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The aeolian system of central Argentina

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ABSTRACT

The central region of Argentina comprises three main geomorphological domains, the Pampean plain, the northern Patagonia plateau and the eastern Andean piedmont. The region characterized by a complex morphostructural setting is covered by a late Quaternary aeolian apron with subordinate alluvial deposits, grading from loess and loess-like deposits in the eastern Pampas to sandy mantles and dunefields in the central, western and southern areas of the region. Eight aeolian units have been identified on the basis of the nature of the deposits, landforms and their geological-structural settings. Loess and loess-like mantles are the dominant aeolian facies of three units extending across the eastern Pampean plain: loess and loess-like mantles, loess and loess-like mantles and blowouts, sandy loess and loessial sand mantles. Dunefields and sand mantles prevail in five other units: central Pampean dunefields, western Pampean sand mantles and dunefields, western Pampean dunefields, Andean piedmont dunefields, northern Patagonia and southern Pampean sand mantles and dunefields. At a regional scale, sandy deposits are proximal facies closer to the main source area of aeolian material corresponding to the floodplain environment of the Colorado River and its tributary Desaguadero–Salado–Curacó fluvial system. The eastern loess deposits correspond to distal aeolian facies. In addition, topography governed by the complex subsurface geology and structure of the region, play a leading role as a primary controlling factor in the distribution of aeolian facies and the resulting landforms.

1. Introduction

The central region of Argentina, between 32°S and 39°S, is a vast region of nearly 600,000 km^2 with a complex geological and structural setting. The region, which encompasses the geomorphological domains of the Andean piedmont, the Pampean plain and the northern Patagonia plateau, is covered by a large aeolian blanket extending from the foot of the Andes Cordillera to the Atlantic coast (Fig. 1). Subordinate alluvial deposits are present along the fluvial systems. One of the first attempts to integrate the aeolian deposits into a major sedimentological scheme was by Iriondo (1990a) who grouped the deposits covering the Pampean plain into the *Pampean aeolian system*, subdivided into the western Pampean sand sea and the eastern loess belt.

The understanding of the aeolian dynamic during the late Quaternary is critical since these deposits are the parent material of presently cultivated soils in a region nowadays affected by climatic variability and deeply modified by agriculture. As a result numerous contributions have been devoted to soil genesis and soil conservation, particularly aeolian erosion in the central part (*e.g.* Buschiazzo et al., 2006). In addition, aeolian deposits have received increasing attention during the past two decades, particularly the eastern loess–paleosol sequences, which are regarded as potential archives of past environmental and climatic conditions (among others Kröhling, 1999; Kemp et al., 2004, 2006; Bidegain et al., 2005; Frechen et al., 2009). Much more recently, efforts have been directed to elucidate the nature of the western dunefields (Tripaldi and Forman, 2007; Tripaldi, 2010) which were barely studied.

Far from supporting the concept of a relatively homogeneous aeolian cover, results reported here reveal a significant complexity documented by geomorphological and sedimentological characteristics, resulting from local as well as regional controlling factors. A wide variety of aeolian landforms are found throughout, including several dunefields and sand mantles in the central and western parts along with loess mantles, dunes and blowouts in the eastern Pampas. The heterogeneous nature and regional diversity of the aeolian cover has not been previously examined.

The main goal of this paper is to better understand the aeolian mantle at a regional scale. The final aim is to provide a basis for future systematic analysis. With this purpose in mind, a general classification of the aeolian cover consisting of aeolian units is proposed. Each unit is defined and characterized providing information on its geological and structural settings, dominant aeolian

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Fig. 1. General location and geomorphological domains of the region under analysis.

landforms, sedimentology and chronology. These topics are discussed within the context of the relative importance of major controlling factors of the aeolian cover.

2. General environmental setting

The central region of Argentina is characterized by temperate climatic conditions. Regionally, wind conditions are controlled by the subtropical high pressure cells (Pacific and Atlantic anticyclones), the intensity of the quasi-stationary low in the Gran Chaco and the prevailing westerlies of the middle latitudes. In general, southerly winds are predominant along the Andes piedmont and the western Pampas; northeasterly winds prevail throughout the year across the eastern Pampas. In winter, westerlies predominate in northern Patagonia and the southern Pampas (Prohaska, 1976). Precipitation, concentrated during spring and summer months, is generated by humid air masses from the Atlantic anticyclone, decreasing gradually from 900 to 1000 mm in the northeastern Pampas to 250–300 mm on the Andean piedmont. The resulting pattern gives rise to a climatic gradient ranging from humid to subhumid conditions in the NE to semiarid–arid in the SW (Burgos and Vidal, 1951). The vegetation cover, at present thoroughly modified and disturbed by agriculture, reflects the climatic gradient and varies from a grass prairie in the NE to xerophytic woodland and shrubs southwestward (Cabrera, 1971).

The geographical limits between the Pampean plain, the Andean piedmont and the northern Patagonia plateau are transitional with different proposed boundaries according to the criteria used. In this paper, the Andean piedmont is defined as the area extending west of the Desaguadero–Salado–Curacó fluvial system (DSC) which is taken as the boundary with the Pampean plain. Further south, the Colorado River is usually considered (Coronato et al., 2008) as the geographical limit between the southern Pampean plain and northern Patagonia (Fig. 1).

The Andean piedmont exhibits a medium to low topographic gradient decreasing in elevation from 900 to 700 m at the foot of the mountain front to around 200 m asl at the DSC fluvial system. The piedmont is traversed by several major rivers (San Juan, Mendoza, Tunuyán, Diamante, and Atuel) with their upper basins draining the Andes Cordillera and the Precordillera (Fig. 1); fluvial discharge depends on the winter snowfall in the high Cordillera generated by humid air masses from the Pacific anticyclonic cell.

The Pampean plain is a heterogeneous geomorphological setting reflecting the major structural characteristics of the subsurface geology and the climatic gradient. The area situated east of the Paraná river, included in the Pampean region by some authors (Daus and Yeannes, 1988) is not analyzed in this paper. It has been traditionally subdivided into several areas according to various different criteria including relief features (*e.g.* undulating (*ondulada*) Pampa; low (*deprimida*) Pampa; inter-range (*interserrana*) Pampa; Fig. 1), the dominant characteristics of the surficial sedimentary cover (Sandy Pampa – *Pampa arenosa*) or the climatic conditions (dry Pampa and humid Pampa). The northern Pampean plain grades into the Chaco plain and is drained by several fluvial systems with their upper basins situated at the Pampean Ranges (Fig. 1). No significant fluvial systems are present in its central part, whereas eastwards and southwards it is drained by several streams flowing either to internal basins or mostly to the Paraná-de la Plata Rivers and the Atlantic ocean (Fig. 1).

The Northern Patagonia plateau consists of several topographic surfaces at different elevations, usually capped by thin conglomerate layers and calcretes. It is cut by two major allochthonous streams, the Colorado and N*egro* Rivers, that drain into the Andes Cordillera (Fig. 1). The Colorado River together with its tributary, the DSC, compose a major fluvial system, presently constituting a misfit fluvial system, that played a significant role as the source area of the aeolian cover under analysis (Iriondo, 1990a; Clapperton, 1993; Zárate and Blasi, 1993; Tripaldi et al., 2010a).

3. Classification of the aeolian system

Eight aeolian units have been identified on the basis of dominant landforms and their geographical and geomorphological settings (Table 1 and Fig. 2). Satellite images (Landsat, ASTER, and SRTM-DEM) and aerial photograms have been used for the identification and characterization of the units, along with information from the available literature and field reconnaissance when possible. Units have been given a number and named according to their general relative location (*e.g.* western Pampean, central Pampean, and northern Patagonia) and the main aeolian landforms. Each unit is characterized on the basis of its geomorphological features and the geological and structural settings. The general stratigraphic relationship of the aeolian deposits with the underlain bedrock is indicated, summarizing the presently available sedimentological and chronological information.

3.1. Unit 1: Loess and loess-like mantles (LLM)

Loess and loess-like mantles extend across the northeastern Buenos Aires, southern Santa Fé and eastern Córdoba Provinces, covering a wide area of the northern Pampas (Fig. 2). The plain in the Córdoba and Santa Fe Provinces gradually descends from 600 m asl at the foot of the Pampean ranges to around 30 m asl at the Paraná River. It is drained by several streams along which relatively large Pleistocene alluvial fans have been reported (Carignano, 1999). This general geomorphological arrangement is the result of the subsurface geology consisting of several tectonic blocks eastwards from the Pampean ranges, covered by a thick sedimentary fill (Chebli et al., 1999; Fig. 3). The northern Pampas of Buenos Aires province comprises the area called *Pampa ondulada* (undulating Pampa), mostly developed on a faulted tectonic block (*Umbral de Martín García*, Cingolani, 2005). It is characterized by a hilly landscape resulting from fluvial erosion by tributaries of the Paraná-de la Plata Rivers.

The loess mantle, making up a 1.5–2 m thick apron, overlies mid-Pleistocene successions composed of loess-like deposits. It blankets the landscape and grades west–southwestward into the dunes of Unit 4 (CPD). Loess deposits are the parent material of present soils (mollisols; INTA, 1990). These deposits have been the subject of numerous papers, especially during the last 30 years, becoming the best known aeolian facies of the region. The features examined include mineralogical composition (*e.g.* González Bonorino, 1966; Kröhling, 1999), magnetostratigraphy (Valencio and Orgeira, 1983; Nabel et al., 2000), geochemistry (Morrás, 1999), environmental magnetism (Bidegain et al., 2005), stratigraphy and vertebrate fossil remains (Tonni et al., 1999) and the first regional paleopedological analysis (Imbellone and Teruggi, 1993 and references therein). Pedological features are ubiquitous throughout the mid-late Pleistocene successions which include several discrete and welded paleosols (Zárate et al., 2002).

Loess is dominantly volcaniclastic, derived from the Andean region. It also includes secondary percentages of particles from

Table 1
Geographical location, geological-structural setting and main features of the aeolian units of central Argentina.

Aeolian units	Name	Geographical location (informal region name)	Geological-structural setting	Main aeolian deposits and landforms
1. LLM	Loess and loess-like mantles	East-central Córdoba, south-central Santa Fé, northeastern Buenos Aires provinces (*Pampa ondulada*)	Tectonic blocks at increasing depth eastward and intrcratonic basins	Very low-relief mantles of loess and loess-like deposits
2. LMB	Loess and loess-like mantles and blowouts	East-central Buenos Aires province (*Pampa deprimida*)	Salado tectonic depression	Discontinuous and low-relief mantles of loess and fluvially reworked loess, associated to blowouts
3. SLM	Sandy loess and loessial sand mantles	Southern Buenos Aires province (*Pampa interserrana*)	Bonaerian positive block (Tandilia and Ventania ranges) and Claromecó basin	Discontinuous and low-relief mantles of sandy loess grading to loessial sand to the S–SW and NE
4. CPD	Central Pampean dunefields	Southern Córdoba, southern Santa Fé, eastern La Pampa province, west-central Buenos Aires provinces (*Pampa arenosa*)	Intracratonic basins like, Macachín, Laboulaye, General Levalle and western part of Salado basin	Linear dunes
5. WPMD	Western Pampas sand mantles and dunefields	East-central La Pampa province (*Pampa arenosa*)	Chadileuvú and Central Pampean tectonic blocks	Sandy mantles in high topographic positions and parabolic and crescentic dunes within the transversal valleys
6. WPD	Western Pampean dunefields	South-central San Luis and west-central La Pampa provinces (*Pampa arenosa*)	Distal Andean and intracratonic basins like Algarrobo del Aguila, Villa Mercedes and sub-Alvear	Simple and compound parabolic dunes and blowouts
7. APD	Andean piedmont dunefields	Southern La Rioja province and eastern San Juan and Mendoza provinces	Tertiary foreland basins: like Salinas, Jocolí, Cuyo and Alvear	Crescentic dunes and megadunes, parabolic and linear dunes
8. PPMD	Northern Patagonia and Southern Pampean sand mantles and dunefields	Southernmost Buenos Aires, southernmost La Pampa and northern Rio Negro provinces	Colorado tectonic basin	Linear dunes and blowouts

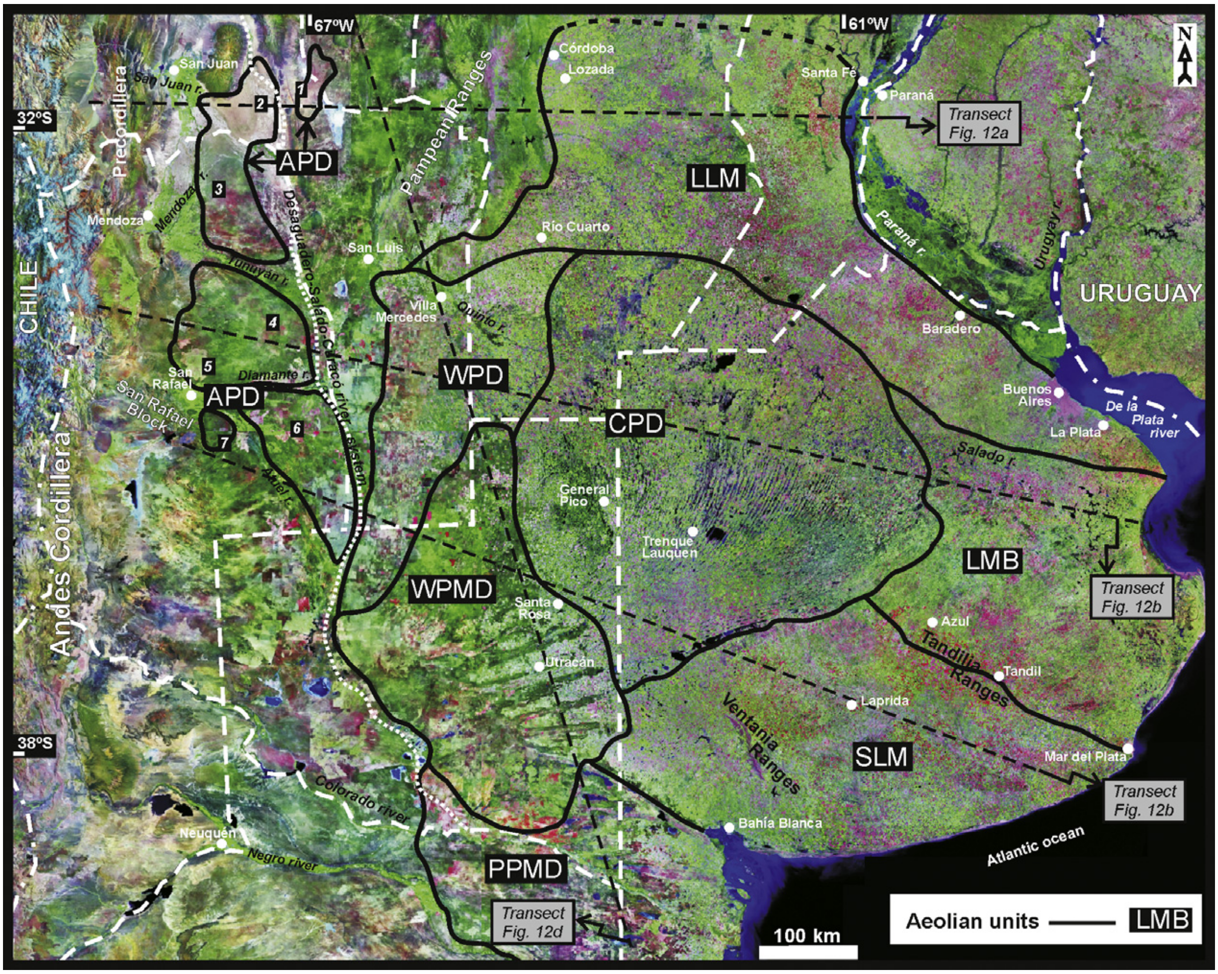

Fig. 2. Aeolian units of central Argentina: LLM, Loess and loess-like mantles; LMB, Loess and loess-like mantles and blowouts; SLM, Sandy loess and loessial sand mantles; CPD, Central Pampean dunefields; WPSD, Western Pampean sand mantles and dunefields; WPD, Western Pampean dunefields; APD, Andean piedmont dunefields; PPMD, Northern Patagonia and southern Pampean sand mantles and dunefields; 1, Médanos Negros; 2, Médanos Grandes; 3, Médanos de Telteca; 4, Médanos de la Travesía; 5, Médanos de los Naranjos; 6, Médanos de Picardo; 7, Pampa de la Varita.

other minor local sources such as the Pampean ranges, the Paraná River basin (González Bonorino, 1966; Kröhling, 1999; Morrás, 1999) and likely the Uruguayan Precambrian outcrops (Zárate et al., 2002).

The chronology of the loess mantle has progressed significantly in the last 10 years by means of OSL dating of several sections across the area (Kemp et al., 2004, 2006; Frechen et al., 2009; Zárate et al., 2009). The numerical ages indicate that the uppermost 3–10 m, involving both loess and loess-like deposits, date back to the last glacial cycle (Fig. 4). Deposits yielding ages older than the last Glaciation are reported at the lower sections of some successions. The higher rates of loess accumulation occurred during the last glacial maximum and the late glacial, decreasing significantly by 10,000–9000 years BP when the present soil formation started. Minor aeolian reactivations have been reported during the late Holocene (Iriondo, 1990b; Kemp et al., 2004).

3.2. Unit 2: Loess and loess-like mantles and blowouts (LMB)

Loess and loess-like mantles and blowouts occupy the central part of Buenos Aires province (Fig. 2), region known as *Pampa Deprimida* (low Pampa). It is an area drained by the Salado River and its tributaries, characterized by a very low gradient (<0.01%), being affected by extensive flooding events during periods of heavy rain. This general geomorphological setting is controlled by its subsurface geology consisting of a tectonic basin (Salado tectonic basin; Cingolani, 2005; Fig. 3). The sedimentary fill consists of up to 8.5 km of Cretaceous and Cenozoic deposits, of which the uppermost 40–50 m are likely of Quaternary age. Loess and loess-like deposits cover mid-late Pleistocene sandy silts and silts exposed along rivers, road cuts and quarries.

The dominant aeolian landforms consist of irregular and low-topography mantles and blowouts. The former are composed of typical loess deposits of around 1–1.5 m in thickness, being the parent material of present soils (mollisols; INTA, 1990). Although traditionally mapped as a continuous apron of primary loess, detailed analysis in the Arroyo del Azul l basin (close to Azul locality, Fig. 3) demonstrated that the loess mantle is discontinuous, grading laterally into fluvially reworked loess facies (loess-like deposits) that make up an extensive low-relief fan emerging from the Tandilia range (Zárate and Mehl, 2010). Satellite images of neighboring fluvial systems show patterns comparable to those described at Arroyo del Azul, likely corresponding to loess-like mantles.

Blowouts, at present occupied by shallow lakes (*lagunas*), are the other prevailing aeolian landform. These deflation basins are common throughout the entire area (Tricart, 1973), with variable sizes ranging from dozens of meters to 3 km in diameter. A relatively rounded shape is evident in planar view; the E–NE flank is characterized by the occurrence of lunettes with a relative height

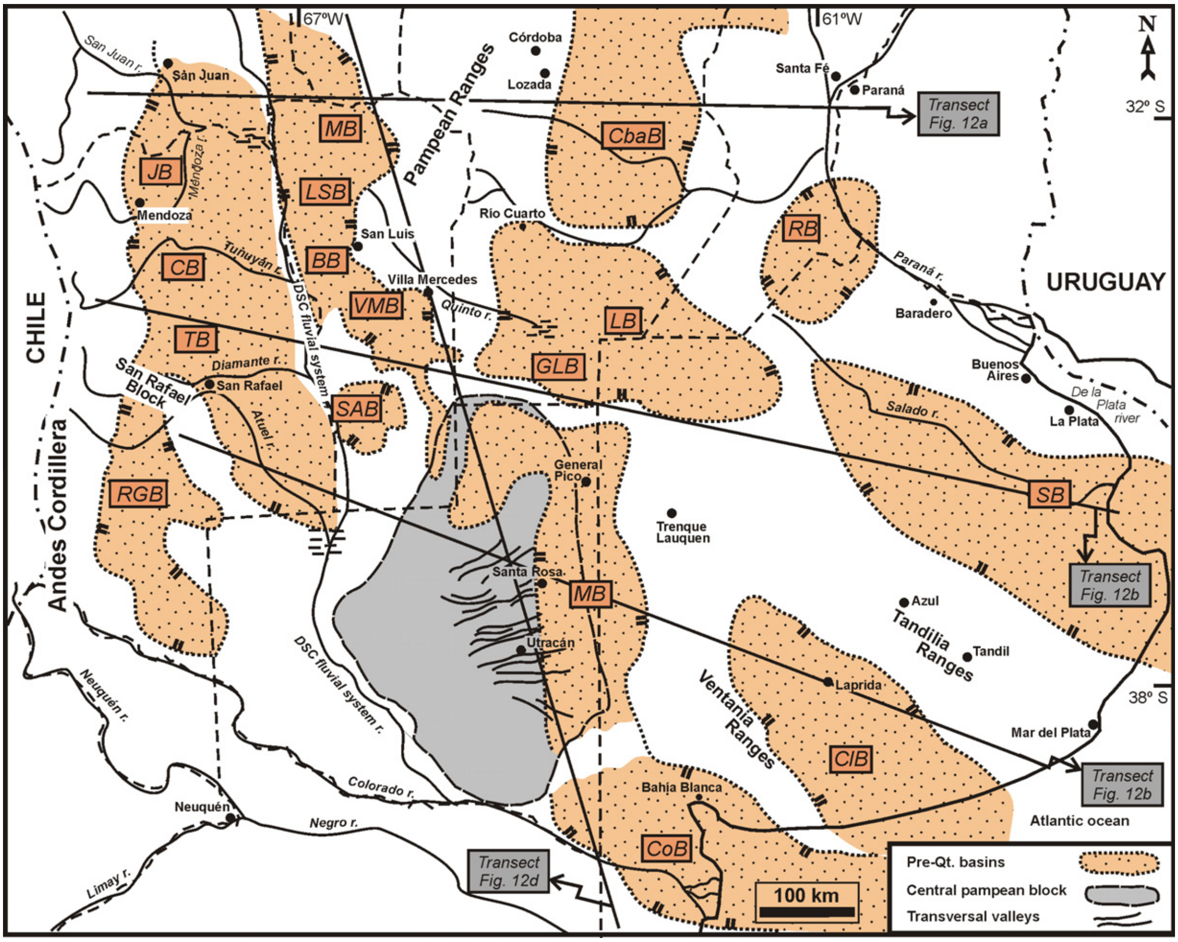

Fig. 3. Morphostructural units of the region under analysis. Reference: JB, Jocolí basin; CB, Cuyo basin; TB, Tunuyán basin; RGB, Río Grande basin; MB, Marayes basin; LSB, Las Salinas basin; BB, Beazley basin; VMB, Villa Mercedes basin; SAB, Sub-Alvear basin; CbaB, Córdoba basin; LB, Laboulaye basin; GLB, General Levalle basin; MB, Mascasín basin; CoB, Colorado basin; RB, Rosario basin; SB, Salado basin, ClB, Claromecó basin.

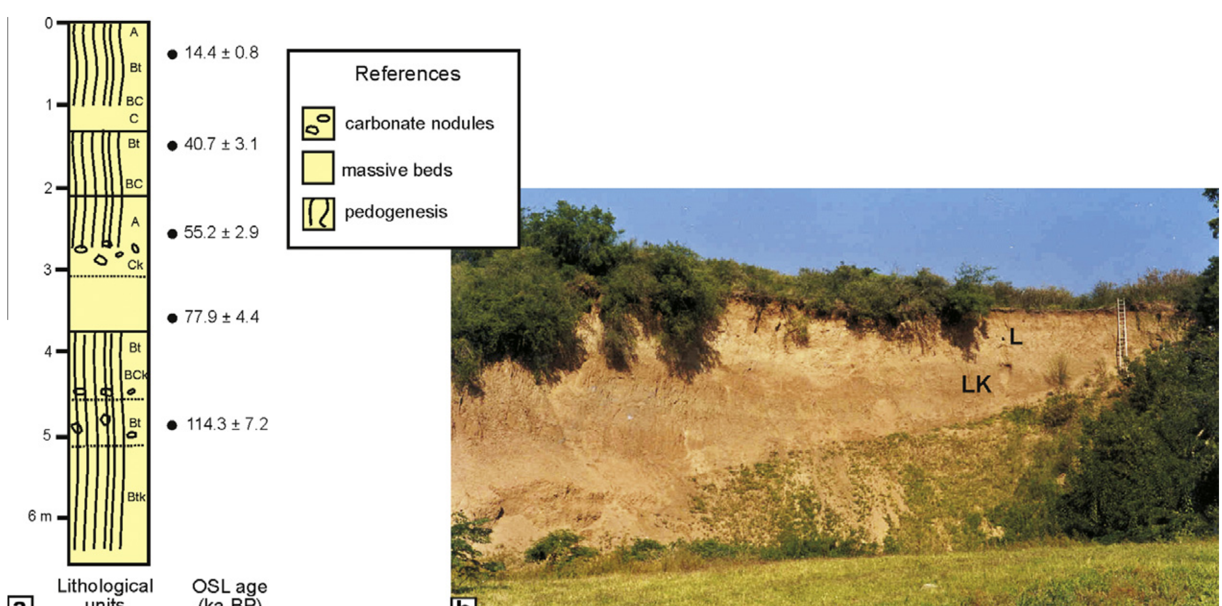

Fig. 4. LLM unit (Baradero locality): (a) panoramic view of loess (L) and loess-like (LK) deposits; (b) present soil, paleosols and OSL chronology of the section (adapted from Kemp et al., 2006).

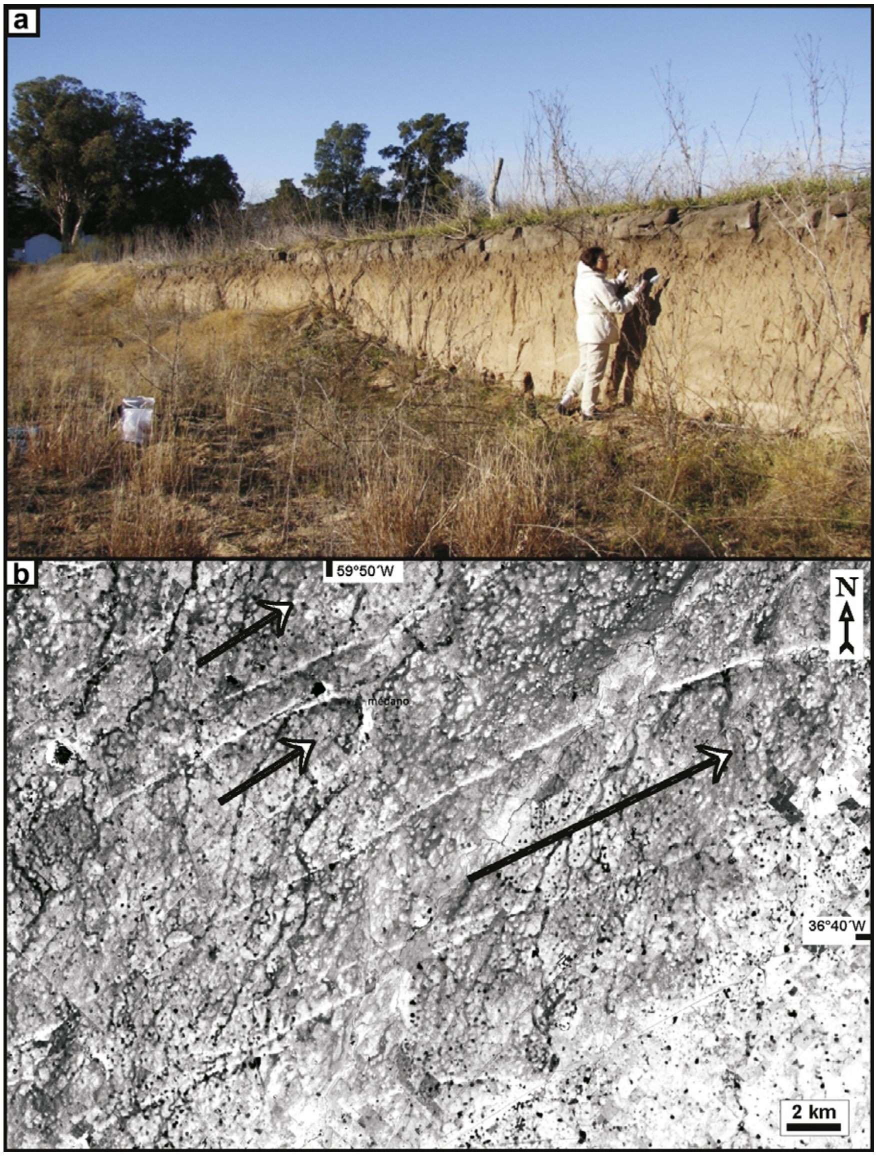

Fig. 5. LMB unit: (a) loess deposits composing a lunette at the Salado river basin; (b) parabolic dunes with very thin and long arms, at present partially modified by the drainage of Arroyo del Azul fluvial basin.

between 1 m and almost 15 m at some major blowouts indicating dominant W–SW winds (Frenguelli, 1950; Dangavs and Reynaldi, 2008). Depending on the local substrate composition, lunettes are formed either by silt, sandy silt or clayey sediments (Fig. 5a; Dangavs, 1979). Studies performed at some lunettes composed of loess reveal a volcaniclastic composition (Dangavs and Blasi, 2002).

Other secondary but important aeolian landforms are linear and parabolic dunes situated across the northern piedmont of the Tandilia Range, on the southern margin of unit 3 (Fig. 5b). Dunes are 20–30 km long and around 0.3–0.5 km wide with a general NNE orientation, and are composed of sandy silt deposits (sandy loess) (Zárate and Mehl, 2010). North of Mar del Plata city, at the southeastern tip of the Tandilia piedmont, W–E oriented parabolic and linear dunes of late Holocene age (OSL date of 700 ± 150 BP at the base of the present A soil horizon) were reported superimposed on older parabolic dunes of unknown age (Martínez, 1998). Dominant west–southwest paleowinds are inferred from the orientation of the dunes and blowouts. The chronology of these aeolian deposits is very poorly known. No numerical ages are available across the Salado River basin where the type section of the Buenos Aires loess deposits was defined (Fidalgo et al., 1973).

3.3. Unit 3: Sandy loess and loessial sand mantles (SLM)

Unit 3 comprises most of the southern Buenos Aires province, an area known as *Pampa interserrana* (inter-range Pampa), due to its general location between the Tandilia and Ventania ranges (Fig. 1). It is an extensive structural plain dissected by several fluvial systems, giving way to a moderately undulating landscape with some low hills. The northern part, known as the Laprida depression (Dangavs, 2005), is a flat and low gradient (<1%) environment characterized by impeded drainage conditions. The SLM unit is situated in a structural complex tectonic block (*Positivo Bonaerense* – Bonaerian Positive, Yrigoyen, 1999). The subsurface geology is characterized by a Paleozoic basin (Claromecó basin; Cingolani, 2005; Fig. 3), located at the central part of *Pampa Interserrana* and surrounded by Proterozoic and Paleozoic outcrops at the Tandilia and Ventania ranges. A late Cenozoic cover of around

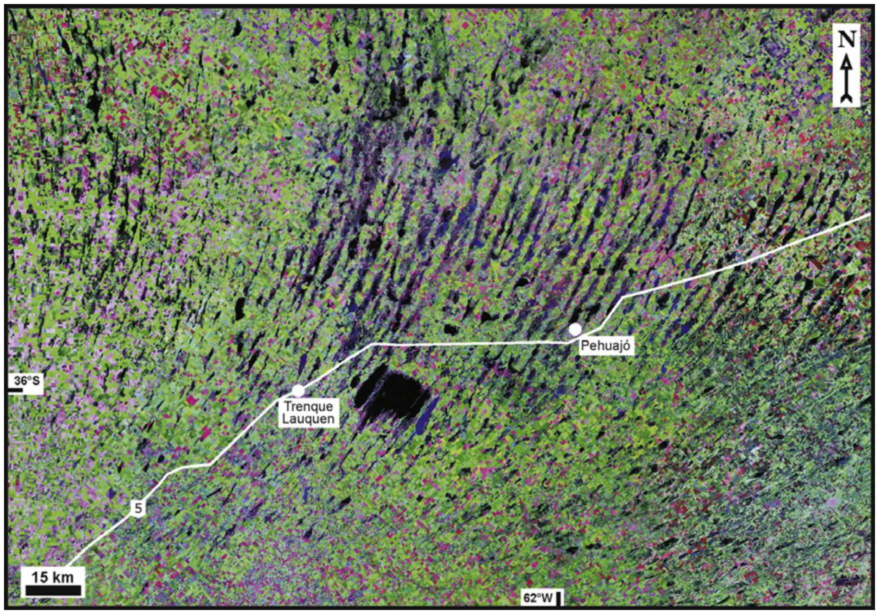

Fig. 6. Linear dunes of CPD unit, with flooded interdune areas (Landsat ETM + image, Bands 742, obtained from https://zulu.ssc.nasa.gov/mrsid/).

150–200 m thickness buries the basement. This cover is composed of Miocene–Pliocene loess and loess-like deposits capped by a calcrete crust. Along the Atlantic margin, these units are unconformably overlain by mid-late Pleistocene fluvial sandy silts, in turn capped by a calcrete. The aeolian cover of the SLM unit blankets both the Miocene–Pliocene and the mid-late Pleistocene deposits.

Aeolian deposits consist of a 1.5–2 m thick mantle of sandy loess grading to loessial sand northeastward (Laprida depression) and south–southwestward where sand mantles become more common. The uppermost meter of these deposits is modified by present soil formation (mollisols; INTA, 1990). Loess mantles with a maximum thickness of 3–4 m are secondary landforms found in the mountain and piedmont areas of Tandilia and Ventania ranges, being the dominant sedimentary fill of numerous small stream valleys. Loess mantles are almost continuous up to an altitude of around 400 m asl in Ventania and 200 m in Tandilia. Subordinate aeolian landforms are represented by some blowouts and lunettes occurring mainly at the Laprida depression and near the Atlantic fringe. Not considered in this paper are the littoral dunes with their own dynamic not necessarily linked to the evolution of the inland landscape.

Mineralogical analysis of the sandy loess deposits indicate a dominant volcaniclastic composition consisting of mesosilicic plagioclases, volcanic lithic fragments, volcanic shards and a minor percentage of quartz grains; very well rounded particles of hornblende and hypersthene are typical of heavy mineral suite. Considering the grain size and the mineral composition the accumulation of this sandy loess was interpreted as the result of transportation by short distance suspension (Zárate and Blasi, 1993). The source area was placed at a distance of around 200–250 km to the S and SW, in the distal floodplain of the Colorado River, an area presently situated on the marine platform (Fig. 1).

The chronology of the SLM aeolian deposits remains poorly defined with no dates obtained in the northern, southwestern and western sectors. Most of the numerical ages (14C, TL, and OSL) have been reported from sandy loess and loess deposits situated at the southeastern part, near Mar del Plata city and within the Tandilia range environment, while three others (TL) come from a locality at the southern piedmont of Ventania (Zárate, 2003 and references therein). The obtained dates together with the occurrence of vertebrate fossil remains suggested several different episodes of aeolian accumulation, at present under revision, during the late Pleistocene–Holocene interval (Fidalgo, 1990; Zárate and Flegenheimer, 1991).

3.4. Unit 4: Central Pampean dunefields (CPD)

The central Pampean dunefield covers the western and southwestern part of Buenos Aires, eastern La Pampa, southern Córdoba and southernmost part of Santa Fé Provinces (Fig. 2). It is characterized by a gentle relief that grades eastward from 120 to 140 m asl along the western margin to around 50 m asl. Its general geomorphological setting is controlled by the subsurface occurrence of several tectonic basins (Macachín, Laboulaye, General Levalle, western Salado; Fig. 3) filled with Cretaceous and Cenozoic deposits (Chebli et al., 1999).

The aeolian apron overlies either Late Miocene loess and loess-like deposits or a Quaternary substratum (mid-late Pleistocene?) composed of massive to poorly stratified sandy silt, with very common carbonate accumulations of unknown origin. The upper meter of the sand dune deposits is modified by pedogenesis (mollisols and entisols; INTA, 1990) including, at several localities, a 1–2 cm thick layer of volcanic ash related to the 1932 Quizapú eruption (Imbellone and Camilión, 1988; Hildreth and Drake, 1992).

The dunes included in this unit play a major environmental role controlling the surficial and poorly integrated drainage system of the area (Cabral and Hurtado, 1990; Malagnino, 1989). Main landforms are linear dunes, 100–130 km long and 2–3 km wide, with a general N–NE trend and a relative relief of around 2 m (Fig. 6). Large parabolic dunes associated with the former are reported at the southern part of the dunefield (Gardenal, 1986; Malagnino, 1989). Dune orientations of both patterns suggest paleowinds from the SW quadrant. Eastward the dunefield extends along the axis of the Salado River basin grading into the loess mantle of unit 2 (Fig. 2).

No detailed sedimentological analysis has been performed in the CPD unit. A general grain-size trend ranging from coarse sand at the bottom to fine sand at the top was reported in the surroundings of General Pico (La Pampa province) where the dunefield attains a thickness of around 10–12 m (Malán, 1983). The age of

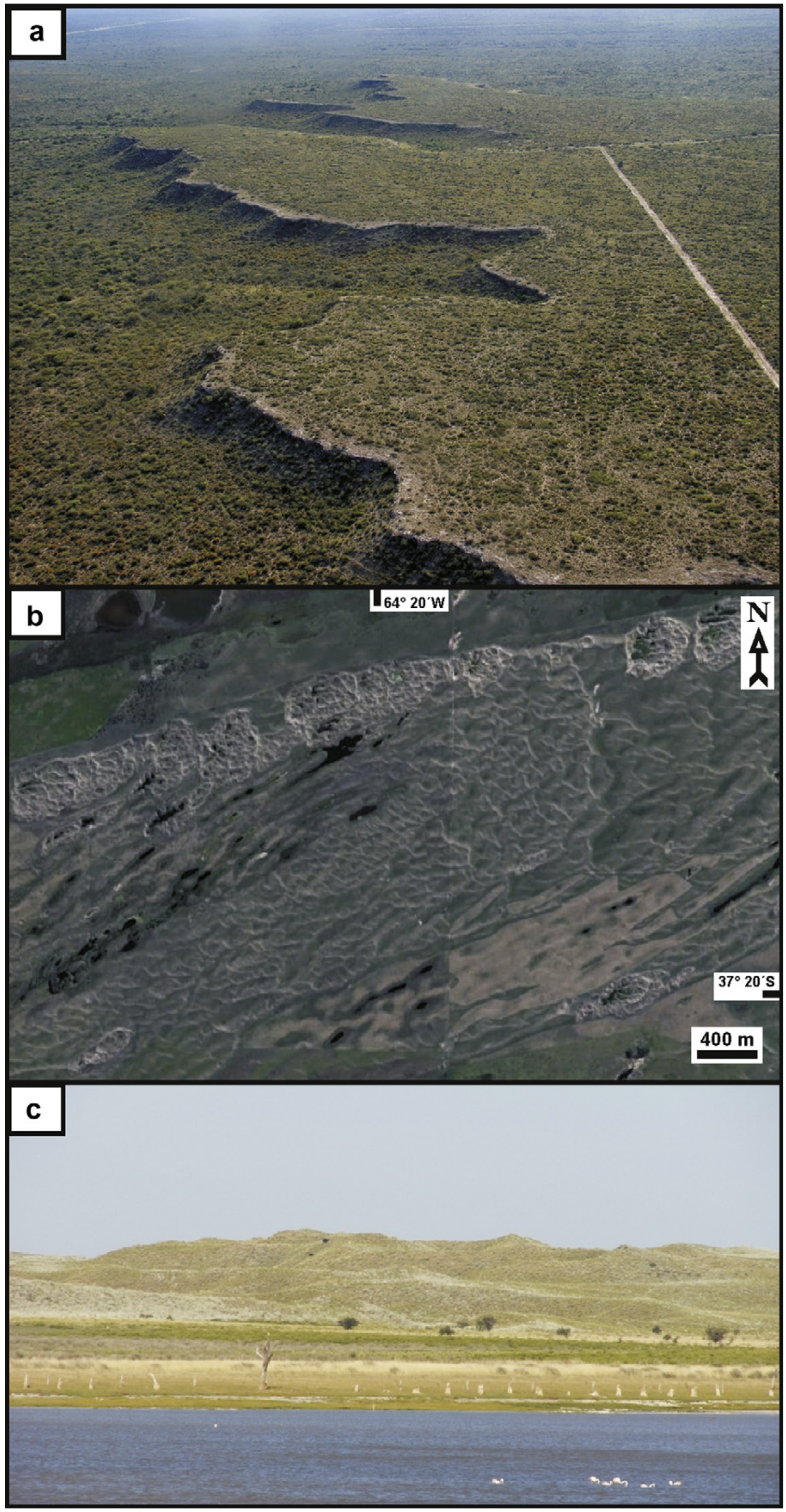

Fig. 7. WPMD unit: (a) air view of a transversal valley margin and calcrete capping the structural plain, covered by thin aeolian sand mantles (west of Santa Rosa locality); (b) crescentic dunes and blowouts within the Utracán-Argentino valley (Google Earth image); (c) crescentic dunes by the Utracán saline.

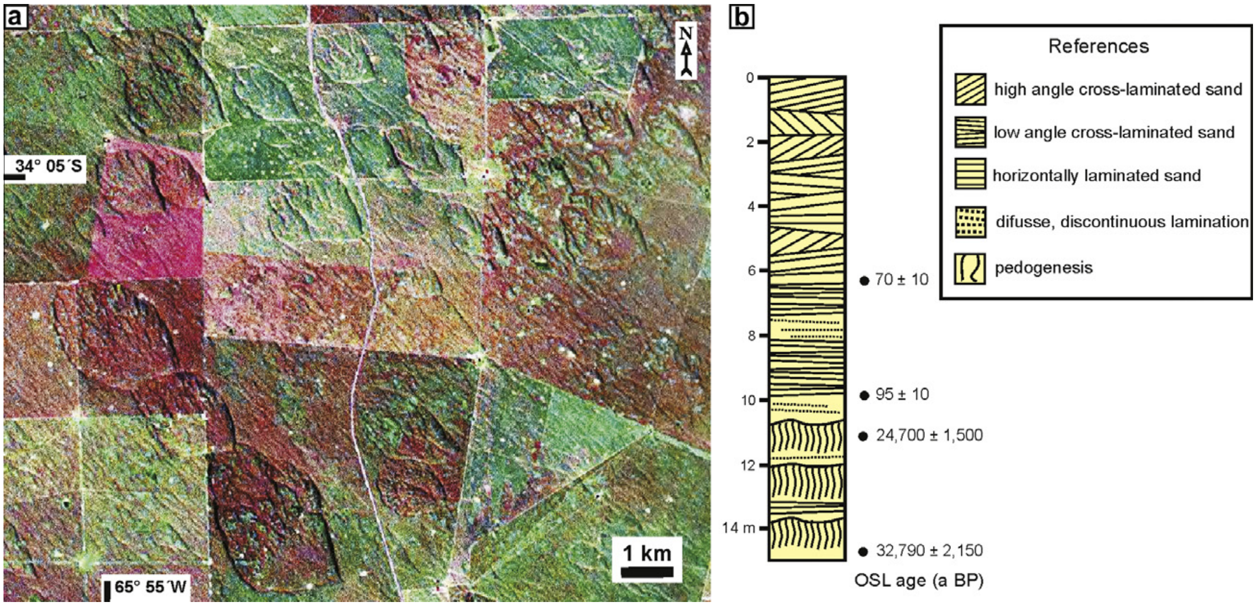

Fig. 8. WPD unit: (a) large compound parabolic dunes, superimposed on a general rolling aeolian landscape; (b) general stratigraphy and OSL chronology of the area formed by aeolian sand mantle deposits, interposed with paleosols, and covered by very recent aeolian sand (adapted from Tripaldi and Forman, 2007).

the CPD unit has usually been based on regional correlations with aeolian successions of the northern Pampas. In addition, the occurrence of megafauna fossil remains at the lower section of a dune in western Buenos Aires (Montalvo, 2010 personal communication) was used to infer active aeolian accumulation sometime during the late Pleistocene age. Recently, OSL ages of 42.7 and 30.0 ka BP were reported from dunes in western Buenos Aires province (Latrubesse and Ramonell, 2010).

3.5. Unit 5: Western Pampas sand mantles and dunefields (WPMD)

This unit is located in the central–eastern La Pampa province (Fig. 2). The aeolian deposits cover a structural plain controlled by the Central Pampean tectonic block (Folguera and Zárate, 2011) and a peneplain developed on the Chadileuvú tectonic block (Linares et al., 1980) (Fig. 3), both composed of Paleozoic and Mesozoic rocks. The central Pampean block is characterized by a 150–200 m thick mantle of late Miocene loess and loess-like deposits capped by a widespread calcrete crust. A remarkable geomorphological feature is the occurrence of a series of large depressions of debatable origin, known as transversal valleys (Malagnino, 1989; Calmels, 1996) cutting across the structural plain and carved into late Miocene deposits. They are major geoforms, 60–100 km long and 80–100 m deep, with a general NE–SW trend (Figs. 2 and 3).

The dominant aeolian landforms consist of sand mantles covering both the structural plain surface and the peneplain, while dunefields occur along the transversal valleys (Fig. 7). The relatively thin (around 1 m) sand mantles are modified by the development of the present soil profile; at some places agricultural activities during the dry spell of the early-mid 20th century gave way to the formation of small dune fields (Tripaldi et al., 2010c). The deposits consist of very fine sand, grading into sandy loess northeastward. Mineralogical analysis of WPMD sand, together with the dune orientations, suggest a mixed provenance with materials mostly coming from the DSC fluvial system and from local rock outcrops (Szelagowsky et al., 2004).

Dunefields occupy the central and northern segment of the transversal valleys, grading into sand mantles along the northern valley slopes; instead southern valley slopes are usually devoid of aeolian deposits or a very thin and discontinuous veneer is present. Preliminary analysis on these dunes, mainly those situated along the Utracán-Argentino valley (Fig. 7), suggest a complex morphology including simple and compound blowout and parabolic dunes. In some cases, mostly near Utracán locality, they are organized in very large dune complexes, 10–24 km long, about 2 km wide and up to 40 m high. They resemble parabolic megadunes due to the presence of a bent sand bulge (nose), from where two long linear arms stretch out. Similar landforms with a large-scale U-shaped geometry were described in coastal dune systems of Brazil, which are interpreted on the basis of their transgressive dynamic nature (Hesp et al., 2009). Dune orientations suggest W–NW and S–SW paleowinds in the northern and southern La Pampa province, respectively (Szelagowsky et al., 2004).

The age control of the sand mantles and dunefields is still very poor. In the surroundings of Santa Rosa city, fossil remains of extinct megafauna (*Megatherium* sp) have been recovered from the very bottom of the aeolian deposits suggesting a Late Pleistocene age. In the Argentino-Utracán valley, OSL ages indicate mid-Holocene and very recent (last 100 years) aeolian episodes.

3.6. Unit 6: Western Pampean dunefields (WPD)

The WPD unit mostly occupies central–southern San Luis and Córdoba Provinces (Fig. 2). It is limited by the DSC fluvial system and some low hills westward and by the southern distal piedmont of the San Luis ranges to the N. This region is characterized by a low relief plain drained by ephemeral streams and the Quinto River, following a tectonic lineament (Kostadinoff and Gregori, 2004). The subsurface geology consists of tectonic basins (Villa Mercedes and sub-Alvear, Fig. 3) formed during Permo-Triassic times and filled with about 2400 m of mainly Cenozoic–Mesozoic sedimentary and volcanic rocks (Kostadinoff et al., 2002, 2006; Kostadinoff and Gregori, 2004). Northeast of the Quinto River the aeolian deposits are the topmost section of the sedimentary filling of the General Levalle basin, a N–S trending intracratonic rift basin related to the opening of the South Atlantic ocean (Webster et al., 2004).

The WPD unit includes diverse dunes surrounded by discontinuous aeolian mantles. This unit is mainly formed by vegetated and

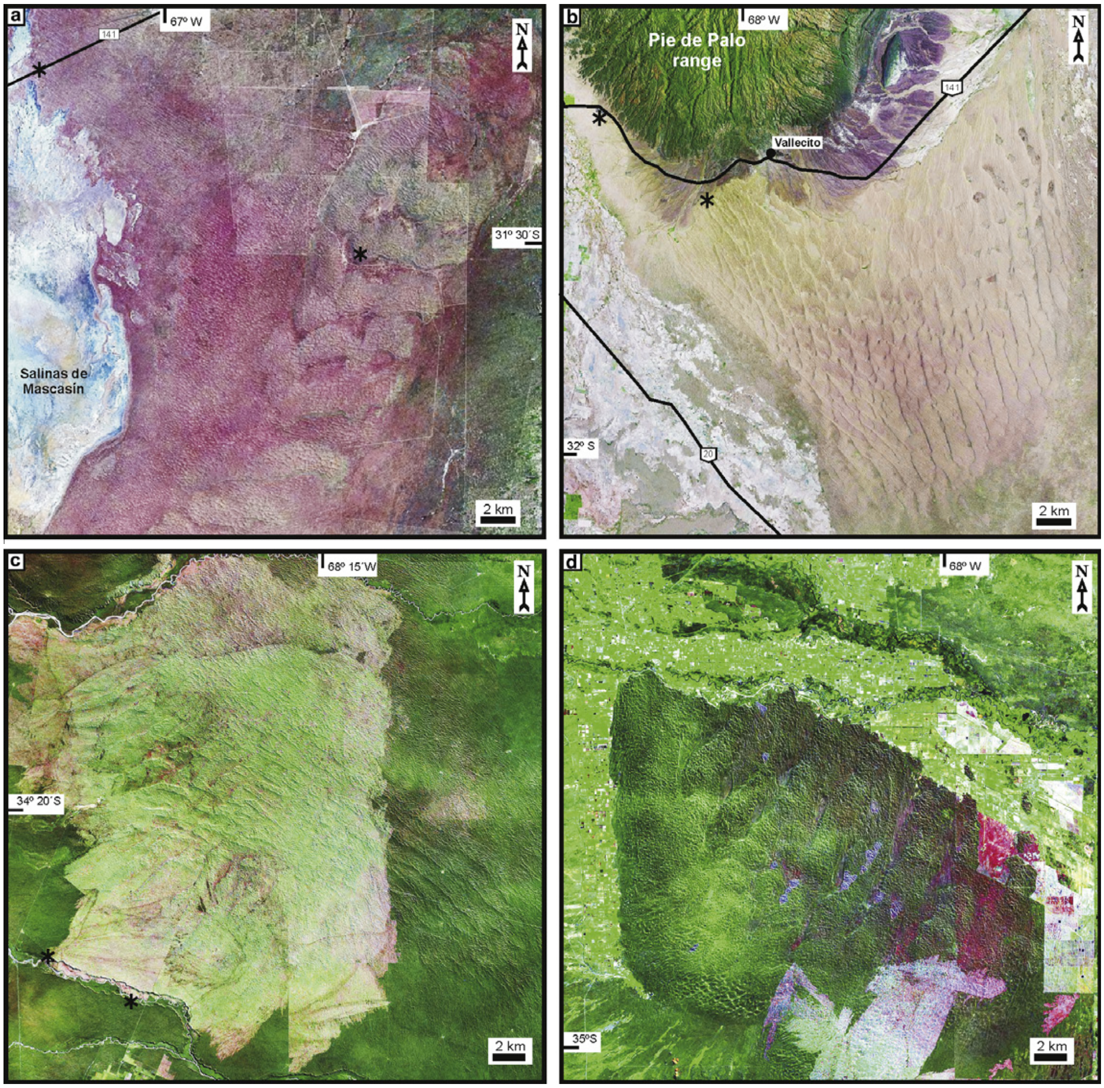

Fig. 9. Some representative dunefields of APD unit showing their main landforms and location (stars) of OSL dated aeolian deposits: (a) Médanos Grandes; (b) Médanos Negros; (c) Médanos de los Naranjos; (d) Médanos de Picardo (for more detail see Tripaldi and Forman, 2007; Tripaldi et al., 2011).

mostly stabilized dunes; the most conspicuous landforms are blowouts and parabolic dunes that rise above a general rolling landscape of likely aeolian origin (Fig. 8; Tripaldi and Forman, 2007). These dunes show two main orientations, revealing southeasterly and northeasterly paleowinds. The central and southern part of WPD in San Luis Province (Fig. 2) presents a pattern of complex linear dunes, with a NNW trend that extend for more than 25 km. This linear pattern is formed by the coalescence of parabolic dunes, suggesting southeasterly paleowinds.

The northern region of WPD is covered by aeolian sand and silty sand mantles, with localized and small dunes and closely associated with ephemeral streams. North of Quinto River the aeolian component is represented by blowout dunes of varied size, occasionally forming compound parabolic dunes, accreted by northeasterly paleowinds. Many of these dunes show more degraded surfaces with active small dunes, related to the early 20th century reactivations (Tripaldi et al., 2010c).

The WPD sand shows variable proportions of quartz and rock fragments, with more abundant K-feldspar than plagioclase (Sánchez and Blarasín, 1987; Tripaldi et al., 2010a). Rock fragments are almost exclusively volcanic grains with variable percentages of fresh pumices and glass shards. In the southern area of the WPD unit dunes are rich in K-feldspar, quartz, alterites, volcanic glass shard and plagioclase (Iriondo and Ramonell, 1993). This composition is related to a provenance from the DCS fluvial system, with secondary inputs from the Pampean ranges (Tripaldi et al., 2010a).

A general exposure of the WPD deposits from central San Luis province shows two main units (Fig. 8). The lower unit, at least 4 m-thick, is composed of horizontally to very low-angle laminated sand, interposed with paleosols, as a result of sedimentation in aeolian sand mantles. These deposits are unconformably covered by very low- to high-angle laminated sand of the upper unit (Tripaldi and Forman, 2007).

Through OSL dating, Tripaldi and Forman (2007) inferred that the lower unit deposits accumulated during the late Pleistocene (ca. 33–27 ka), while the upper unit reveals episodes of sand mantle accretion and dune migration during early 20th century times (ca. 95–65 years BP). On the basis of OSL dates, Latrubesse and Ramonell (2010) assigned an age of ca. 41.4 ka to large linear dunes of southern San Luis province. They inferred also that parabolic dunes were active at ca. 16.7 ka. Evidence of Holocene aeolian activity was also found in central and southern San Luis province (Tripaldi and Forman, 2007; Latrubesse and Ramonell, 2010).

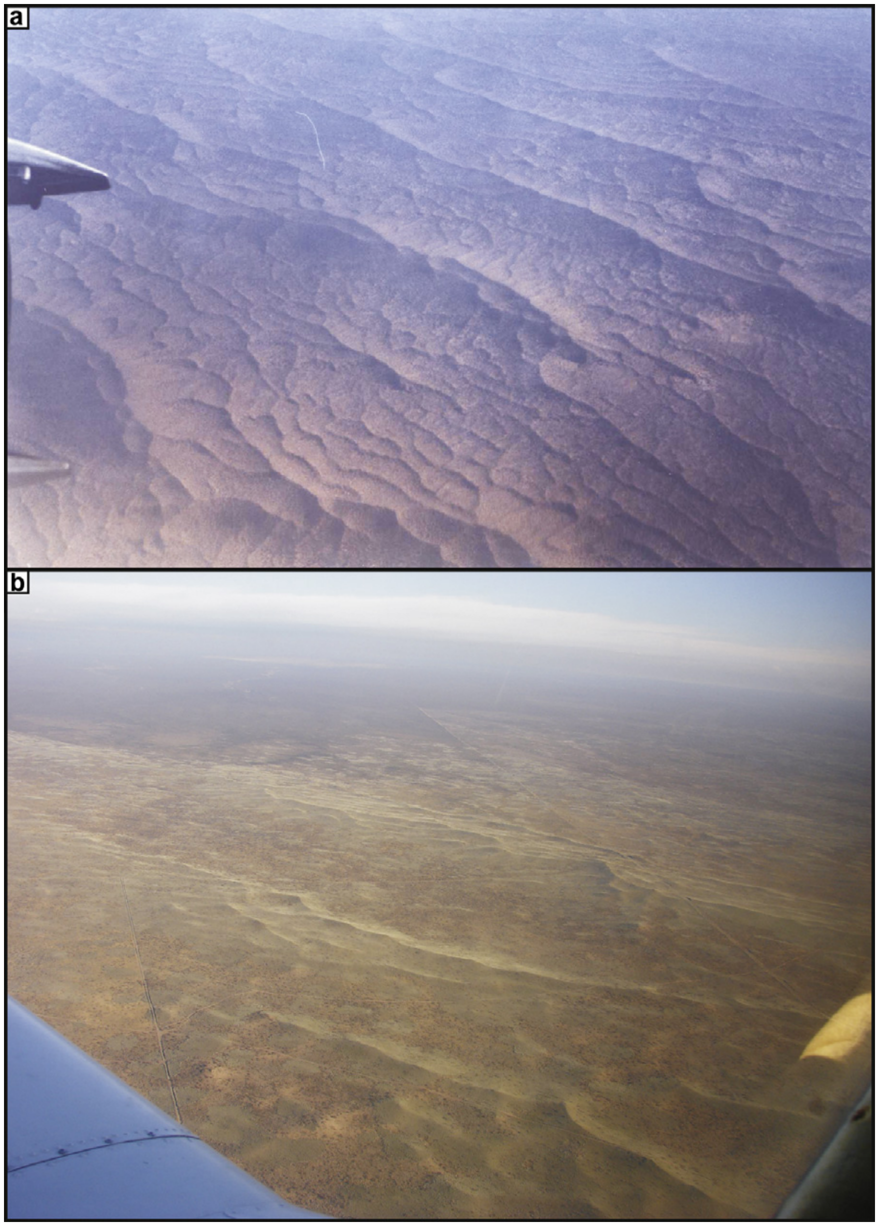

Fig. 10. Air view of large dunes of APD unit: (a) southern region of Médanos Grandes dunefield; (b) western region of Médanos de los Naranjos dunefield.

3.7. Unit 7: Andean piedmont dunefields (APD)

Western Argentina landscape is strongly controlled by the Andean tectonic dynamic. The Andean piedmont is characterized by the subsurface occurrence of several tectonic basins (north to south, de las Salinas, Jocolí, Cuyo, Alvear, Fig. 3), filled by up to 3000 m of Tertiary synorogenic deposits (Ramos, 1999).

Climatically, the Andes produces a foehn-like effect blocking the Pacific westerly humid winds inducing the prevalence of arid–semiarid conditions. Most of APD is partially vegetated by shrub steppe (*Larrea* spp and Gramineae, Rundel et al., 2007; Abraham et al., 2009) while pedogenesis is very weak, dominated by entisols and occasionally aridisols (INTA, 1990). The aeolian sandy cover laterally grades into fluvial and lacustrine deposits of the San Juan, Mendoza, Tunuyán, Diamante and Atuel Rivers, wetlands (Guanacache lakes) and saline mud flats (*e.g.* Salinas de Mascasín). Unit APD includes dunefields of San Juan and Mendoza Provinces that cover most of the piedmont, spreading out from the mountain front to the DSC fluvial system eastward (Fig. 2). APD includes the largest, most diverse and best preserved dunes of the region under analysis, with numerous other dunefields, not here analyzed, enclosed in intermontane valleys (Tripaldi, 2002a). From north to south the main dunefields, summarized below, are Médanos Negros, Médanos Grandes, Médanos de Telteca, Médanos de la Travesía, Médanos de los Naranjos, Médanos de Picardo and Pampa de la Varita (Fig. 2).

Médanos Negros dunefield is placed in an endorheic basin (Salinas de Mascasín, Fig. 2). This dunefield shows a complex set of dune-like landforms of various scales (Tripaldi and Forman, 2007). The largest landforms arise as a regular pattern of west-to-east oriented ridges and troughs spaced ~2–4 km apart (Fig. 9a). The resulting rolling landscape of about 50 m of relief with asymmetric ridges shows steeper sides facing south. They are variably preserved, incised by small streams and covered in places by coarse colluvium. Superimposed on these dunes are 5–10 m high, transverse dunes facing SSW to SW (Fig 9a). Both

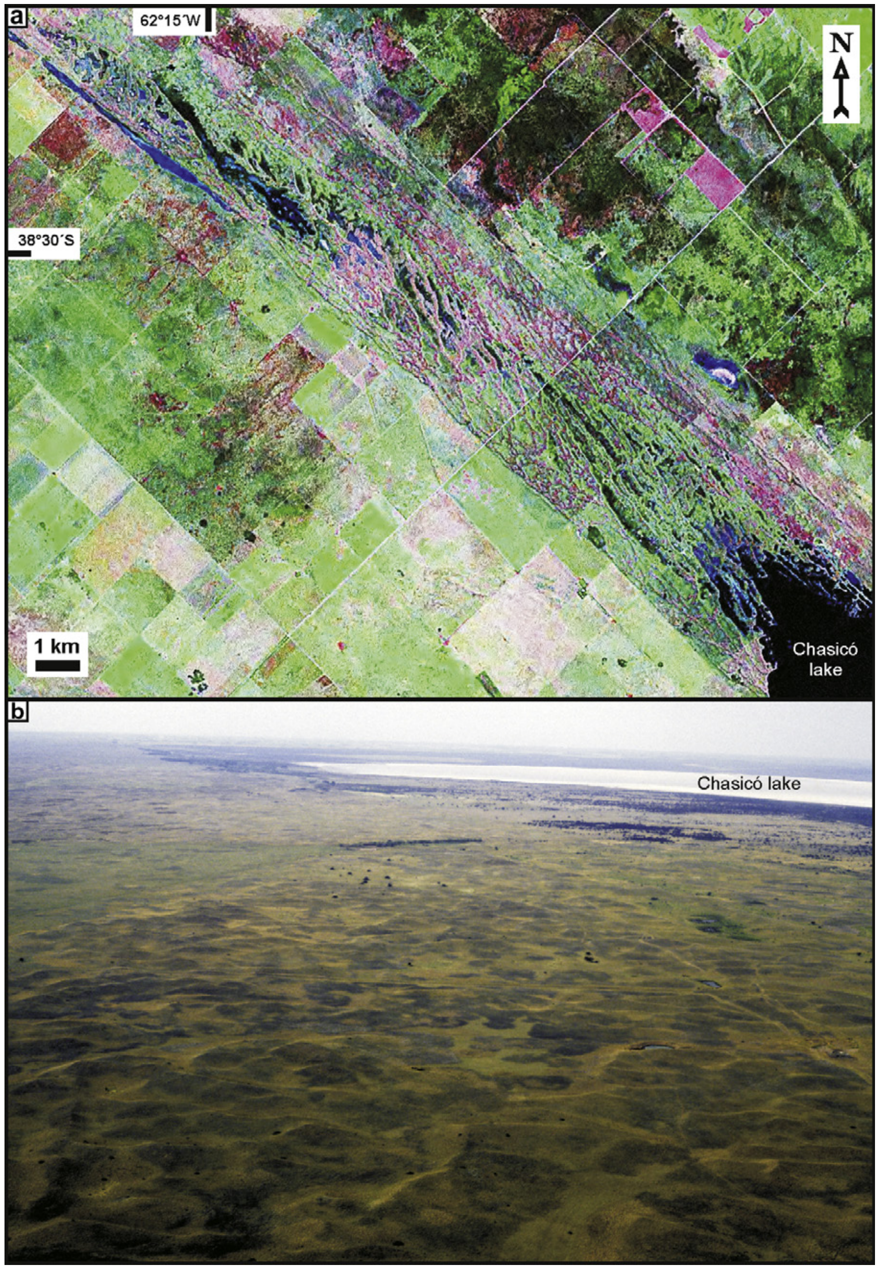

Fig. 11. PPMD unit at the Chasicó depression: (a) Landsat image of the area (ETM + image, Bands 742, obtained from https://zulu.ssc.nasa.gov/mrsid/); (b) aerial view of the dunes towards SE.

landforms suggest northeasterly paleowinds. Northward, linear dunes, 3–5 m high and 20–30 m wide and surrounded by sand mantles are located closer to a saline (Fig. 9a).

Médanos Grandes dunefield, at San Juan Province, shows several patterns of dunes and megadunes of different types, size, spacing and alignment (Fig. 9b; Tripaldi, 2002b). This dunefield extends to the SE of the Pie de Palo range (Fig. 2). Larger landforms with 2000-meter spacing and height up to 55 m, consist of crescentic megadunes with superimposed smaller dunes (Fig. 10a). Northern megadunes are oriented NE while southern megadunes have slipfaces facing to the southwest, suggesting southwesterly and northeasterly paleowinds.

Médanos de los Naranjos dunefield covers the piedmont of the Andes and San Rafael basement block, Mendoza province (Fig. 2). It is dominated by crescentic dunes and megadunes with diverse sizes and orientations (Fig. 10b, Sepúlveda et al., 2007; Tripaldi, 2010). In the western area the dune pattern is formed by partially eroded megadunes, with NE–SW oriented crests and steep sides facing W–NW (Fig. 9c). Smaller, NW–SE trending, crescentic dunes are superimposed over these megadunes, with leewards to the NE. These dunes become larger eastward, creating a better preserved and oblique megadune pattern (Fig. 9c).

Médanos de Picardo dunefield occurs closer to high relief areas, about 15 km eastward of the San Rafael block (Fig. 2). It is mainly formed by NW–SE trending, few meters high, crescentic dunes with lee slopes facing to NE (Sepúlveda et al., 2007; Tripaldi, 2010). Remote sensing images show the presence of a larger pattern of N–S trending, crescentic ridges likely of an older dune system, now partially eroded by water and reworked by aeolian processes. These dunes are up to 40 m high and have west-oriented lee slopes (González Díaz, 1972; Krömer, 1996).

Other dune systems of the eastern Mendoza piedmont are Médanos de la Travesía (MT) and Pampa de la Varita (PV) that were mapped by Krömer (1996). Both extend from the previously

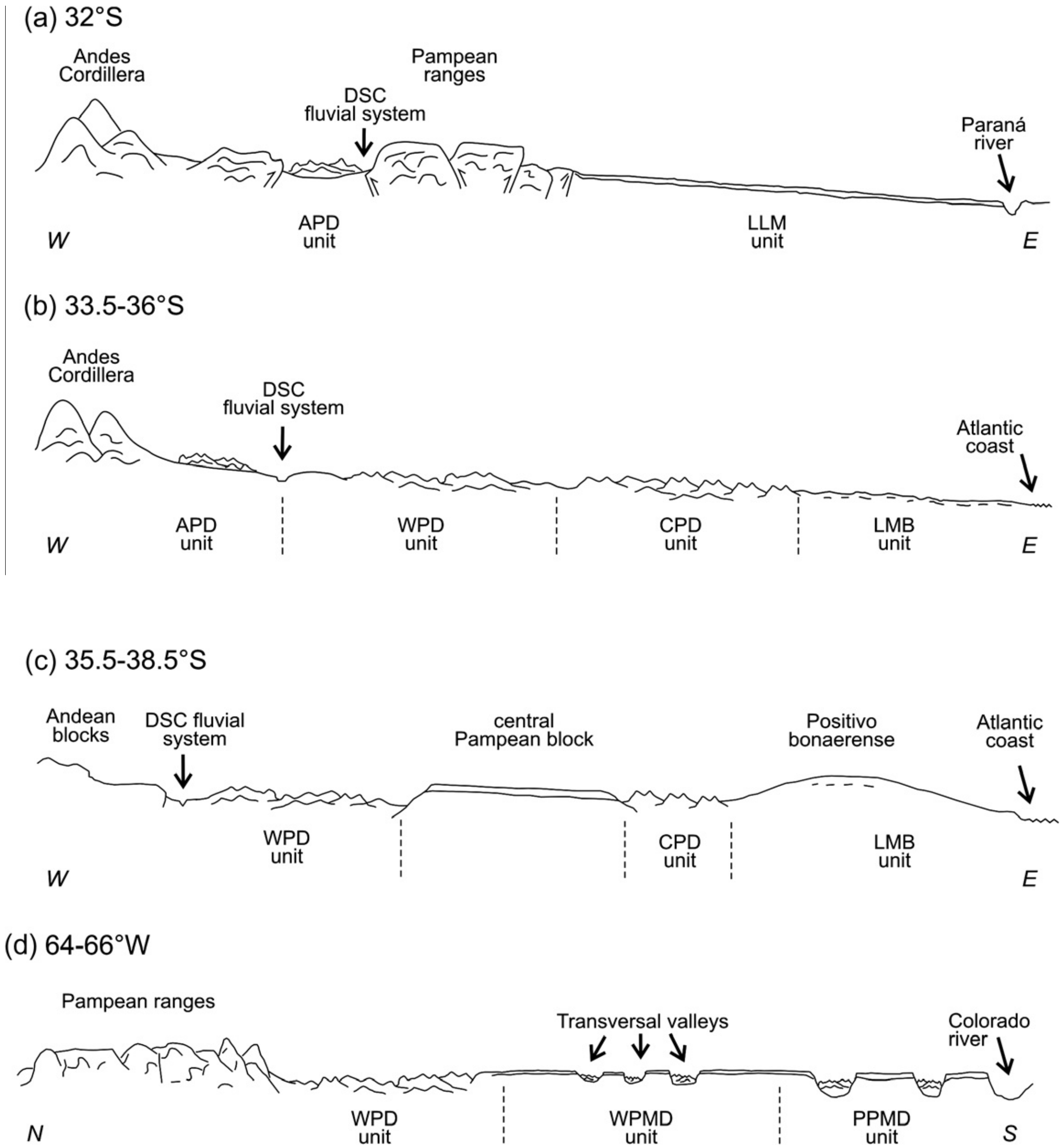

Fig. 12. Regional transects across central Argentina illustrating the distribution of main aeolian landforms as a function of the different geological and structural settings.

described dunefields to the DSC fluvial system (Fig. 2). MT is formed by few meters high, NW–SE trending, crescentic dunes with lee slopes facing NE in the western area. Dunes gradually vanish eastward, reworked by large compound parabolic dunes, up to 4 km long and 1.5 km wide, oriented to the NW (Tripaldi, 2010). Linear dunes up to 5 m high and extending along a NW–SE trend occur in the eastern area. South of the Diamante River, PV is formed basically by the same pattern of crescentic, parabolic and linear dunes previously described at MT dunefield (Tripaldi, 2010).

Well-constrained ages from APD are limited, with some OSL ages from Médanos Grandes, Médanos Negros and Médanos de los Naranjos dunefields. Sections of Médanos Grandes, representing two different settings (marginal sand mantle and dune areas), yielded ages suggesting significant aeolian accumulation during Holocene times (4.3–4, 2.1 and 0.6–0.4 ka; Tripaldi and Forman, 2007). Late Holocene aeolian activity was also inferred by these authors at Médanos Negros. Further south, at Médanos de los Naranjos dunefield, OSL dating of aeolian sand (sand mantle and dune facies) yielded ages between ca. 21 and 14 ka suggesting aeolian accumulation during the LGM (Tripaldi et al., 2011).

Taking into account the large size of the APD dunes (Tripaldi et al., 2010b), the thick accumulation of sand and the record of late Pleistocene aeolian sand and loess deposits eastwards, the construction of APD may be traced back in time at least to the last glacial maximum, although earlier aeolian activity cannot be ruled out.

3.8. Unit 8: Northern Patagonian and southern Pampean sand mantles and dunefields (PPMD)

This unit extends across the southern most part of Buenos Aires, southern La Pampa and northern Rio Negro Provinces (Fig. 2). It is located within the domain of the Colorado tectonic basin (Fig. 3), generated during the opening of the South Atlantic ocean. This basin is filled with up to 7 km of late Jurassic, Cretaceous and Cenozoic deposits (Yrigoyen, 1999; Cingolani, 2005). The landscape consists of several aggradational surfaces of ages varying from the late Miocene to the Pleistocene (Folguera and Zárate, 2009), composed of fluvio-aeolian sediments of volcaniclastic composition. These deposits, grouped into the Rio Negro Formation (Andreis, 1965) and capped by a calcrete crust, have been regarded as one of the main source areas of the aeolian deposits of SLM unit (Zárate and Blasi, 1993).

Dominant aeolian landforms consist of sand mantles (up to 2 m thick) that cover the Miocene–Pleistocene aggradational surfaces. In the central eastern area Etcheverría et al. (2005) pointed out a grain-size trend with coarser deposits (sands) to the W grading to sandy loess to the NE. The sediments are mainly volcano-pyroclastic including a secondary input of metamorphic rocks. The authors inferred predominant W–SW winds. As observed in the previously described WPMD unit, dunes occur mainly along the linear depressions and paleovalleys, occupying their central and northern segments. In the eastern region, about 40 km to the W of Bahía Blanca city, some dunes occur, mainly linear ridges and blowouts (Fig. 11). Neither detailed geomorphological nor sedimentological and chronological studies have been performed, this being by far the least known area of the aeolian system of central Argentina.

4. Discussion

The regional analysis of the aeolian cover of central Argentina indicates that sandy deposits show a wide distribution whereas silty deposits (loess) are more restricted than previously indicated (Teruggi, 1957; Zárate, 2007), forming a more or less continuous apron that blankets the northeastern Pampas of Buenos Aires, the central areas of Córdoba and southern Santa Fé (Fig. 2). Further south, discontinuous patches of loess are found at intramountain settings of the Tandilia and Ventania ranges, as well as in small areas of the structural plain of the central La Pampa province (Fig. 2). Earlier regional mapping of loess deposits (Zárate, 2007 and references therein) pointed out the occurrence of a continuous loess apron at the Salado River basin in the eastern Pampas of Buenos Aires (*Pampa deprimida* – low Pampa). However, recent field work suggests that reworked loess (loess-like deposits) generated by fluvial activity is an important component, likely more widespread than primary aeolian deposits, along the southern margin of the Salado River basin (here included in the LMB unit, Fig. 2). Some parts of the SLM unit are characterized by loessial sands and sandy loess conforming a sedimentological transitional area to the northeastern loess units (Fig. 2). As a result, the aeolian cover exhibits a regionally continuous grain size decrease eastward and northeastward. The deposits making up the APD, WPD and WPMD units, and the southeastern PPDM unit (Fig. 2) are proximal aeolian facies closer to their source area (Colorado River system and its major tributary the DSC fluvial system, Fig. 1). The relatively coarse grain size of the aeolian facies distributed across the southeastern part of Buenos Aires province (SLM unit, Fig. 2) must be attributed to their location close to the source area represented by the distal reaches (delta) of the Colorado River during the late Pleistocene.

Concerning the geomorphology of the aeolian cover, sand mantles are dominant aeolian landforms in northern Patagonia, southern and central Pampas and the margins of the Positivo Bonaerense (PPMD, WPMD and SLM units, Fig. 2). Dunes prevail across the Andean piedmont and western and central Pampas (APD, WPD, and CPD units, Fig. 2). They are characterized by a very variable

Table 2
Main source areas, ages and prevailing winds of the aeolian units of central Argentina.

Aeolian units	Composition and source of aeolian material	Ages	Prevailing winds
Loess and loess-like mantles (LLM)	Dominant volcaniclastic material derived from the Andean region; secondary sources from the Pampean ranges, the Paraná river basin and likely the Uruguayan Precambrian outcrops	TL, OSL and IRSL dates on loess deposits. Uppermost 3–10 m of loess and loess-like successions dating back to the last glacial cycle; lower sections older than MIS 5; Holocene aeolian episodes Tortugas (Santa Fe) OSL ages from ca. 1 to 150 ka BP (Kemp et al., 2004). Lozada (Córdoba) from ca. 105 to 5.7 ka BP Baradero (Buenos Aires) from 114 to 144 ka BP (Kemp et al., 2006). Corralito-Monte Ralo (Córdoba) IRSL ages from ca. 13.6 to 68.2 ka BP (Frechen et al., 2009). Gorina (Buenos Aires) OSL ages from 187–194 to 9 ka BP (Zárate et al., 2009)	SW,W
Loess and loess-like mantles and blowouts (LMB)	Dominant volcaniclastic material derived from the Andean region with secondary sources from the Pampean ranges	OSL age (dune) near Mar del Plata: ca. 700 ka BP (Martínez, 1998)	W,SW
Sandy loess and loessial sand mantles (SLM)	Dominant volcaniclastic composition (Andean derived), secondary sources from the Tandilia and Ventania ranges	TL ages at: Saldungaray: ca. 10.8 ka, 9.8 ka BP; Sauce Chico: 4.4 ka BP (Zárate, 2003); Cerro El Sombrero: ca. 21.5 and 9.5 ka BP (Zárate, 2003). Cerro La China: ca. 4.5 ka BP (Zárate and Flegenheimer, 1991)	SW,W
Central Pampean dunefields (CPD)	Dominant volcaniclastic composition (Andean derived)	Late Pleistocene age according to fossil remains (megafauna). OSL ages: ca. 42.7 and 30.0 ka BP (Latrubesse and Ramonell, 2010)	W,SW
Western Pampas sand mantles and dunefields (WPMD)	Mixed provenance with volcaniclastic material mostly coming from the DSC fluvial system (draining the Andes) and from local rock outcrops (Lihue-Calel range)	Late Pleistocene age according to fossil remains (megafauna)	SW
Western Pampean dunefields (WPD)	Mixed provenance from the Andes Cordillera, the metamorphic-igneous Pampean ranges and glass shards from the Andes	OSL ages at San Luis dune field: LGM deposition (ca. 33–20 ka BP) and reactivation during 20th century times (ca. 95–65 a BP) (Tripaldi and Forman, 2007)	SE,NE
Andean piedmont dunefields (APD)	Mixed provenance from the Andes Cordillera, the metamorphic-igneous Pampean ranges and Andean volcaniclastic material. Médanos Grandes, mixed provenance (metamorphic-igneous, volcanoclastic) Médanos Negros, major input from ultramafic–mafic rocks of Sierras Pampeanas. Other dunefields not studied	OSL ages at Médanos Grandes: ca. 4.2, 2.1, and 0.6–0.4 ka BP; Médanos Negros: ca. 2.5 and 0.4 ka and 0.9 a BP (Tripaldi and Forman, 2007). Médanos de los Naranjos: LGM deposition (ca. 21–14 ka BP) (Tripaldi et al., 2011)	SW,SE,NE
Northern Patagonian and southern Pampean sand mantles and dunefields (PPMD)	Sandy deposits of volcanoclastic composition	No ages available	W–SW

morphology, size and orientation even within the same dunefield (dune generations according to Lancaster, 1999), suggesting a complex history of aeolian deposition and reactivation (Tripaldi, 2010). Most of these dune orientations reveal winds from the south quadrant (southeasterly and southwesterly), in accordance with the present dominant wind pattern, accompanied by some northeasterly paleowinds (*e.g.* Médanos Negros, Médanos Grandes and San Luis area, Fig. 9a and b).

The spatial distribution of the aeolian sand landforms is not only related to their relative location with respect to the source areas but also it is controlled by regional and local topographic changes, in turn related to the subsurface geological and structural setting. Fig. 12 summarizes the location of the aeolian units in relation to major topographic features and Table 2 the provenance, ages and inferred prevailing winds. A main aeolian pathway was developed between the Pampean ranges and the central Pampean block, permitting sand migration eastwards from the DSC fluvial system (Fig. 3). The aeolian transportation of sand continued further east, along the low relief areas occupied by the Laboulaye, General Levalle and the Salado tectonic basins reaching remarkable distal eastern locations of more than 500 km from the DSC system (Fig. 12b).

North of the Quinto River, the Pampean Ranges formed a major topographic barrier which did not allow the migration of sandy facies to the E (Figs. 3 and 12a). Further south the central Pampean block constitutes a higher relief area that separates the WPD and CPD units. The major depressions (transversal valleys) crossing the block may have acted as aeolian pathways. Through these corridors sand migrated eastwards from the DSC fluvial system to the southern tip of CPD unit (Figs. 3 and 12d). In addition, the relief changes of nearly 80–100 m between the depressions and the structural plain surface controlled the local distribution of aeolian landforms. In this way, dunefields are located along the transversal valleys whereas sandy loess mantles blanket the structural plain (Fig. 7).

In the southern Pampas of Buenos Aires, the high relief of the Positivo Bonaerense area includes several different geomorphological settings that locally controlled the distribution of aeolian deposits. Hence, aeolian mantles of loessial sands and sandy loess are the dominant landforms, while finer deposits (loess) prevail at the relatively highest topographic settings of the ranges. In addition, it is hypothesized that the Tandilia Range may have controlled the distribution and development of the linear and parabolic dunes found along its northern piedmont (LMB unit).

The general tectonic setting of LMB unit in the presently subsiding Salado basin constitutes a low relief area of large extent (Fig. 3), under humid–subhumid conditions. The resulting geomorphological environment is characterized by very poor drainage conditions and affected by major flooding events, which may explain the occurrence of fluvially reworked aeolian deposits (loess-like) along with the frequent presence of parabolic dunes and blowouts.

The PPMD unit is characterized by the occurrence of dunefields along paleovalleys and topographic depressions. Instead, the surface of major alluvial fans are covered by sand and sandy loess mantles.

Prior to the availability of modern-age dating techniques, the chronology of the aeolian cover was based on its vertebrate fossil content which together with the identification of buried soils suggested the occurrence of several aeolian episodes of accumulation, starting sometime during the late Pleistocene and continuing at intervals during the Holocene (Fidalgo, 1990). As a result, the deposits have been traditionally regarded as part of a major aeolian cycle of late Pleistocene–Holocene age. This hypothesis is in part supported by numerical ages recently obtained at localities of the eastern Pampas and, more recently, at some dunefields of the Andean piedmont. The still small number of age dates points to a significant aeolian activity during the last glacial maximum and the late glacial. Aeolian accumulation extended continuously to the early Holocene at some localities, although with decreasing sedimentation rates, followed by the beginning of present soils formation. At the locality of Lozada, Córdoba piedmont of the Pampean ranges (LLM unit, Fig. 2), loess deposition was continuous since the last glacial maximum to the mid-Holocene when the present soil began to develop (Kemp et al., 2006). Holocene episodes of aeolian reactivation are clearly recorded at several different sites across the region particularly during the mid-late and late Holocene, suggesting a dry spell. An important aeolian event is reported during the early-mid 20th century in the west related to both drier conditions and land management (Tripaldi et al., 2010c). These episodes are mainly recorded in the semiarid–arid areas of the studied region, the most sensitive to climatic fluctuations.

5. Conclusions

The regional analysis performed reveals the vast extension, heterogeneity and volume of the aeolian deposits covering central Argentina. The distance to the source areas is a primary control in the distribution of aeolian facies and resulting landforms. The subsurface geology and structure below each aeolian unit has governed the topographic relief which favored the formation and distribution of some landforms.

Although considered so far as part of a major aeolian cycle generated during the last glacial conditions, some questions arise. Was the entire volume of aeolian deposits originated as a result of primary deflation from the source areas (river floodplains) during the last glacial cycle? Or, were newly generated aeolian deposits accumulated together with the reworking and reactivation of older aeolian materials? Is this the case, among others, of the fine sand dunes of the CPD unit, located at far distances from the source areas? Several aspects remain to be studied and understood. This contribution is a first approach to systematize the complexity of the aeolian cover. Future efforts will be oriented to revise the characterization of the aeolian units identified through detailed sedimentological, geomorphological and geochronological analysis.

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