 57, 289–304.
Litvak, V.D., Poma, S., 2005. Estratigrafía y facies volcánicas y volcaniclásticas de la Formación Valle del Cura: magmatismo paleógeno en la Cordillera Frontal de San Juan. Revista Asociación Geológica Argentina 60 (2), 402–416.
Litvak, V.D., Poma, S., Kay, S.M., 2007. Paleogene and Neogene magmatism in the Valle del Cura region: new perspective on the evolution of the Pampean flat slab, San Juan province, Argentina. Journal of South American Earth Sciences 24, 117–137.
Llambías, E.J., Kleiman, L.E., Salvarredi, J.A., 1993. El Magmatismo Gondwánico. In: Ramos, V.A., (Ed.), Geología y Recursos Naturales de Mendoza, Relatorio, XII Congreso Geológico Argentino y II Congreso de Exploración de Hidrocarburos (Mendoza), pp. 53–64.
Llambías, E.J., Quenardelle, S., Montenegro, T., 2003. The Choiyoi Group from central Argentina: a subalkaline transitional to alkaline association in the craton adjacent to the active margin of the Gondwana continent. Journal of South American Earth Sciences 16, 243–257.
López Gamundí, O., 2006. Permian plate margin volcanism and tuffs in adjacent basins of west Gondwana: age constraints and common characteristics. Journal of South American Earth Sciences 22, 227–238.
McLennan, S.M., 1989. Rare earth elements in sedimentary rocks: influence of provenance and sedimentary processes. In: Lipin, B.R., McKay, G.A. (Eds.), Geochemistry and Mineralogy of Rare Earth Elements, vol. 21. Reviews in Mineralogy, pp. 169–200.
Morrás, H.J.M., 1999. Geochemical diferentiation of Quaternary sediments from the Pampean region based on soil phosphorus contents as detected in the early 20th century. Quaternary International 62, 57–67.
Morrás, H.J.M., 2003. Distribución y origen de sedimentos loéssicos superficiales de la pampa norte en base a la mineralogía de arenas. Resultados preliminares. AAS Revista 10 (1), 53–64.
Muhs, D.R., Zárate, M., 2001. Late Quaternary eolian records of the Americas and their paleoclimatic significance. In: Markgraf, V. (Ed.), Interhemispheric Climate Linkages. Academic Press, pp. 183–216.
Muhs, D.R., Reynolds, R.L., Been, J., Skipp, G., 2003. Eolian sand transport pathways in the southwestern United States: importance of the Colorado River and local sources. Quaternary International 104, 3–18.
Naranjo, J., Haller, M., 2002. Erupciones holocenas principalmente explosivas del volcán Planchón, Andes del sur (35 15′S). Revista Geológica de Chile 29 (1), 93–113.
Net, L.I., Limarino, C.O., 2006. Applying sandstone petrofacies to unravel the Upper Carboniferous evolution of the Paganzo Basin, northwest Argentina. Journal of South American Earth Sciences 22, 239–254.
Norte, F.A. 1988. Caracteristicas climatológicas del viento Zonda en la región de Cuyo. Ph.D. Thesis, Universidad de Buenos Aires, Argentina.
Orgeira, M., Walther, A., Tófalo, R., Vásquez, C., Berquó, T., Favier Dubois, C., Bhonel, H., 2002. Environmental magnetism in fluvial and loessic Holocene sediments and paleosols from the Chacopampean Plain (Argentina). Journal of South American Earth Sciences 16, 259–274.
Osae, S., Asiedu, D.K., Banoeng-Yakubo, B., Koeberl, C., Dampare, S.B., 2006. Provenance and tectonic setting of Late Proterozoic Buem sandstones of southeastern Ghana: evidence from geochemistry and detrital modes. Journal of Asian Earth Sciences 44, 85–96.
Otamendi, J.E., Vujovich, G.I., de la Rosa, J.D., Tibaldi, A.M., Castro, A., Martino, R.D., Pinotti, L.P., 2009. Geology and petrology of a deep crustal zone from the Famatinian paleo-arc, Sierras de Valle Fértil and La Huerta, San Juan, Argentina. Journal of South American Earth Sciences 27, 258–279.
Pease, P.P., Tchakerian, V.P., 2003. Geochemistry of sediments from Quaternary sand ramps in the southeastern Mojave Desert, California. Quaternary International 104 (1), 19–29.
Potter, P.E., Huh, Y., Edmond, J.M., 2001. Deep-freeze petrology of Lena River sand, Siberia. Geology 29, 999–1002.
Powers, M.C., 1953. A new roundness scale for sedimentary particles. Journal of Sedimentary Petrology 23 (2), 117–119.
Prohaska, H.E., 1976. The climate of Argentina, Paraguay and Uruguay. In: Landsberg (Ed.), Climates of Central and South America. World Survey of Climatology, vol. XXII. Elsevier, Amsterdam, pp. 13–112.
Prospero, J.M., Ginoux, P., Torres, O., Nicholson, E.E., Gill, T., 2002. Environmental characterization of global sources of atmospheric soil dust identified with NIMBUS-7 TOMS absorbing aerosol products. Review Geophysics 40, 1–31.
Pye, K.E., 1987. Eolian Dust and Dust Deposits. Academic Press, New York. 334 pp.
Ramos, V.A., 1999. Rasgos estructurales del territorio Argentino. In: Caminos, R. (Ed.), Geología Argentina. Servicio Geológico Minero Argentino, pp. 715–784.
Remesal, M., Fauqué, L.A., Limarino, C.O., 2004. Late Palaeozoic calc-alkaline volcanism in the Precordillera of La Rioja: petrology and lithostratigraphical characterization of the Punta del Agua Formation (Late Carboniferous–Early Permian). Revista Asociación Geológica Argentina 59 (3), 462–476.
Risso, C., Németh, K., Combina, A.M., Nullo, F., Drosina, M., 2008. The role of phreatomagmatism in a Plio-Pleistocene high-density scoria cone field: Llancanelo Volcanic Field (Mendoza) Argentina. Journal of Volcanology and Geothermal Research 169, 61–86.
Rollinson, H.R., 1993. Using Geochemical Data. Longman, New York. pp 352.
Sánchez, M.L., Blasarín, M.T., 1987. Depósitos eólicos cuaternarios de la zona de cuatro vientos. Dto. de Río Cuarto, provincia de Córdoba, República Argentina. X Congreso Geológico Argentino (San Miguel de Tucumán). Actas 3, 293–296.
Schellenberger, A., Veit, H., 2006. Pedostratigraphy and pedological and geochemical characterization of Las Carreras loess–paleosol sequence, Valle de Tafí. NW-Argentina Quaternary Science Reviews 25, 811–831.
Schultz, P., Zárate, M., Hames, W., Koeberl, C., Bunch, T., 2004. The Quaternary impact record from the Pampas, Argentina. Earth and Planetary Science Letters 219 (3–4), 221–238.
Siebert, L., Simkin, T., 2002. Volcanoes of the World: An Illustrated Catalog of Holocene Volcanoes and their Eruptions. Smithsonian Institution, Global Volcanism Program Digital Information Series, GVP-3. Available from: <http://www.volcano.si.edu/world/largeeruptions.cfm>.
Smith, J., Vance, D., Kemp, R.A., Archer, C., Toms, P., King, M., Zárate, M., 2003. Isotopic constraints on the source of Argentinian loess with implications for atmospheric circulation and the provenance of Antarctic dust during recent glacial maxima. Earth and Planetary Science Letters 212, 181–196.
Strasser, E., 1982. Textura y mineralogía de la fracción arena, en los suelos de la zona cubierta por la Hoja Catastral No. 8, San Luis. Dirección Investigaciones Agropecuarias (inédito), 89 pp.
Taylor, G., Eggleton, R.A., 2001. Regolith Geology and Geomorphology. Wiley, Chichester. 375 pp.
Teruggi, M.E., 1957. The nature and origin of Argentine loess. Journal of Sedimentary Petrology 27, 322–332.
Tófalo, O.R., Orgeira, M.J., Ramos, A.M., Alonso, M.S., 2008. Sucesión sedimento-pedológica del Cenozoico Tardío de Zárate (Buenos Aires): registro continental del MIS 5 e intervalos interglaciales más antiguos. Revista Asociación Geológica Argentina 63 (3), 430–441.
Tonni, E.P., Nabel, P., Cione, A.L., Etchichury, M., Tófalo, R., Vargas, D., Scillato Yané, G., San Cristóbal, J., 1999. The Ensenada and Buenos Aires Formations (Pleistocene) in a quarry near La Plata, Argentina. Journal of American Earth Sciences 12, 273–291.
Tricart, J.L., 1973. Geomorfología de la Pampa Deprimida. Base para los estudios edafológicos y agronómicos, INTA, vol. XII, Colección Científica, 202 pp.
Tripaldi, A., 2002a. Sedimentología y evolución del campo de dunas de Médanos Grandes (provincia de San Juan, Argentina). Revista Asociación Argentina de Sedimentología 9, 65–82.
Tripaldi, A. 2002b. Análisis sedimentológico de depósitos eólicos de valles intermontanos, su aplicación al estudio de secuencias terciarias del noroeste argentino. Ph.D. Thesis, Universidad de Buenos Aires, Argentina.
Tripaldi, A., Forman, S.L., 2007. Geomorphology and chronology of Late Quaternary dune fields of western Argentina. Palaeogeography, Palaeoclimatology and Palaeoecology 251, 300–320.
Vujovich, G.I., Kay, S.M., 1996. Evidencias geoquímicas del origen y ambiente geológico de las rocas metamórficas de composición máfica a intermedia de las Sierras Pampeanas Occidentales. 13° Congreso Geológico Argentino and 3° Congreso Nacional de Hidrocarburos. Actas 5, 273–291 (Buenos Aires).
Vujovich, G.I., Kay, S.M., 1998. A Laurentian? Grenville-age oceanic arc/back-arc terrane in the Sierra de Pie de Palo, Western Sierras Pampeanas, Argentina. In: Pankhrust, R.J., Rapela, C.W. (Eds.), The Proto-Andean Margin of Gondwana, vol. 142. Geological Society, Special Publications, London, pp. 159–180.
Wronkiewicz, D.J., Condie, K.C., 1987. Geochemistry of Archean shales from Withwatersrand Supergroup, South Africa: source area weathering and provenance. Geochimica et Cosmochimica Acta 51, 2401–2416.
Yang, X., Zhu, B., White, P.D., 2007. Provenance of aeolian sediment in the Taklamakan Desert of western China, inferred from REE and major-element data. Quaternary International 175, 71–85.
Zárate, M., 2003. Loess of southern South America. Quaternary Science Reviews 22, 1987–2006.
Zárate, M., Blasi, A., 1991. Late Pleistocene and Holocene deposits of the southeastern Buenos Aires province, Argentina. Geojournal 24 (2), 211–220.
Zárate, M., Blasi, A., 1993. Late Pleistocene–Holocene aeolian deposits of the southern Buenos Aires Province, Argentina: a preliminary model. Quaternary International 17, 15–20.