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The Holocene 2013 23: 1731 originally published online 8 October 2013
DOI: 10.1177/0959683613505338

Research paper

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23(12) 1731–1746

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Abstract

Drought episodes during the early–mid 20th century were recognized and described in several places around the world, with extreme dry conditions and widespread landscape denudation, like during the famous 'Dust Bowl' in North America. However, there is scant documentation of droughts in southern South America, particularly from the Pampas, and none based on the geological record. In this article, we provide clear evidence of aeolian reactivation and sand deposition in some areas of La Pampa and San Luis provinces, western Pampas (Argentina), during early–mid 20th century in response to drier conditions, probably amplified, like historic droughts in North America, by anthropogenic factors (e.g. significant population increase and agriculture expansion into a fragile environment). Evidence includes widespread bare sand blowouts, extensive surfaces with active sand migration, steep dune lee slopes, and sharp crests covered by weak soil development (A/C profile), accompanied by historical documents. Optically stimulated luminescence (OSL) ages on aeolian beds confirm mobilization and sedimentation by wind processes *c.* 95–60 yr BP. Considering the dominant (over 70%) austral spring–summer precipitation, it is possible the rainfall deficit in western Pampas was linked to positive sea surface temperature (SST) anomalies in the western subtropical South Atlantic Ocean (20–30°S and 30–50° W), according to significant canonical correlation between the precipitation field in subtropical South America and the Atlantic Ocean SST anomalies.

Keywords

20th century, aeolian record, optically stimulated luminescence dating, Pampas Dust Bowl, South America, western Pampas

Received 19 November 2012; revised manuscript accepted 19 July 2013

Introduction

The Argentine Pampas is a broad, low-relief plain (Figure 1), covered by a widespread late Quaternary aeolian mantle, consisting of mostly loess and loessoid deposits across the eastern Pampas that grade into sandy mantles and dune fields in the western Pampas (Iriondo, 1999; Zárate, 2003; Zárate and Tripaldi, 2012). In the late 19th century, the type and coverage of vegetation for substantial areas of the western Pampas were extensively modified by agricultural practices and sheep/cattle grazing. Open cattle grazing was extensive into the 1960s with a concomitant increase in grain cultivation in the past 50 years and intensified since 1980 (Baldi and Paruelo, 2008; Demaría et al., 2008; Viglizzo et al., 1995, 1997). Thus, in the 20th and 21st centuries, the land surface response reflects complex interactions among human land use, anthropogenic changes in regional hydrology (Jayawickreme et al., 2011; Jobbágy et al., 2008), and climatic variability (Magrin et al., 2005; Viglizzo and Frank, 2006; Viglizzo et al., 2011).

In North America, the juxtaposition of agricultural overproduction, poor soil conservation practices, a pronounced reduction in spring precipitation (~30–40%) and warmer than average summer temperatures from *c.* 1930 to 1939 resulted in epic drought conditions across much of North America (the 'Dust Bowl', for example, Cook et al., 2007; Egan, 2006; Worster, 1979). This drought was associated with large-scale denudation of the land surface and in some places, the reactivation of dune systems (e.g. Forman et al., 2008; Woodhouse and Overpeck, 1998). Climate modeling indicates that the broad footprint of this and earlier decadal-scale droughts reflects hemispheric climate forcing with cooler sea surface temperatures (SSTs) in the eastern Pacific Ocean with La Niña–like variability and concomitant warming in the North Atlantic Ocean, which significantly reduced the flux of moisture from subtropical sources into central North America (Feng et al., 2008, 2011; Schubert et al., 2004b). These dry conditions were exacerbated by land surface, vegetation and albedo changes, and a regional dust flux, which can deepen and spatially extend drying (e.g. Cook et al., 2009).

Early precipitation records indicate that the Pampas of Argentina, similar to the semi-arid Great Plains in North America, has had significant climate variability in the 20th century with decadal to subdecadal scale dry and humid periods (Compagnucci et al., 2002). Historical records of climate conditions in the western

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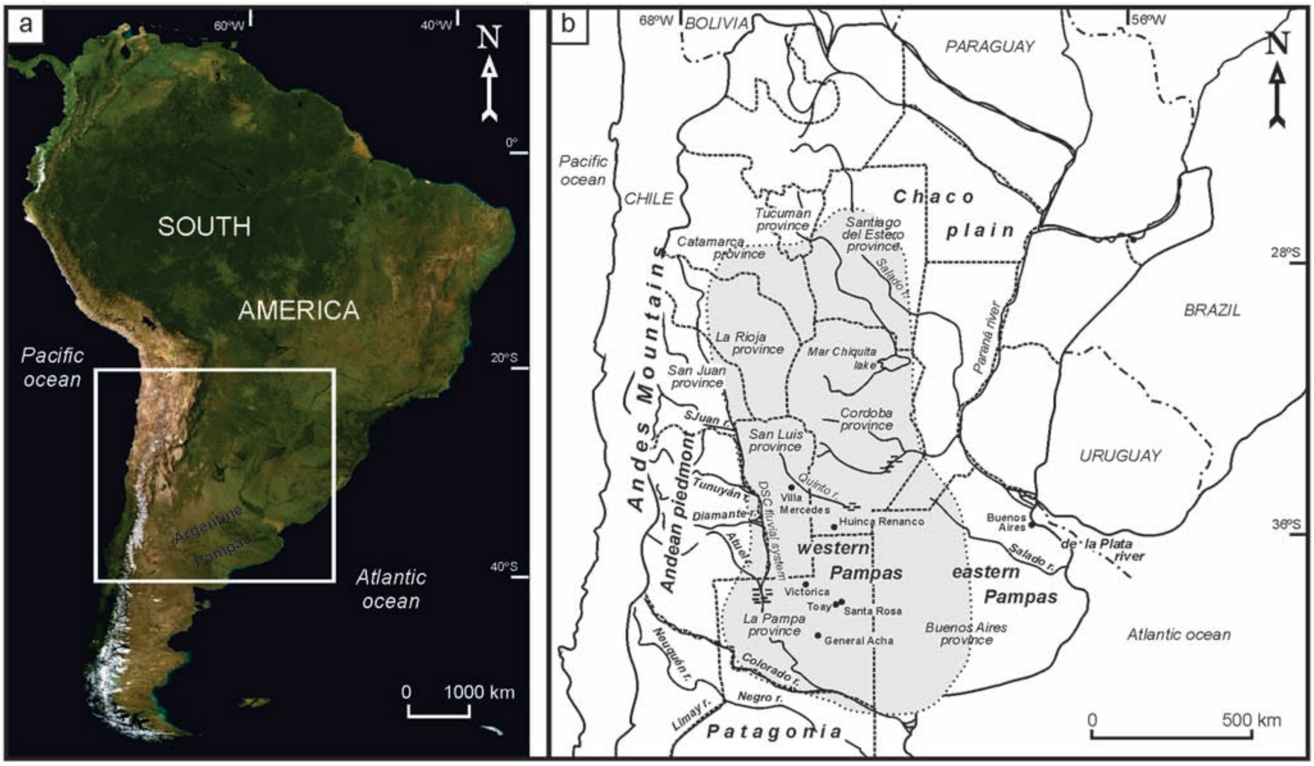


Figure 1. (a) Location of the Argentine Pampas in southern South America, boxed area is shown in (b) with the studied localities of western Pampas and the estimated region affected by the Pampas 'Dust Bowl Drought', in gray, according to observations by Guiñazú (1939); DSC means Desaguadero-Salado-Curacó, main fluvial system collecting waters from several Andean rivers.

Pampas indicate significant drought episodes during early–mid 20th century, with the severest drying ('climate crisis') in the 1930s (Guiñazú, 1939; Zarrilli, 1999). Analysis of effective moisture variability for the western Pampas through the calculation of the Palmer Drought Severity Index (PDSI), a climatic index that reflects rainfall, evapotranspiration, and antecedent soil-water content (Palmer, 1965), indicates particularly severe droughts (<-2 PDSI) during early–mid 20th century (Scian and Donnari, 1997).

The Pampas is the 'breadbasket' for Argentina, with annual acreage in wheat of approximately 1.7 Mha during the 20th century with crop yield influenced by precipitation variability, among a number of variables (Verón et al., 2004). Historical and archaeological studies show open cattle grazing was a common practice of the Ranquel people on the western Pampas since the 18th century (Fernández, 1998; Tapia, 2005), with a landscape dominated by closed forests mainly of Caldén (*Prosopis caldenia Burkart*) (Dussart et al., 2011). Post *c.* 1879, there was a massive deforestation mostly for sheep farming and for railway sleepers and fuelwood (Garbarino, 2008), inducing a savanna landscape with dispersed trees of Caldén (Dussart et al., 2011). In the early 20th century, cultivation expanded to marginal lands in the western Pampas reflecting the availability of pristine land, the high prices of cereals, the westward expansion of the railway and several years of ample harvests (Alonso, 2009; Lluch and Salomón Tarquini, 2009; Zarrilli, 1999). Recent studies infer that the drying and flooding events in the western Pampas during the late 20th century reflect complex landscape-scale interactions of hydroecologic, climatic and agricultural factors (Jayawickreme et al., 2011; Viglizzo et al., 2011). Specifically, overcultivation appears to have surpassed critical ecological thresholds, and during dry (wet) years triggered drought (flooding) events, partially linked to changes in evapotranspiration (Viglizzo and Frank, 2006).

Historical accounts (Guiñazú, 1939; Zarrilli, 1999) and climatic analysis (Compagnucci et al., 2002; Scian and Donnari, 1997) indicate that the 1930s drought on the Pampas of Argentina was the severest drought in the past *c.* 100 years, described as the 'Pampas Dust Bowl' (Seager et al., 2010; Viglizzo and Frank, 2006). However, little is known about the spatial extent of this drought and associated landscape response of semi-arid grasslands of the western Pampas. This article presents geomorphic evidence for dune reactivation and the sedimentary record of aeolian sand deposition on the western Pampas during the first half of the 20th century (Figure 1). These changes in aeolian processes are related to corresponding precipitation series and historical accounts of landscape conditions. The magnitude of aeolian erosion, dune reactivation, and soil denudation is documented across the region, together with an analysis of the possible synoptic climatic linkages related to the drying events in the western Pampas, which appears to persist throughout the Holocene (Tripaldi and Forman, 2007, 2010; Zárate and Tripaldi, 2012).

Methodology

The early–mid 20th-century drought episode in the western Pampas of Argentina is documented by meteorological time series, historical data, geomorphic observations, and associated aeolian stratigraphic studies. Monthly precipitation and hourly wind strength and direction is derived from weather station data of La Pampa (Santa Rosa city) and San Luis (Villa Mercedes and Villa Reynolds cities) provinces (Figure 1), provided by the Argentine National Weather Service (SMN, *Servicio Meteorológico Nacional de Argentina*) and the National Institute of Agricultural Research (*Instituto Nacional de Tecnología Agropecuaria* (INTA)). Villa Mercedes (INTA) and Villa Reynolds (SMN) are 10 km apart. Precipitation data in the western Pampas from Santa Rosa (1921–2003) and Villa Mercedes sites (1903–2003) are the longest available time series.

Wind data, especially wind velocity, are somewhat sparse for the western Pampas. A reliable time series of wind data is available from *c.* 1995 to 2009 for two weather stations, Villa Reynolds and Santa Rosa, which are in proximity to dune fields. To better understand seasonal changes in aeolian processes, the seasonal sand drift potential (DP), using the Fryberger (1979) method, was calculated using daily, 24-hourly wind measurements (1 January 1995 to 31 December 2009) from the mentioned stations and is illustrated by sand roses. The sand DP is calculated by vectorial analysis of wind velocity and direction data, which is a measure of efficiency of winds to move medium sand grains (Fryberger, 1979).

Geomorphic analysis and aeolian stratigraphic investigations focused on central-southern San Luis and central-eastern La Pampa provinces, transitional areas between the more humid eastern Pampas and the drier western Andean piedmont (Figure 1b). Chronological control for the deposition of historical aeolian sediments was deduced from associated cultural, geological, and pedological context in La Pampa localities and by optically stimulated luminescence (OSL) dating of quartz grains, from exposures in San Luis Province. Optical dating methods are similar to Tripaldi and Forman (2007). Additional evidence of land surface conditions was assessed through technical reports, publications, and historical photographs obtained from the *Archivo Histórico Provincial de La Pampa* (Provincial Historical Archive of La Pampa), the Photograph Library Bernardo Graff and personal pictures provided by colleagues.

The western Pampas of Argentina

The western Pampas is characterized by an incompletely integrated surficial drainage system with numerous endorheic basins; many are deflated and others are saline lakes. Transverse SW–NE trending valleys (Calmels, 1996) are a common feature of central La Pampa Province, at times occupied by ephemeral creeks, whereas in central-southern San Luis Province, the only major permanent drainage is the Quinto River (Figure 1b). The dominant parent material of surface soils is medium to fine sand, aeolian in origin, with relatively weak pedogenesis with A/C horizonation (INTA, 1990). The current vegetation cover is highly modified by cattle grazing and agriculture and includes xerophytic grasslands with woodlands in patches and psammophytic species on the dune field areas (Anderson et al., 1970; Cabrera, 1976).

The population of the western Pampas increased considerably by the end of the 19th century mainly due to European settlers, and the territory was transformed by the establishment of towns and villages and agricultural development (Alonso, 2009; Lluch and Salomón Tarquini, 2009). In San Luis and La Pampa provinces, the rural population grew by 20% and 70%, respectively, between AD 1895 and AD 1914 (Chiozza and Figueira, 1982). As a result, the original forested landscape was extensively modified and replaced with crops, mainly wheat and maize (Viglizzo and Frank, 2006). Large-scale denudation ensued because trees were cut down to fuel the railroad, and the use of the iron plowshare was effective in disaggregating the surface soil, and exposing silts and sands prone for aeolian transport (Guiñazú, 1939; Zarrilli, 1999). Aeolian erosion has been demonstrated to be a significant degradation process in the Pampas (Buschiazzo et al., 1999), where 60% of total soil nitrogen and phosphorus losses were attributed to wind erosion (Buschiazzo and Taylor, 1993).

Climatic conditions

Precipitation

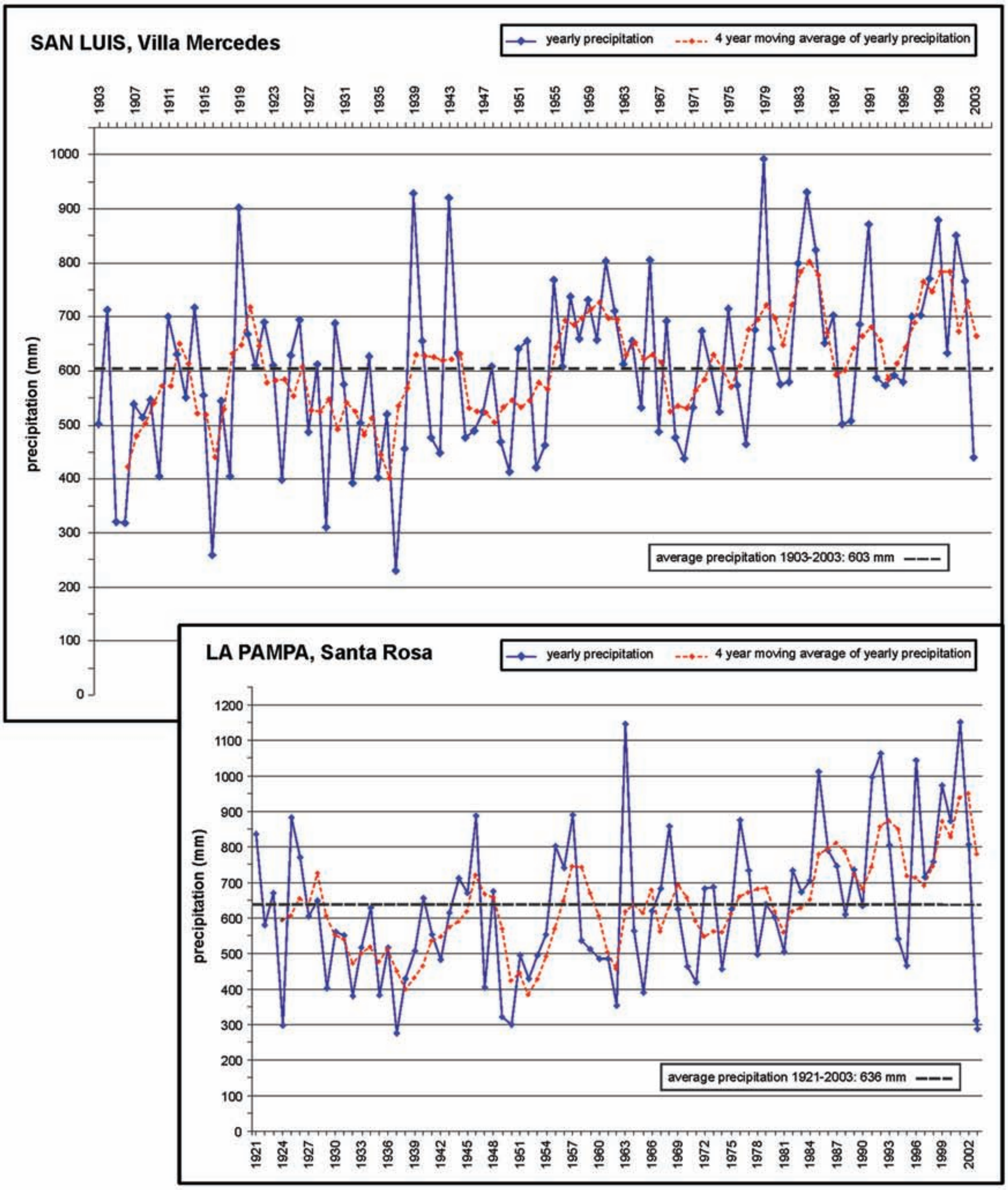
Western Argentina has a pronounced east to west precipitation gradient, similar to the Great Plains in North America, with mean annual values near Villa Mercedes of 700 mm to about 90 mm near San Juan Province (Compagnucci et al., 2002; Figure 1b). A distinct pattern is the seasonal distribution of precipitation with over 70% of precipitation occurring in austral spring and summer months (October through March), often associated with the southward expansion of the South American Convergence Zone and the southernmost effect of the Intertropical Convergence Zone (e.g. Barros and Silvestri, 2002; Labraga and Villalba, 2009). The source of this precipitation and warmth is cyclonic activity spawned from the subtropical South Atlantic anticyclone (Compagnucci et al., 2002) and the low-level meridional Chaco Jet which brings warm and moist air, derived from tropical jungles and humid lowlands of Bolivia and Brazil, southward along the eastern margin of the Andes (Saulo et al., 2000; Wang and Paegle, 1996).

Numerous studies indicated that on interannual timescales for many areas of southeastern South America, particularly in southern Brazil, there is an increase in precipitation with strong El Niño events (e.g. Giannini et al., 2001; Grimm, 2003; Haylock et al., 2006; Pscheidt and Grimm, 2009). The El Niño-Southern Oscillation (ENSO) teleconnection to precipitation variability in the western Pampas is less clear particularly during the austral summer, with potential linkages to equatorial Atlantic Ocean surface temperatures (Grimm, 2003; Haylock et al., 2006), changes in the South American Jet Stream and turbulence (e.g. Seager et al., 2005) and soil-moisture atmosphere feedbacks, which enhance spring precipitation (Grimm and Zilli, 2009).

A critical synoptic-scale element for the import of moisture to central-western Argentina is the pressure gradient between a thermal-orographic low east of the Andes and the subtropical South Atlantic anticyclone. This pressure gradient increases during the austral summer resulting in northeasterly flow and the net import of moisture from Atlantic Ocean and Bolivian sources. In winter, with less surface heating and the northward displacement of the Westerlies, the import of moisture significantly declines (Compagnucci et al., 2002).

Moisture variability on interannual and interdecadal timescales in western Argentina indicates hemispheric climate controls linked to changes in SSTs, particularly in the equatorial Atlantic Ocean (Agosta and Compagnucci, 2012; Penalba and Vargas, 2004; Seager et al., 2010). Analysis of precipitation data from 1901 to 1998 from Argentina, including the western Pampas, documents significant interannual and multidecadal fluctuations (18–21, 6, 4, and 2 years) in summer rainfall (Compagnucci et al., 2002). In general, annual precipitation was lower during the first half of the 20th century than during the second half in eastern La Pampa and southern San Luis provinces (Berton and Echeverría, 1999; Penalba and Vargas, 2004; Viglizzo et al., 1995). Seager et al. (2010) explored these precipitation anomalies over southeast South America, through atmosphere–ocean climate models forced by historical (1880–2005) SSTs and found that about 40% of precipitation variability largely reflects SSTs changes in the equatorial Atlantic Ocean, which is highly correlated ($r = .84$) to the Atlantic Meridional Oscillation.

Previous climatological analysis identified a noticeable increase in rainfall values in the mid-1970s, particularly in western Argentina (Agosta and Compagnucci, 2008; Barros et al., 2008). This trend is also identified in the precipitation records of the western Pampas at Villa Mercedes and Santa Rosa stations where the driest years, with annual precipitation below 400 mm (about 200 mm less than the 20th century average), occurred predominantly in the first half of the 20th century (Figure 2). Moreover, the severest droughts occurred during the 1930s. Three of the 10 driest years between 1903 and 2003 at Villa Mercedes occurred between 1929 and 1937, with a 33–62% reduction in rainfall compared to the long-term record. In Santa Rosa, 4 of the 10 driest years between 1921 and 2003 occurred between 1929 and 1937 with a 37–57% reduction in precipitation. Other significant dry periods occurred



Villa Mercedes station, San Luis province

	Year	Total annual precipitation	% precipitation reduction
1	1937	230,0	61,5
2	1916	259,0	56,7
3	1929	310,0	48,1
4	1906	318,0	46,8
5	1905	320,0	46,5
6	1910	385,5	35,5
7	1924	399,1	33,2
8	1935	402,3	32,7
9	1918	405,0	32,2
10	1950	413,0	30,9

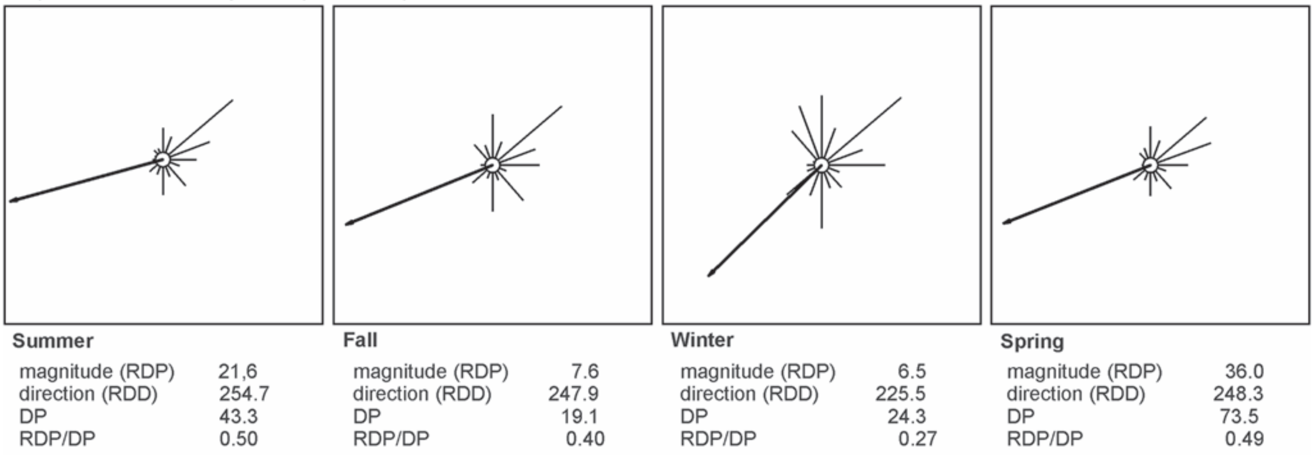
Santa Rosa station, La Pampa province

	Year	Total annual precipitation	% precipitation reduction
1	1937	274,5	56,8
2	1924	297,0	53,2
3	1950	298,5	53,1
4	1949	320,5	49,6
5	1962	354,0	44,3
6	1932	380,5	40,2
7	1935	383,0	39,8
8	1965	389,0	38,8
9	1929	403,0	36,6
10	1947	314,0	36,5

Figure 2. Annual precipitation trend during the 20th century in the studied area represented by the annual yearly rainfall (solid lines) and 4-year moving averages of the annual yearly rainfall (dotted lines) in weather stations of Villa Mercedes and Santa Rosa (San Luis and La Pampa provinces, respectively). Below, the reduction (total and percentage) of annual precipitation with respect to the 20th-century average, for the 10 driest years.

between 1905 and 1906 at Villa Mercedes, when annual rainfall was about half of the 1903–2003 average, and during 1949–1950, especially at Santa Rosa, with a 49–53% reduction compared to the mean record (Figure 2). Post 1950, precipitation values in

a) SAN LUIS, Villa Reynolds (1995-2009)



b) LA PAMPA, Santa Rosa (1995-2009)

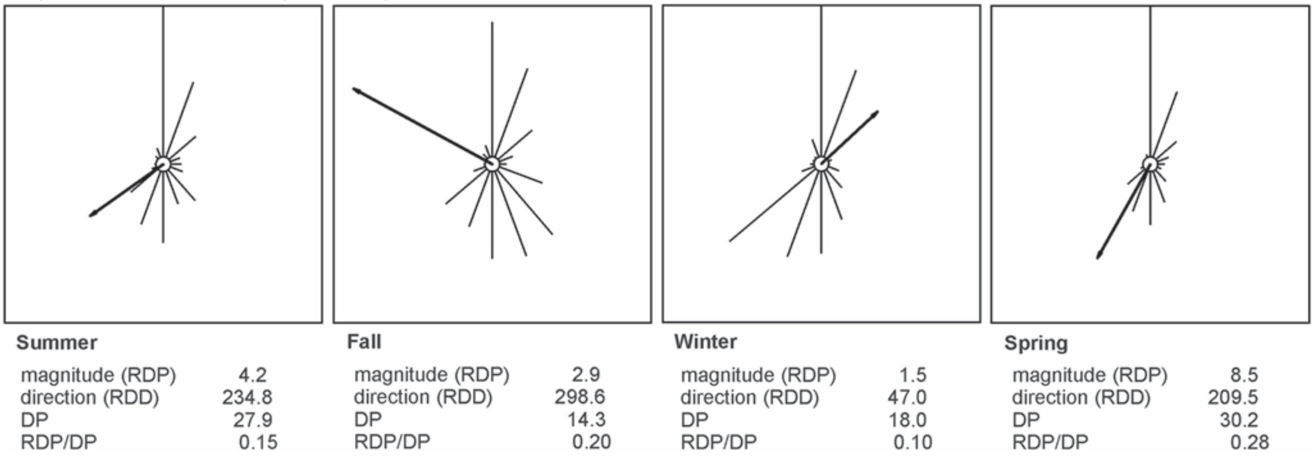


Figure 3. Seasonal wind transport capacity at the western Pampas: (a) Villa Reynolds (San Luis Province) and (b) Santa Rosa (La Pampa Province). In the rose diagrams, the dimensionless vectors are proportional to the potential sand transport from each major wind direction and the arrow points the direction of the RDP of sand. Values of DP and RDP/DP are indexes of seasonal wind energy and directional variability of the wind respectively (methodology by Fryberger, 1979).
DP: drift potential; RDP: resultant drift potential; RDD: resultant drift direction.

central and western Pampas increased significantly (>20% of the 20th-century mean; cf. Agosta and Compagnucci, 2012; Penalba and Vargas, 2004).

Wind

In the Pampas, the wind speed and direction depend primarily on the position and intensity of the subtropical South Atlantic anticyclone, with prevailing directions from the north and northeast throughout the year (Prohaska, 1976). The seasonal wind data (hourly values) for two sites on the western Pampas, represented by sand roses, reveal considerable variation in prevailing wind direction and velocity, reflecting seasonal changes in synoptic-scale circulation and local topographic effects. The different vectors of the annual sand rose for Villa Reynolds (1995–2009) show a resultant drift direction (RDD) to the SW-WSW (RDD: 225–255°; Figure 3a). During the austral spring–summer months, the resultant DPs are four times larger than during the fall–winter, accompanied by higher DP (43.3–73.5) depicting intermediate to high wind energy environments according to recalibration of Fryberger's (1979) classification by Bullard (1997).

The average annual wind direction of Santa Rosa is dominantly from the north, but there is considerable seasonal variability of sand drift directions (Figure 3b) with dominant vectors to the NW during fall, to the NE in winter and finally to SW during spring and summer. This wind rotation to the N quadrant during austral fall and winter months is probably related to a northward displacement of the subtropical South Atlantic anticyclone (Prohaska, 1976). Similar to Villa Reynolds, the DP reveals low wind energy during the fall–winter months while DP shows higher values depicting an intermediate wind energy environment (Bullard, 1997; Fryberger, 1979) along the spring–summer months.

The western Pampas aeolian record during the early 20th century

Aeolian sediments on the western Pampas are thought to have been initially deposited during the Late Pleistocene and were partially reworked during later episodes (Iriondo, 1999). OSL ages of quartz grains of *c.* 33–20 ka from aeolian sands from the San Luis dune field in the western Pampas (Tripaldi and Forman, 2007) indicate active aeolian systems during the Late Pleistocene. Loess deposits from the northern and eastern Pampas yield similar OSL ages, indicating widespread aeolian deposition between *c.* 25 and 9 ka followed by Holocene reactivations (Iriondo et al., 2009; Kemp et al., 2006; Zárate, 2003; Zárate et al., 2009). Holocene episodes of dune migration and sand sheet accretion are also recognized in western areas (Tripaldi and Forman, 2007, 2010).

San Luis Province

A large portion of central and southern San Luis Province, included in the Western Pampas Dunefields (WPD; Zárate and Tripaldi, 2012), exhibits diverse aeolian bedforms and landforms ranging from ripples and small coppice dunes to large parabolic and barchanoid dunes (Tripaldi and Forman, 2007). In San Luis area, the WPD is mainly composed of vegetated paleodunes, where Tripaldi and Forman (2007) recognized different types of parabolic dunes with simple, elongate geoforms (900 m long and 250 m wide) toward the west and larger digitate compound parabolic dunes (2000 m long and 1130 m wide) dominating the central region. Most of these dunes are inactive, relict geoforms likely formed during the Late Pleistocene (Iriondo and Kröhling, 1995; Tripaldi and Forman, 2007). The orientation of these dunes suggests paleowinds from the southeast, which are distinctly different from the current wind DP from the northeast (Figure 3a).

The eastern region of San Luis dune field shows different degrees of deflation and aeolian reworking in the form of blowouts, parabolic and barchanoid dunes. Blowouts vary from nearly circular to irregular hollows, tens of meters to 1.5 km long, surrounded by depositional lobes frequently covered by loose sand (Figure 4b–e). Parabolic dunes include simple and compound types, in many cases with well-developed, barchanoid dunes that have migrated over parabolic dune noses. This dune movement is associated with winds mostly from the northeast, which are common through the year (Figure 3a).

Previous studies documented Late Pleistocene aeolian deposition in central and southern San Luis Province, and several reactivation episodes during the Holocene (Tripaldi and Forman, 2010) that produced dune forms locally and widespread deposition of a sand sheet composed of well-sorted, fine-to-medium sand of variable thickness. In many places, a pedogenically unaltered, centimeter- to decimeter-thick mantle of very friable, well-sorted, fine sand buries a very recent soil, and where these aeolian sediments are absent, the ‘paleosol’ merges with the surface soil. Six measured sections record aeolian deposition, burying a near-surface soil, during the early 20th century. Five of the study sites (Nueva Escocia, Blowout, Nicolas, Fede, and Diego sections) are located to the south of Villa Mercedes, at the most disturbed dune area, whereas the Esteban section exposes the northern sand sheet deposits (Figure 4a).

In the blowout and the Nueva Escocia sections, both located within a blowout dune (Figure 4b), there are Late Pleistocene sand sheet deposits covered by recent aeolian sand. In the Nueva Escocia section, there are three aeolian units, separated by paleosols and characterized by a very well-sorted medium to fine sand, with horizontal to subhorizontal millimeter- to centimeter-scale bed remnants (Figure 5a), indicating aggradation due to wind ripple migration. The uppermost unit shows well-developed horizontal laminations, from which quartz grains (at 170 cm below the surface) yielded an age of 65 ± 5 ka (UIC1610Bl, Tripaldi and Forman, 2007).

The blowout section, ~20 m south of Nueva Escocia section, exposes over 9 m of aeolian sand. This section also shows pedogenically altered sand sheet deposits of Late Pleistocene age (*c.* 32.7–27.6 ka; Tripaldi and Forman, 2007), unconformably overlain by early 20th-century sand sheet and dune deposits (Figure 5f and g). The base of these deposits is a well-sorted medium sand that exhibits horizontal to very-low-angle lamination and inversely graded beds, indicating ripple bed migration (units B1–B3) of a sand sheet. Covering the sand sheet beds, there are almost 4.5 m of very well-sorted, fine-to-medium sand (B4) with high-angle cross-laminations (Figure 5f and h). Individual beds are millimeter to centimeter in scale, and many coarse sand beds are asymptotic down the bedding plain, reflecting grainflow. Reactivation surfaces are common indicating active dune migration. The uppermost unit, capping the section, is a very well-sorted fine sand with diffuse low angle to horizontal bedding. The blowout section yielded several luminescence ages, indicating an early 20th-century aeolian reactivation (*c.* 95–70 yr BP; Figure 5f), and a more recent episode of aeolian deposition *c.* 15 yr BP (Tripaldi and Forman, 2007).

Nicolas, Fede, and Diego sections are present in the south of the Quinto river, at the depositional lobes of compound parabolic dunes (Figure 4c–e) located 20–30 km from each other (Figure 4a). Nicolas section is a 3.5-m-thick exposure of well-sorted, fine sand, subdivided into three units according to the sedimentary structures (Figure 5c). The lower unit (N1), about 1 m thick, exhibits horizontal lamination, indicating aeolian ripples, and yielded an OSL age of 200 ± 20 years (UIC2377; Table 1); it is covered by a cross-laminated bedset (N2), reflecting dune migration, that yielded an OSL age of 70 ± 10 years (UIC2376; Table 1). On top of the dune deposit, there is aeolian fine sand (N3) with diffuse and discontinuous laminae, mostly horizontal and very low angle, and undulating beds related to lenses of coarser sand.

Fede section exposes a similar record, with horizontal laminated sand deposited by wind ripple migration below (unit F1), covered by cross-laminated bedsets (unit F2) due to dune migration (Figure 5d). Quartz grains from unit F2 yielded an OSL age of 60 ± 5 ka (UIC3272; Table 1), indicating dune reactivation during the early–mid 20th century.

Diego section shows about 3 m of well-sorted, fine sand in sets of high-angle cross-bedding (unit D3 in Figure 5e), indicating aeolian accumulation by lee face advances due to grainflow and grainfall processes. Below, there are two other units (D1 and D2), formed by massive, well-sorted, fine sand with disperse calcareous nodules and separated by irregular surfaces. Units D1 and D2 were interpreted as aggradation of wind-transported material over partially vegetated surfaces. Quartz grains at the base and near the top of unit D3 yielded OSL ages of 75 ± 10 ka and 70 ± 10 ka, respectively (UIC3286 and UIC3281; Table 1), that attest, like the Fede section, the migration of dunes during the early–mid 20th century, about 27 km to the south of the latter (Figure 4a).

Esteban section presents about 8 m of sediments recently exposed by incision of a newly formed river tributary north of Villa Mercedes (Figure 4a; González Tomassini and Tripaldi, 2012). The lowest unit (E1 in Figure 5b) is ~2.5 m of massive sandy silt with common calcareous nodules, rhizoconcretions (2–5 cm long) and some burrow casts. Above these units, there are 4.7 m of massive, well-sorted silty sand (unit E2). Some burrow casts are more common to the unit top where a 15-cm-thick weak, buried A horizon is present covered by 10 cm of tephra (unit E3), partially mixed or interlayered with epiclastic sediment. The tephra is pale to very pale brown, massive or with diffuse horizontal lamination. Capping the tephra is a 65-cm-thick bed of massive to faintly horizontally laminated silty sand.

The fine and homogeneous grain-size (sandy silt to silty sand) and the absence of current sedimentary structures and erosional surfaces indicate that units E1 and E2 reflect aggradation of wind-transported material, probably in a sand sheet peripheral to the southern dune fields. The tephra layer is from a volcanic ash fall episode and was partially reworked by aeolian and possibly over land flow processes, whereas unit E4 was deposited by wind ripple migration. Quartz grains of the upper beds of unit E2, below the tephra layer, yielded an OSL age of 1905 ± 140 ka (UIC2802; Table 1). Quartz grains from the base of unit E4, immediately overlying the tephra layer, yielded an OSL age of 70 ± 10 ka (UIC2805; Table 1), and indicates aeolian reactivation deposited at least 50 cm of sand during the early 20th century. This surface aeolian sand, *c.* 70 years old, immediately overlying the tephra layer is consistent with widespread dispersal of ash in central Argentina during the Quizapú volcanic eruption (Chilean Andes) on 10–11 April 1932 (Hildreth and Drake, 1992).

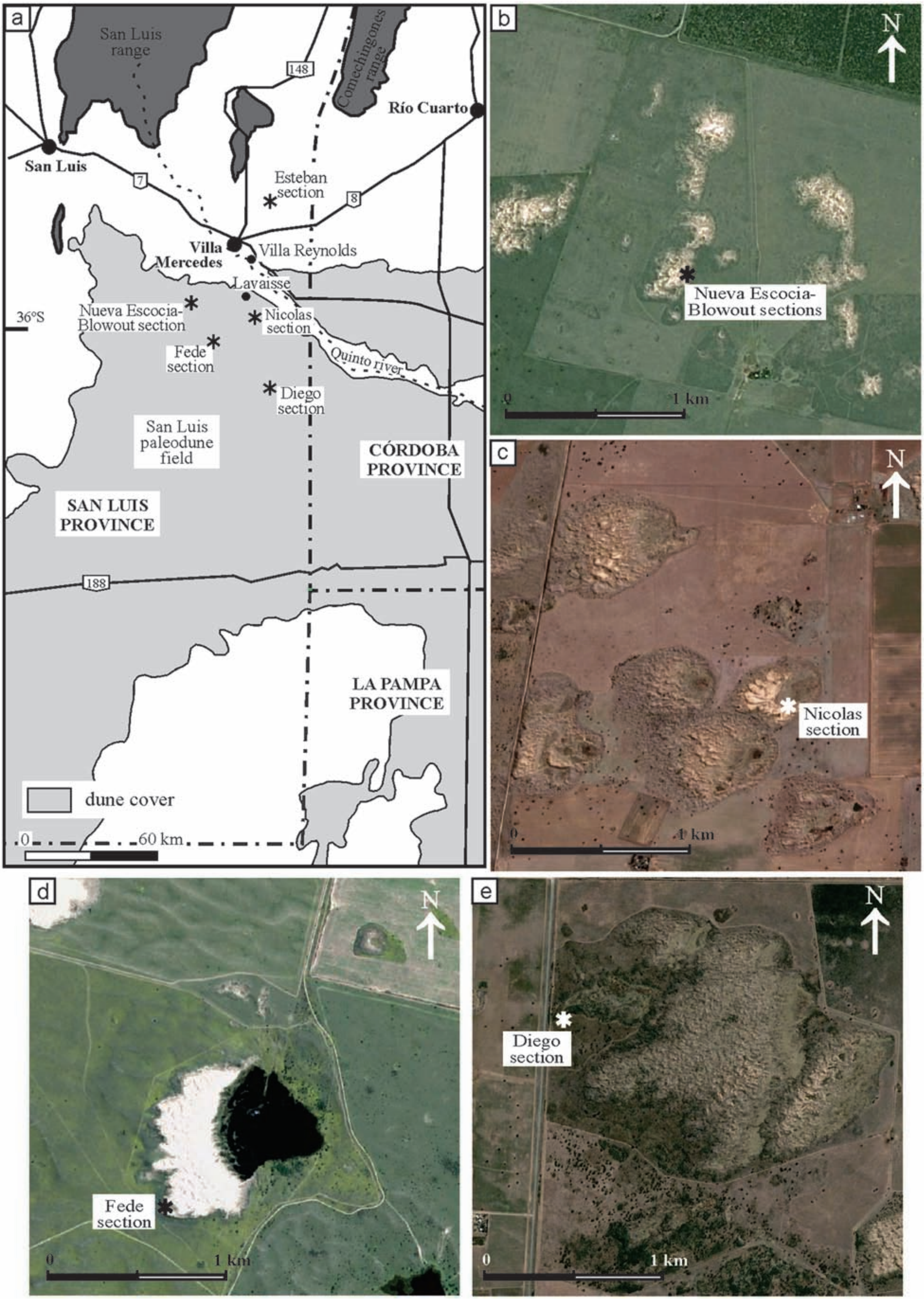


Figure 4. (a) Location of the surveyed sections in the San Luis dune field in the surroundings of Villa Mercedes city and details of the geomorphic features at the dune sites of (b) Nueva Escocia-Blowout (33° 49.197′ S; 65° 43.322′ W), (c) Nicolas (33° 51.215′ S, 65° 24.290′ W), (d) Fede (33° 58.049′ S, 65° 34.550′ W), and (e) Diego (33° 08.535′ S, 65° 21.773′ W) sections. Esteban section is at 33° 32.068′ S, 65° 19.872′ W. Satellite images courtesy of Google Earth®.

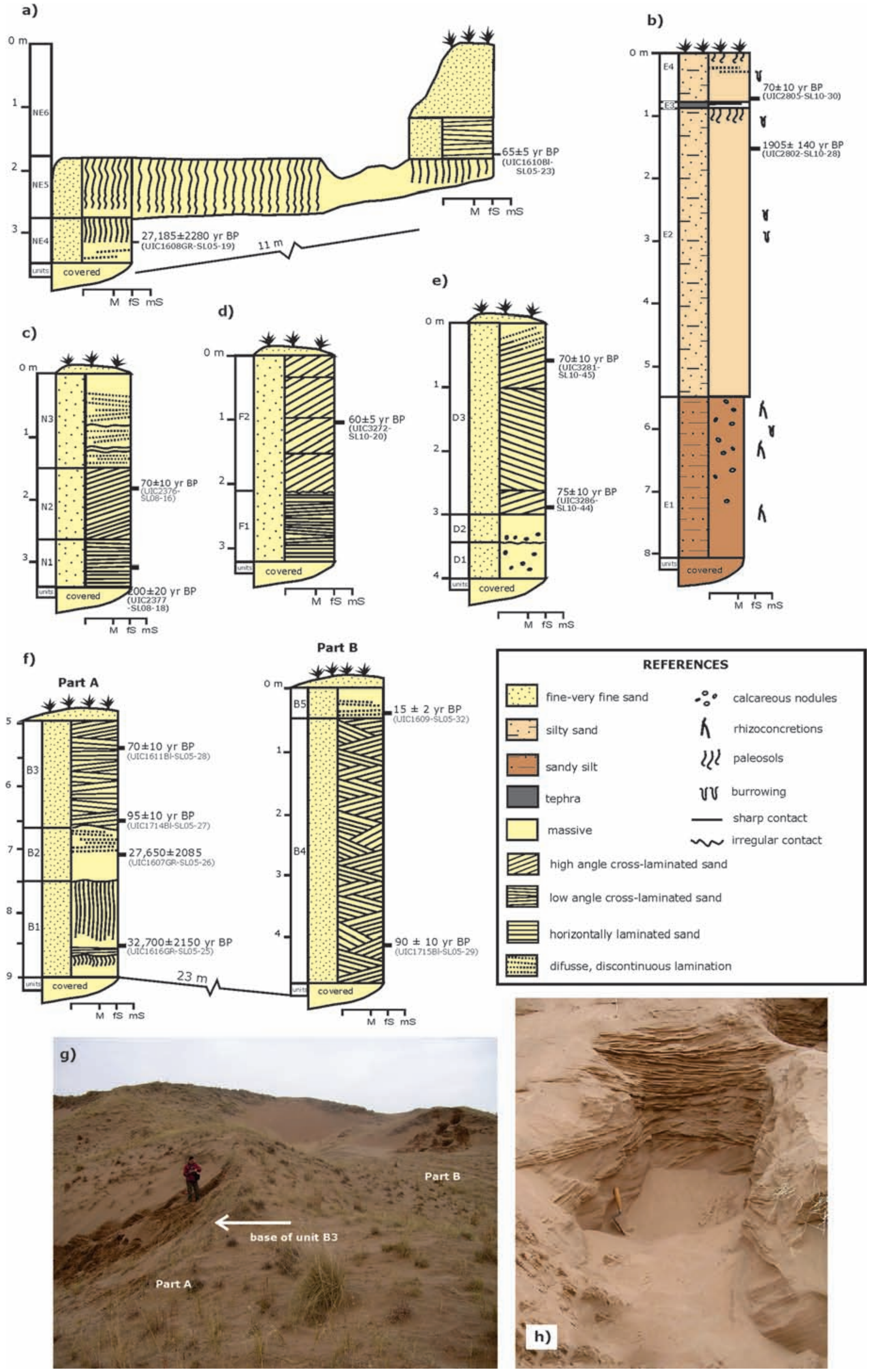


Figure 5. Sedimentary record of aeolian activity during the early–mid 20th century represented by aeolian sand sheet and dune deposits in localities of San Luis Province (partially modified from Tripaldi and Forman, 2007). (a) Nueva Escocia section, (b) Esteban section, (c) Nicolas section, (d) Fede section, (e) Diego section, (f) Blowout section, (g) Blowout section in the field, and (h) high-angle cross-laminations of unit B4 at Blowout section.

Table 1. Optically stimulated luminescence ages for aeolian sand depositional events at San Luis paleodune field, western Pampas.

Field no.	OSL lab no.	SAR aliquots[a]	SAR D_e (Gy)[a]	MAR D_e (Gy)[b]	U (ppm)[c]	Th (ppm)[c]	K_2O (%)[c]	H_2O (%)	Cosmic dose rate (mGy/yr)[d]	Dose rate (mGy/yr)	MAR age (year)	SAR age (year)[e]
SL05-19	UIC1608GR			96.36 ± 3.29	2.3 ± 0.1	9.4 ± 0.1	2.74 ± 0.03	5 ± 2	0.13 ± 0.01	3.54 ± 0.16	27,185 ± 2280	
SL05-23	UIC1610BI	30/30	0.26 ± 0.01[f]		2.5 ± 0.1	9.4 ± 0.1	2.88 ± 0.03	5 ± 2	0.12 ± 0.01	4.04 ± 0.17		65 ± 5
SL05-25	UIC1616GR			122.97 ± 1.06	2.4 ± 0.1	8.9 ± 0.1	2.79 ± 0.03	5 ± 2	0.13 ± 0.01	3.76 ± 0.16	32,700 ± 2150	
SL05-26	UIC1607GR			107.23 ± 4.07	2.5 ± 0.1	9.0 ± 0.1	2.87 ± 0.03	5 ± 2	0.14 ± 0.01	3.88 ± 0.17	27,650 ± 2085	
SL05-27	UIC1714BI	29/30	0.35 ± 0.051[f]		2.3 ± 0.1	7.9 ± 0.1	2.66 ± 0.03	5 ± 2	0.17 ± 0.02	3.67 ± 0.16		95 ± 10
SL05-28	UIC1611BI	30/30	0.26 ± 0.03[f]		2.2 ± 0.1	8.2 ± 0.1	2.78 ± 0.03	5 ± 2	0.18 ± 0.02	3.95 ± 0.17		70 ± 10
SL05-29	UIC1715	28/30	0.33 ± 0.003[f]		2.2 ± 0.1	7.6 ± 0.1	2.70 ± 0.03	5± 2	0.16± 0.02	3.78 ± 0.17		90 ± 10
SL05-32	UIC1609	28/30	0.060 ± 0.003[f]		2.1 ± 0.1	7.5 ± 0.1	2.60 ± 0.03	5 ± 2	0.18 ± 0.02	3.78 ± 0.17		15 ± 2
SL08-16	UIC2376	50/50	0.32 ± 0.01[g]		2.0 ± 0.1	7.1 ± 0.1	2.18 ± 0.02	10 ± 3	0.16 ± 0.02	3.32 ± 0.16		70 ± 10
SL08-18	UIC2377	30/30	0.63 ± 0.06[g]		2.1 ± 0.1	7.5 ± 0.1	2.17 ±0.03	10 ± 3	0.15 ± 0.02	3.15 ± 0.16		200 ± 20
SL10-20	UIC3272	31/45	0.22 ± 0.02[g]		2.2 ± 0.1	7.5 ± 0.1	2.06 ± 0.02	5 ± 2	0.20 ±0.02	3.22 ± 0. 16		60 ± 5
SL10-28	UIC2802	25/30	6.66 ± 0.30[f]		2.7 ± 0.1	8.4 ± 0.1	2.16 ± 0.03	5 ± 2	0.18 ± 0.02	3.48 ± 0.18		1905 ± 140
SL10-30	UIC2805	25/30	0.23 ± 0.02[g]		2.0 ± 0.1	7.4 ± 0.1	2.30 ± 0.02	5 ± 2	0.21 ± 0.02	3.02 ± 0.15		70 ± 10
SL10-44	UIC3286	44/50	0.26 ± 0.02[g]		2.1 ± 0.1	7.0 ± 0.1	2.07 ± 0.02	5 ± 2	0.14 ± 0.01	3.08 ± 0.16		75 ± 10
SL10-45	UIC3281	24/30	0.26 ± 0.02[g]		2.2 ± 0.1	7.4 ± 0.1	2.18 ± 0.02	5 ± 2	0.16 ± 0.02	3.16 ± 0.16		70 ± 10

[a] SAR: single aliquot regeneration protocols used for equivalent dose (D_e) determination (Murray and Wintle, 2003; Olley et al., 2004), under blue light (BI) excitation (470 ± 20 nm).
[b] MAR, multiple aliquot regeneration procedures used equivalent dose (D_e) determination (Jain et al., 2003); GR: green light excitation (514 ± 20 nm).
[c] U, Th, and K_2O content determined by inductively coupled plasma mass spectrometry (ICP-MS) by Activation Laboratory Inc. Ontario, Canada.
[d] From Prescott and Hutton (1994).
[e] All ages are calculated from the datum year AD 2000 and errors include systematic and random errors.
[f] SAR equivalent dose calculated using the central age model (Roberts and Galbraith, 2012), with over dispersion values of £20% at two sigma errors.
[g] SAR equivalent dose calculated using the minimum age model (Roberts and Galbraith, 2012) with over dispersion values of ³20% at two sigma errors.

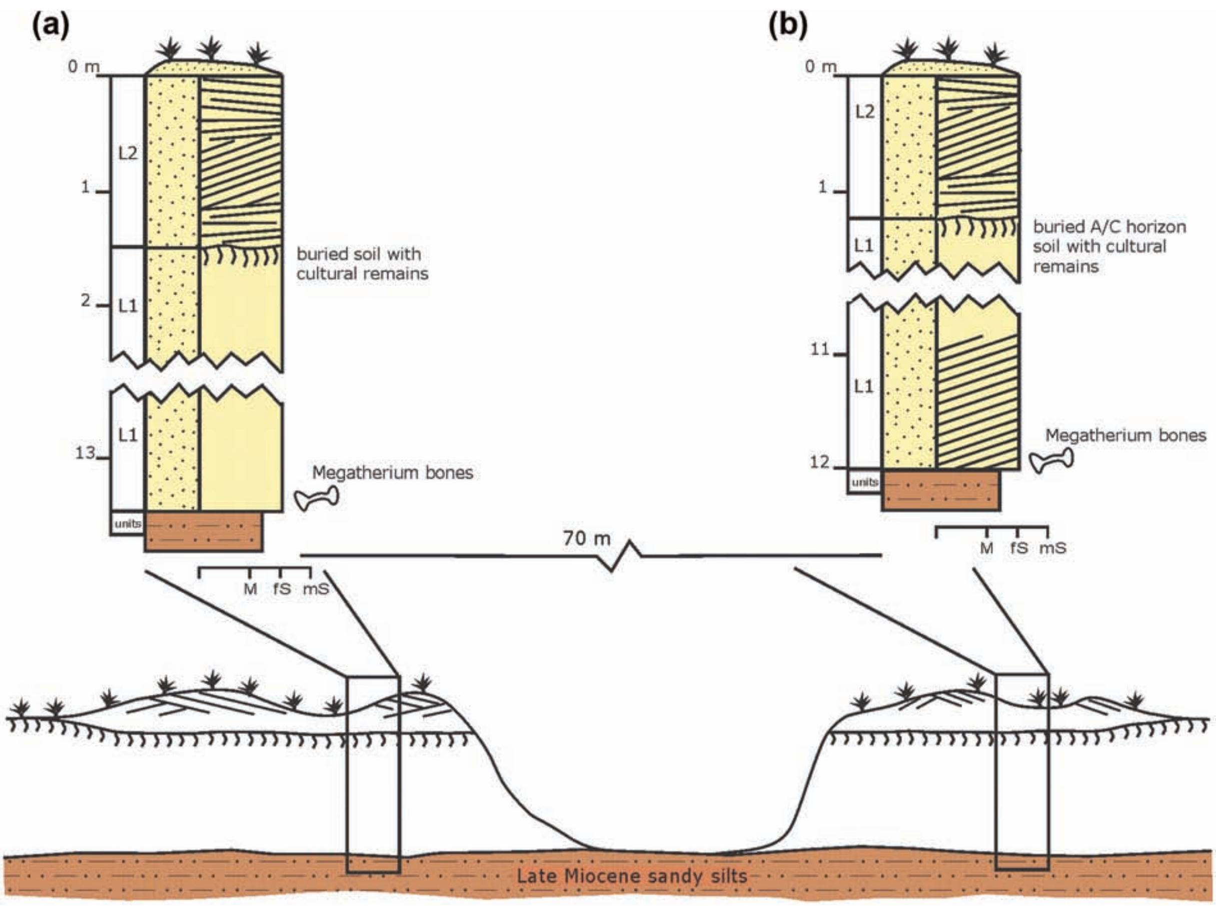


Figure 6. Sedimentary record of recent dune migration recorded at Cantera Lorda (36° 40.833′ S, 64° 24.200′ W, Toay, La Pampa Province); references in Figure 5: (a) Zetti's (1964) section and (b) Toay section.

In conclusion, sedimentological features of sandy deposits, constrained by OSL ages, from six sites of the San Luis dune field reveal significant aeolian activity due to wind ripple and dune migration during *c.* 95–60 yr BP (Figure 5). Other episodes of aeolian reworking would have occurred at *c.* 1905, 200 yr BP and 15 yr BP.

La Pampa Province

Several areas of La Pampa Province near the towns of Victorica, General Acha, Toay, and Santa Rosa also show evidence of recent aeolian activity, like fresh blowouts and extensive mantles of loose, laminated, fine-to-very-fine sand, often covering weakly developed soil. In this article, we focus on evidence from the Toay–Santa Rosa region (Figure 1b), where there is a documented record of late Quaternary aeolian deposition (Calmels, 1996; Kruck et al., 2011; Szelagowski et al., 2004). This area is part of the Western Pampas Sand Mantles and Dunefields (WPMD) (Zárate and Tripaldi, 2012), characterized by an aeolian apron of very fine sandy silts with an average thickness of 1 m and locally some small dunes, while major dune fields with complex and large bedforms occur along the transverse valleys of La Pampa Province (Zárate and Tripaldi, 2012).

Close to the Toay locality, the aeolian deposits consist of a sand mantle that exhibits patches of small ridges, elongated blowouts and nascent parabolic dunes, indicating southwesterly paleowinds; a wind direction from the southwest is currently dominant during the winter (Figure 3b). Some exposures appear along the walls of a quarry (Cantera Lorda, 1 km to the west of Toay locality). They contain aeolian sand up to 12–14 m thick that unconformably overlie continental sandy silts of late Miocene age, cropping out at the quarry floor (Figure 6). The aeolian sand deposits consist of a lower unit (L1) of moderately compacted massive or cross-bedded sands. Fossil remains of *Megatherium americanum*, a typical member of the extinct Late Pleistocene megafauna of the Pampean plain, were exhumed from the lower massive sands (Figure 6a; Zetti, 1964). Another almost complete skeleton of the same species was found, in 2004, around 70 m laterally from the remains reported in 1964, covered by 1-m-thick, tabular cross-bedded sands that are massive to the upper part (Figure 6b). A discrete buried soil (A and C horizons) is present along the quarry exposure at the upper part of the aeolian succession (Figure 6). Fragments of bottle glass and a wire fence were recovered from this buried soil, which is covered by cross-bedded, very friable and well-sorted, fine sand with a dune surface morphology (unit L2 in Figure 6). These cultural remains cannot be older than the late 19th century when farms were established; the town of Toay was founded in 1894 (Alonso, 2009; Lluch and Salomón Tarquini, 2009). Two infrared-stimulated luminescence ages from dune sand of 3.8 ± 0.4 ka and 300 ± 100 years at 5.5 and 3.5 m depth, respectively, were reported from the Lorda quarry (Kruck et al., 2011), but the stratigraphic context remains undocumented.

Surrounded the quarry are 2- to 5-m-high barchanoid dunes composing a small dune field of around 2 ha, that is stabilized by vegetation. The dunes are asymmetric with steep lee slopes, and the crest are sharp and show two dominant orientations: N24°E with lee sides to the NW and N90°E with lee sides to the S (Szelagowski et al., 2004), which suggest dominant southeasterly and northerly winds, consistent with predominant wind directions in the fall and spring–summer (Figure 3b). The dune field grades into an aeolian sand mantle with a progressively decreasing thickness away from the quarry site until the buried (A and C horizons) soil welds with the surface soil. The presence of sharp crests on

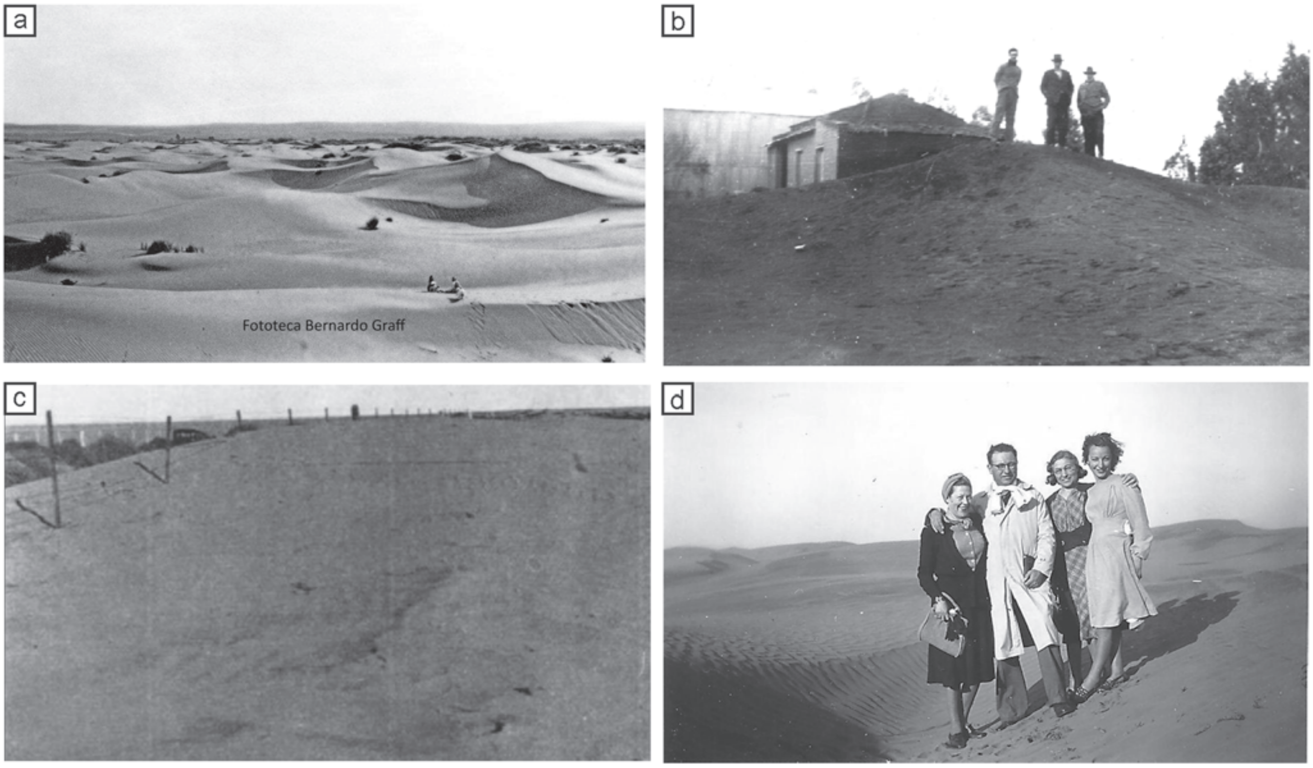


Figure 7. Historical photography of the 1930s drought at La Pampa and San Luis provinces: (a) panoramic view of a dune landscape at Toay, La Pampa Province, *c.* 1939 (source: Photograph Library Bernardo Graff); (b) sand accumulation almost covering a house at the town of Toay, *c.* 1930s (source: Provincial Historical Archive of La Pampa); (c) wire fences covered by aeolian sand along a route in northern La Pampa Province sometime in 1939 (source: Guiñazú, 1939); and (d) a family portrayed in a dune landscape at Lavaisse, near Nicolas section (Figure 5a), last years of the 1930s (Giraudi M and Geuna S, 2012, personal communication).

dunes, extremely weak soil development on dune surfaces and 20th-century cultural remains from the buried soil suggest a possible recent reactivation of the aeolian landscape and deposition of the upper aeolian sands that locally bury the present soil. We suspect that the latest aeolian reactivation in the Toay–Santa Rosa region is linked to the intense drought and concomitant aeolian activity that took place in central-western Pampas during the 1930s as indicated by historical observations (Guiñazú, 1939; Zarrilli, 1999; Zetti, 1964).

The 1930s drought had a significant impact on agricultural production and sustainability of population in the Pampas. Thus, the National Department of Agriculture (of Argentina) supervised a survey of the affected areas of La Pampa Province and surrounding areas in 1939. The leader of this survey, Mr José Guiñazú, reported observations about the state of the landscape, specifically the effects on agriculture lands (Guiñazú, 1939).The drought, starting in 1929, affected the central-western region of Argentina and was attributed to several years of precipitations below the ‘normal’ amounts. According to Guiñazú (1939), the most drought affected areas were western Buenos Aires Province, all the territory of La Pampa, south and western Córdoba and San Luis provinces, and parts of northwestern provinces of Argentina (La Rioja, Catamarca and Santiago del Estero). The estimated area affected by the drought was about 700,000 km^2 (Figure 1b).

This drought was associated with loss of grain harvests and livestock mortality but also with extensive and unprecedented aeolian erosion of arable soils, often in areas of deforestation under cultivation (Guiñazú, 1939). In several places near Toay (Figure 1b), active and migrating dunes up to 30 m high originally described as *medano vivo* (alive dunes) were observed. Panoramic photographs taken of this dune landscape document the dominance of loose sand, wind ripples, and multiple sharp dune crests, largely devoid of vegetation cover except for a few bushes and trees, some partially buried by sand (Figure 7a). Other photographs show meters-thick aeolian sand in a barchanoid form burying a house in the town of Toay (Figure 7b) and a wire fence along a route in northern La Pampa Province subsumed by aeolian sand (Figure 7c). A similar active aeolian landscape is documented in San Luis Province near the town of Lavaisse, ~3.5 km away from the Nicolas section (Figure 4a), where a family in the late 1930s poses in a peculiar scene of bare and active dunes (Figure 7d). This photograph documents the lack of vegetation and a surface covered by aeolian ripples and the dominance of blowouts and dune crest forms. Today, this area near Toay and other areas of the western Pampas mostly support a grassland with a mosaic of trees; little bare sand remains.

Stabilized dune fields were documented by the first military surveys (1840s and 1870s) into the western Pampas (Fernández, 1998; Tapia, 2005) and by topographers who surveyed and mapped this province between 1881 and 1885 (*Dirección General de Tierras, Archivo de Mensuras de La Pampa* (DGT-AM)). According to military diaries, the area of Toay was surrounded by stabilized dunes covered by extensive, tall and dark forests in 1846 (Dussart et al., 2011). In the cadastral maps (section II, lots 19 and 20; DGT-AM, 1881), this area was similarly characterized as covered by extensive forest (*montes de Toay* in Figure 8b). An area with stabilized dunes is indicated by *Medos* (shorthand for *medanos*), as shown in Figure 8b, while the reports for the cadastral map described the region as ‘nice lands with beautiful forest, good grasses and numerous water holes’ (‘*Este lote es hermoso, tiene preciosos bosques, buenos pastos y aguadas abundantes*’, DGT-AM, 1881: 97). These middle- to late-19th-century observations indicate that dunes were inactive geoforms, in stark contrast to the observations in the 1930s. Aerial photographs of the Toay region taken in 1961 still show a disturbed landscape with several patches of exposed dunes (Figure 8c); at present, most if not all areas are stabilized by vegetation (Figure 8a).

Figure 8. Landscape conditions in the Toay–Santa Rosa area (La Pampa Province) along the last ~120 year; (a) satellite image, dated 16 December 2011 (courtesy of Google Earth®); (b) cadastral map of 1881 (section II, lots 19 and 20; DGT-AM, 1881) covering the same area of the image in (a); and (c) aerial photomosaic, year 1961, of the nearly same landscape represented in the cadastral map in (b) showing several patches of exposed dunes (arrowed), at present mostly stabilized (arrowed the same area in (a)).

Unfortunately, to our knowledge, there are no studies to systematically record and analyze interviews about the 1930s drought from the eldest inhabitants of the western Pampas. Such documentation of environmental conditions in the 1930s from contemporary inhabitants is vital information, and efforts have now commenced to collect this evidence. In turn, several colleagues in Argentina, who lived or have had family in San Luis and La Pampa provinces, told us that relatives often discuss about *la seca* (the dry) of the 1930s that caused significant loss of grain harvest and, in some cases, forced families to leave farms (Giraudi M and Geuna S, 2012, personal communication).

Discussion

Instrumental climatic records from southern San Luis and eastern La Pampa provinces show that the western Pampas was on average drier during the first half of the 20th century than the latter half of the 20th century (Figure 2). Annual precipitation trends, tree ring analysis (Villalba et al., 1998) and PDSI series (Scian and Donnari, 1997) document the occurrence of several dry episodes in the 20th century. Precipitation time series indicate that the average rainfall was about 20% lower during the first half of the 20th century than the average of the second half, with the driest periods occurring in 1905–1906, 1929–1937, and 1949–1950 (Figure 2). In northwestern Argentina, on the upslope of the eastern Andes (Tucumán Province; Figure 1b), tree ring analysis of *Juglans australis* spanning the past 190 years, reveals reduced growth between *c.* 1860 and 1940, and renewed growth in the late 20th century in association with regional rainfall variability (Villalba et al., 1998). The PDSI time series revealed the occurrence of several episodes of moderate to extreme droughts during the first half of the 20th century in various localities of the western Pampas (Scian and Donnari, 1997; Scian et al., 2006). Specifically, PDSI values of <-2 in the time series Santa Rosa, General Acha, Victorica, and Huinca Renancó (Figure 1b) show droughts at 1909–1912, 1925, almost all the 1930s, and 1949–1950. A 20-year periodicity for extreme droughts was inferred from the limited 20th-century record (Scian and Donnari, 1997) with an increase in moisture supply since the beginning of the 1940s and a lack of significant drought episodes since *c.* 1972.

The Holocene aeolian sedimentary record of San Luis and La Pampa provinces indicates a recent landscape disturbance with denudation and reworking by wind, broadly contemporaneous with drought conditions in the 1930s. Features such as widespread bare sand blowouts, extensive surfaces with actively migration sand, steep dune lee slopes and sharp crests with extremely weak soil development and present cultivated soils covered by aeolian sand indicate recent aeolian reactivation of a formerly vegetated landscape. In addition, OSL ages on aeolian beds from sections in San Luis Province (Figure 5) confirm mobilization and sedimentation by aeolian processes (both ripple and dune migration) *c.* 95–60 yr BP. This 20th-century geomorphic, sedimentologic, and stratigraphic record of aeolian activity is also found across La Pampa Province. At present, the occurrence of small dune fields in farming areas, stabilized by vegetation, that interrupt the flat relief of the sandy silt mantle of the western Pampas are, for the most part, a result of recent aeolian activity as suggested by sharp crests of dunes and truncation and burial of the surface soil in places. Aeolian reactivation in the first half of the 20th century probably also affected neighboring areas of southern Córdoba and western Buenos Aires provinces (Figure 1b) characterized by high erosivity as depicted on a map of soil erosion for central Argentina of the early 1950s (Provincial Historical Archive of La Pampa).

An intriguing question is what anthropogenic, landscape, and climate factors contributed to the widespread transport and accumulation of aeolian sand in the western Pampas. Of the three broad controlling factors in aeolian systems, sediment availability, sediment supply and transport capacity (Kocurek and Lancaster, 1999), the latter two have prevailed in western Argentina. The thick sequence of Late Pleistocene–Holocene aeolian deposits provided a ready supply of sand with the most suitable grain-size (well-sorted, fine to very fine sand) for wind transport. The high-angle cross-lamination displayed by early 20th-century aeolian deposits (Figures 5 and 6) suggests an ample sand availability in some localities on the western Pampas. This renewal of sand availability would have occurred at different stages during the first half of the 20th century, reflecting a decline in vegetation cover triggered by a precipitation decrease (Figure 2) and human-induced land surface changes (Garbarino, 2008; Guiñazú, 1939; Zarrilli, 1999). Paleowind directions inferred from landforms suspected to be associated with aeolian activity in the 1930s are consistent with northeasterly wind DPs in San Luis Province and southeasterly and northerly winds in La Pampa Province (Figure 3).

We suspect that anthropogenic factors may have amplified the effect of drier conditions. Unprecedented environmental changes occurred by the end of the 19th century with the arrival of European settlers and the associated western expansion of agriculture (Alonso, 2009; Lluch and Salomón Tarquini, 2009; Zarrilli, 1999). The native grasses and woodland trees of vast areas were removed and replaced by wheat. With no available measures to control aeolian erosion, the devegetated fields were affected by soil erosion generating land degradation (Guiñazú, 1939), likely frequent dust storms and the aeolian reactivation of dune systems and sand mantles here revealed. The result was the formation of deflation hollows, small dunes, truncation of soils and burial of the once surface soil. During the 1930s, the predominant dry conditions gave rise to widespread land degradation in the western Pampas that caused severe economic losses and the emigration of numerous farmers to other provinces of Argentina, leaving behind unproductive barren fields (Zarrilli, 1999).

In North America, there was also a period of profound aridity on the western Great Plains in the 1930s, commonly referred to as the ‘Dust Bowl Drought’ for the large clouds of black dust and widespread landscape denudation (Cook et al., 2007; Egan, 2006; Worster, 1979). This ‘Dust Bowl’ was the result of extreme dry conditions that were amplified by agricultural practices, which promoted soil erosion and the generation of dust storms (e.g. Cook et al., 2009). Our analysis indicates that there were similar drought conditions, aeolian activity, and landscape denudation on the western Pampas of Argentina, particularly in the 1930s, together with expanded area and intensity of wheat cultivation.

The occurrence of severe droughts during the beginning of the 20th century in North America is linked to SSTs in the tropical Pacific Ocean and tropical Atlantic Ocean (Seager et al., 2010). The development of cool ‘La Niña–like’ SST in the eastern tropical Pacific region suppresses precipitation by circulation anomalies that force descent to North America, not only in the 1930s but also during the beginning of the 21st century (Hoerling and Kumar, 2003; Schubert et al., 2004b) and possibly the Mediaeval Warm Period (Feng et al., 2008). This broad footprint of decadal-scale droughts in North America reflects hemispheric climate forcing with cooler SST in the eastern tropical Pacific Ocean reflecting La Niña–like variability and warming in the tropical Atlantic Ocean (Feng et al., 2011; Schubert et al., 2004a).

The dry and humid episodes of the Argentine Pampas in the 20th century are also associated to changes in equatorial Atlantic Ocean SST (e.g. Compagnucci et al., 2002; Mo and Berbery, 2011) and related strength of the South American monsoon and increased ascension of air masses (Doyle and Barros, 2002; Seager et al., 2010). Climate model ensemble simulations (Feng et al., 2008; Herweijer and Seager, 2008) and analysis of climatological data from the 20th century (Hoerling and Kumar, 2003; Schubert et al., 2004a) identified a global pattern of multiyear extra-tropical drought regimes that involve in phase extra-tropical drought, including western North America, southern South America, parts of Europe and Western Australia. These studies reveal that sustained, anomalously cool east central tropical Pacific Ocean SSTs (La Niña–like conditions) combined with warm Indian Ocean and tropical Atlantic Ocean SSTs (positive North Atlantic Oscillation (NAO)) correspond to persistent droughts in several extra-tropical regions. Both the Great Plains of North America and the Pampas of Argentina sustained significant droughts in the 1930s and 1950s; the climatic 'bridge' for drought on both continents is possibly a warmer tropical Atlantic Ocean that displaces summer precipitation northward, though there may be influences from the tropical Pacific Ocean that affect cyclonic activity (e.g. Giannini et al., 2001; Grimm, 2003; Haylock et al., 2006; Pscheidt and Grimm, 2009).

Conclusion

The late Quaternary record of the western Pampas of Argentina, along with historical documents, indicate that this region suffered significant drought conditions with concomitant aeolian activity and landscape denudation during the first half of the 20th century, in agreement with meteorological information. We present evidence for the reactivation of aeolian landforms and deposition of aeolian sediments in some areas of La Pampa and San Luis provinces in western Argentina, in response to drier conditions. These are the first results of ongoing research in the region where current studies will further evaluate the effects of drought on the landscape. Like historical droughts in North America, there were probably significant regional amplifiers from dust loading in the lower atmosphere, albedo changes, and decrease in evapotranspiration. There is reported stratigraphic and geomorphic evidence for past periods of aridity in the early and late Holocene (4 ka; Forman et al., 2011; Gil et al., 2005; Kemp et al., 2006; Tripaldi and Forman, 2007, 2010), without an anthropogenic agent, which may reflect droughts of greater severity than the instrumental record.

We infer that pronounced aeolian activity in western Pampas in the 1930s was triggered by drier conditions amplified by the unprecedented land surface changes with a significant increase in population and expansion of wheat cultivation into this fragile environment (Alonso, 2009; Chiozza and Figueira, 1982; Garbarino, 2008). It is noteworthy that the same pattern of agricultural overproduction, poor soil conservation practices, and a pronounced reduction in spring precipitation (~30–40%) occurred in North America also during the 1930s and triggered the epic 'Dust Bowl' drought (Worster, 1979). Both the Great Plains of North America and the Pampas of Argentina sustained significant droughts in the 1930s and the 1950s; the climatic 'bridge' for drought on both continents is possibly a warmer tropical Atlantic Ocean, which results in summer cyclonic activity displaced northward (e.g. Giannini et al., 2001; Grimm, 2003; Haylock et al., 2006; Pscheidt and Grimm, 2009). In this context, sustainable agricultural practices should be a priority in the fragile western Pampas of Argentina where natural climate variability and human actions may reactivate the Holocene and Pleistocene dune systems.

Acknowledgements

The authors wish to thank to Esteban Jobbágy and Ernesto F. Viglizzo for constructive discussions that helped improve the manuscript. Pablo Forte, Federico González Tomassini, Tomás Luppo, Liliana Marin, Adriana Mehl, and Jimena Perelló gave valuable assistance during field trips. Meteorological data from the central-west Argentina were kindly provided by the *Servicio Meteorológico Nacional* (National Weather Service) and by Manuel R. Demaría and Juan C. Colazo from INTA Villa Mercedes. Special thanks to Marta Giraudi and Silvana Geuna for providing a photograph of their family when living in San Luis Province during the 1930s. The authors also thank to the *Archivo Histórico Provincial de La Pampa* (Provincial Historical Archive of La Pampa) for other historical pictures and the *Dirección Nacional de Castastro* (National Agency of Cadastre, Government of La Pampa Province) for the aerial photographs and cadastral maps. Constructive comments by two anonymous reviewers and the Associate Editor J. Mason are highly appreciated.

Funding

This work was supported by the Universidad de Buenos Aires (UBACyT 20620100100009), the Consejo Nacional de Investigaciones Científicas y Técnicas (PIP-CONICET 112-201001-00123), the Universidad Nacional de La Pampa (Grant 234), and the National Geographic Society (Grant 8607-09).

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