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Loess of southern South America

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Abstract

Loess and loessoid (loess-like, reworked loess) sediments extend across the Chaco–Pampean plains and the NW mountain environments of Argentina, and in neighbouring countries (Paraguay, Brazil, Uruguay, Bolivia). Loessoid sediments are much more abundant than primary loess. The beginning of the loessoid sedimentation cycle was related to a phase of Late Miocene orogeny in the Andes. The Plio-Pleistocene record is mostly composed of loessoid sediments modified by pedogenesis, which produced welded palaeosols. The Late Pleistocene/Holocene loess record reveals a heterogeneous composition across the region. Coarse textures and an Andean-derived volcanic composition prevail in the southern Pampas. Finer textures and material coming from the Andes and the other two sources (Sierras Pampeanas and the Paraná basin) characterize the loess deposits of the northern Pampas and the eastern Chaco. A southern Patagonian source is also suggested for the mountain valley loess of Tucumán, although a western Andean provenance has been proposed. It is believed that the material in the western Chaco was derived from the Bolivian Andes. Loess deposition was related to a multistage transport mechanism, involving fluvial and aeolian processes. Inferred westerly and southwesterly wind directions, as dominant carriers of the aeolian deposits, are in agreement with westerly palaeowind simulations using climate models. However, the role played by westerly tropospheric winds and northerly winds remains to be established.

1. Introduction

The largest loess deposits in South America extend from 23°S to 38°S in the southern plains of the continent. Initially reported as clay (d'Orbigny, 1842 in Frenguelli, 1955), and silt (Darwin, 1846; Ameghino, 1880), the sediments from the Pampas were first defined as loess (Heusser and Claraz, 1866) on the basis of the "stratigraphic and structural" similarities with European loess, particularly the Upper Rhine loess (Frenguelli, 1957). Later authors continued to refer to the Pampean sediments as loess (e.g., Doëring, 1882; Wright and Fenner, 1912; Keidel, 1916; Roth, 1920). During the first half of the 20th century, Frenguelli (1918, 1921, 1955, 1957) provided extensive information on the stratigraphy, grain-size, mineralogy, morphology and distribution of loess deposits. However, it was a paper entitled "The Nature and Origin of Argentine loess" by Teruggi (1957) that proved to be the seminal contribution, providing the fundamental basis for later studies.

During the past 20 years, renewed interest in loess has resulted in numerous contributions dealing with its distribution, composition, magnetostratigraphy, age, fossil contents, source areas and palaeoenvironmental implications. Recently, the Late Quaternary loess records of both South and North America were reviewed and analysed in respect of their palaeoclimatic significance (Muhs and Zárate, 2001).

The purpose of this paper is to provide a review of the loess record of southern South America. Identification of the loess, its distribution and the geological record it provides are considered first. Analysis focuses on the distribution, composition and source areas of the Late Pleistocene/Holocene aeolian deposits and their climatic and environmental implications.

2. Distribution

The terms loess and loessoid (equivalent to reworked loess or loess-like deposits) sediments have been loosely used in the geological literature. As a result, several deposits across southern South America were mapped as loess on the basis of their field characteristics (massive and homogeneous appearance, colour and relatively fine texture) and sometimes their mineralogical composition (*loessic mineralogy* referring to sediments with a high content of volcanic-derived particles). The problem of

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differentiating primary loess and loessoid materials was the subject of a special contribution by Frenguelli (1955), who analysed several properties of these two deposits (among others, texture, colour, lithological composition, morphology and palaeontological content). The identification of primary loess is a debatable topic. The issue is important because the well-known map of loess distribution in Argentina by Teruggi (1957; Fig. 1a and b) includes both loess and loessoid sediments, with the latter, as Teruggi pointed out, being much the more abundant.

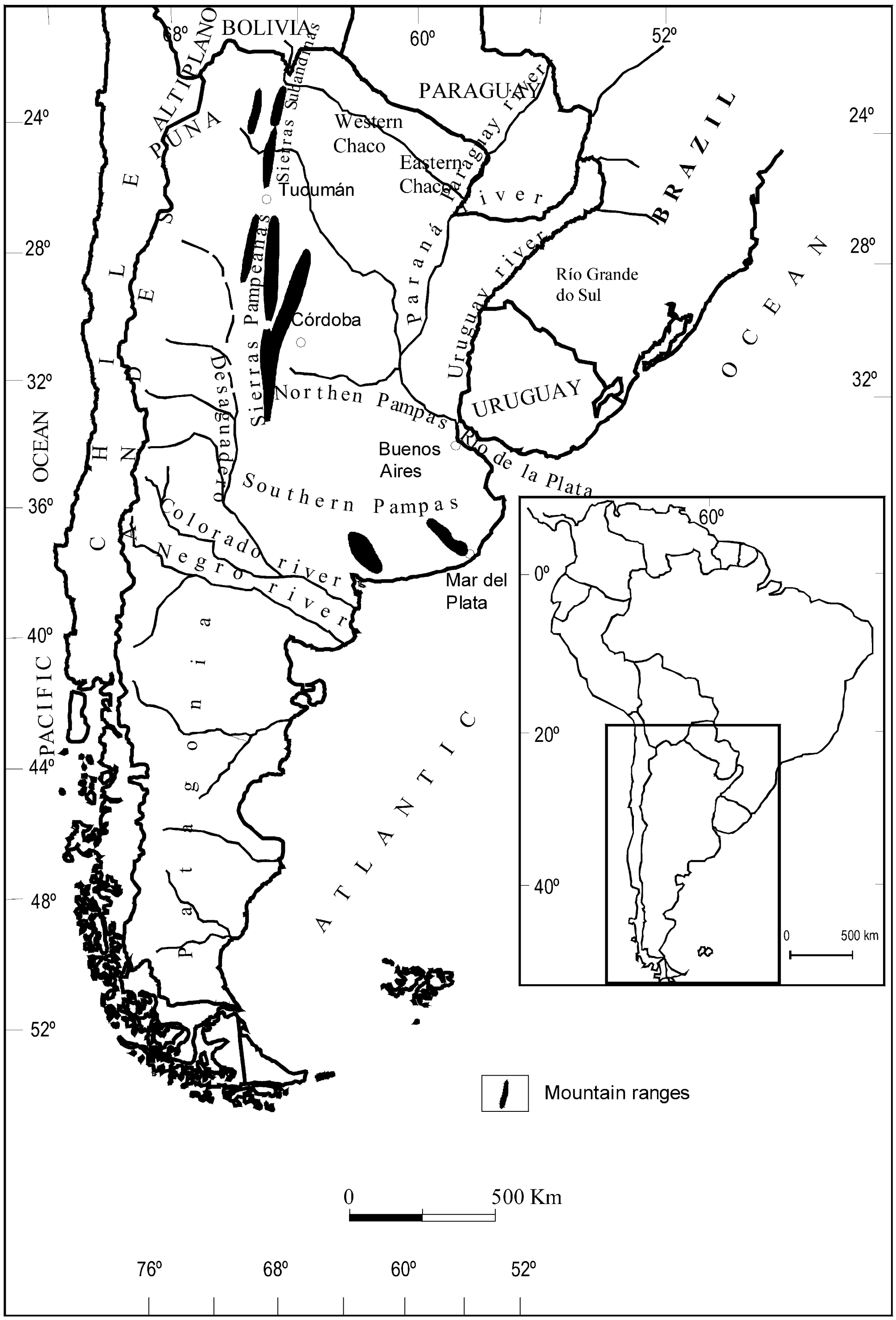

Fig. 1. (a) Map of southern South America showing loessoid distribution by Teruggi (1957). (b) Geographical domains, mountain ranges and main fluvial systems.

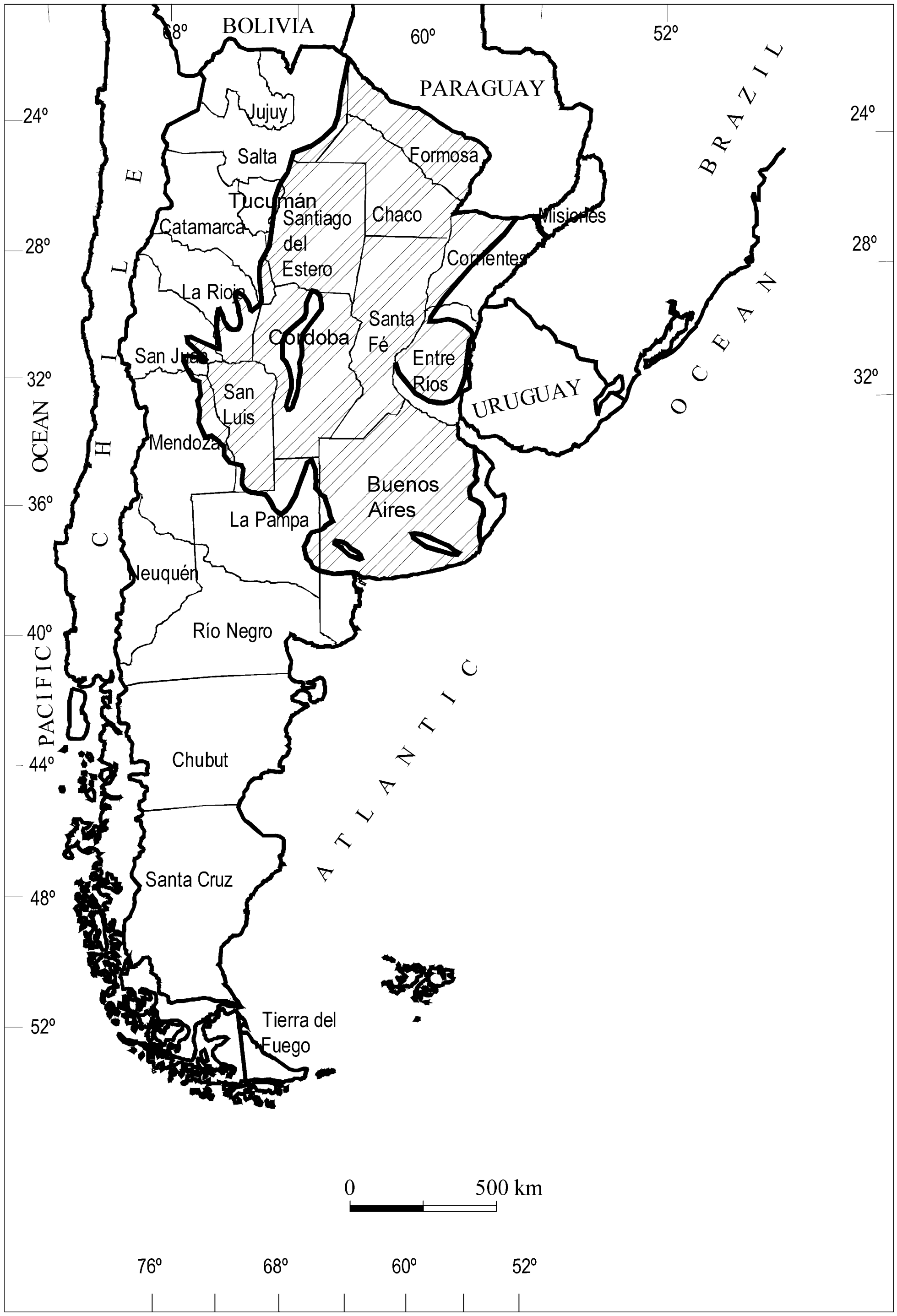

Fig. 1 (*continued*).

Iriondo (1990a, 1997) and Sayago (1995) presented two other maps of loess distribution (Fig. 2). According to Iriondo, the Late Pleistocene/Early Holocene loess extends along a belt in the northern Pampas, and parts of the southern Pampas, as well as large areas in the western Argentinean Chaco; the rest of the region is covered by aeolian sands or alluvial deposits. According to Iriondo (1997), a thin layer of loess was deposited regionally during the Holocene, covering the loess of the Last Glacial, and alluvial sediments north of latitude 34°S. The loess distribution shown by Sayago (1995) is, with slight modifications, very similar to Teruggi's representation, extending the cover of loessic materials as far south as latitude 40°S (Fig. 2).

Detailed mapping in progress by several research teams is showing that primary loess is quite restricted in

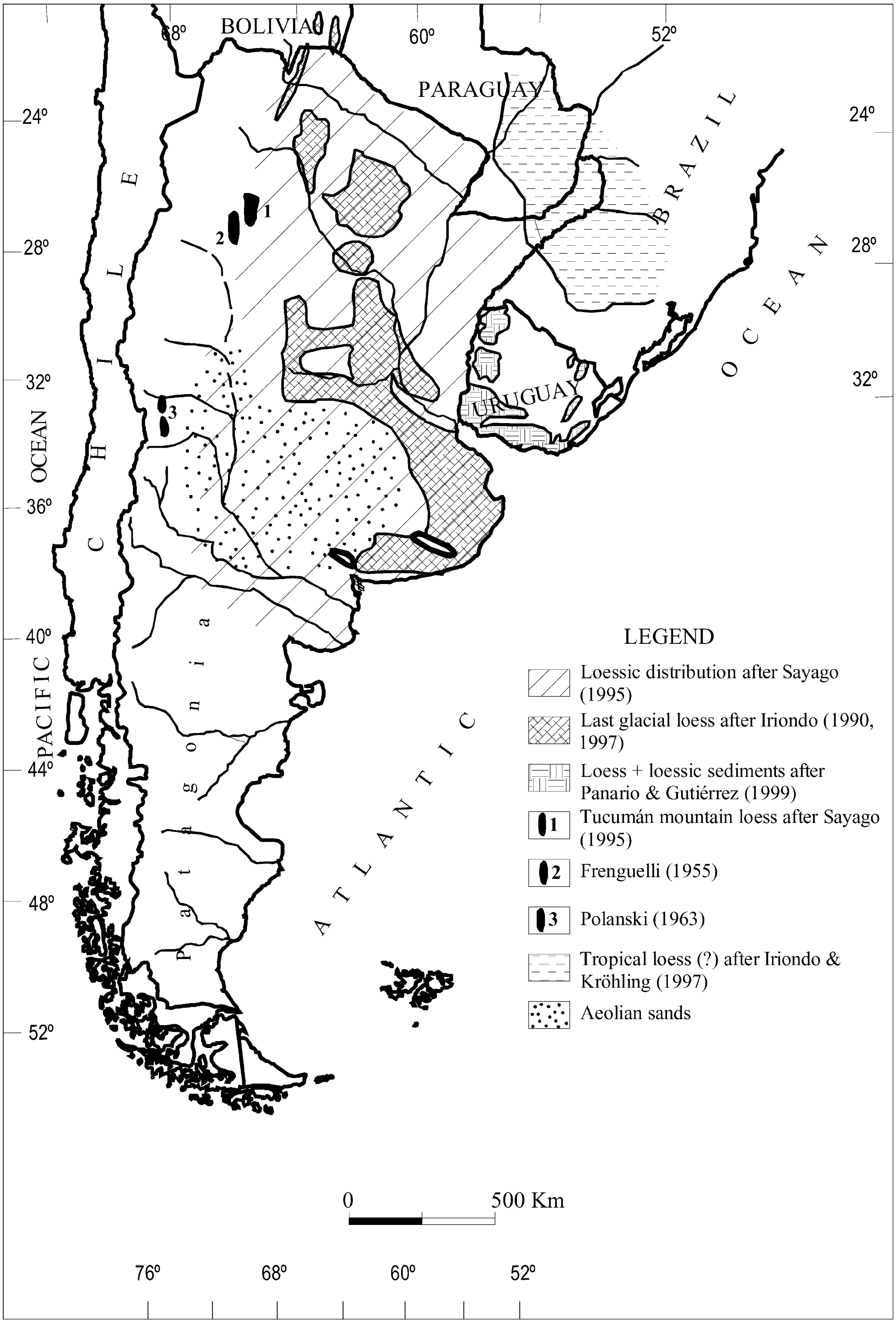

Fig. 2. Loess and loessoid distribution according to several authors. The late Holocene loess represented by Iriondo (1997) is not included. (1) Sayago (1995), (2) Frenguelli (1955), (3) Polanski, 1963.

distribution, as Teruggi originally indicated. Geomorphological and soil studies across the southwestern and western areas of the Pampas, also known as the *Pampa Arenosa* (Sandy Pampa), shows the occurrence of an extensive aeolian sand cover (Fig. 2). This region consists of a large and complex sand dune system (Cantú and Degiovanni, 1984; Gardenal, 1986; Hurtado and Giménez, 1988) that corresponds to the *Mar de*

Table 1
Mineralogical composition of the late Pleistocene-early Holocene loess and loessoid deposits. Data summarized from (1) Zárate and Blasi (1991), Teruggi et al. (1957), Camilión, (1993); (2) G. Bonorino (1965, 1966); Nabel et al. (1999); Blasi et al. (submitted); (3) Kröhling (1999a, b); (4) Sayago (1995); (5) Iriondo (1997); (6) Morrás and Delaune (1985)

Area	Mineralogical composition	Source rocks
Southern Pampas (1)	*La Postrera Formation (modal fraction)*: volcanic glass shards, plagioclase (albite to labradorite), feldspar (+ + + orthoclase), quartz, volcanic rocks (basaltic, andesitic, rhyolitic); *heavy minerals*: opaques (+ + + magnetite), amphiboles, orthopyroxenes, clinopyroxenes, micas	Volcaniclastic rocks
	Clay minerals: illite, traces of kaolinite	Volcanic ashfalls Piedmont of Ventania–Tandilia: crystalline and sedimentary rocks
Pampa Ondulada (2)	*Buenos Aires Formation*: fresh calcic to intermediate plagioclases, quartz, lithic fragments (metamorphic and granitic rocks, argillized quartz, porphyry, and basalt); volcanic glass shards	Metamorphic and igneous rocks
	Clay minerals: illite, montmorillonite, kaolinite	Volcanic ash falls
Santa Fé (3)	*Tezanos Pintos Formation*: quartz, feldspar, mica (illite), montmorillonite, kaolinite, calcite, goethite, hematite and allophane	Metamorphic and igneous rocks, volcaniclastic material
	Pampean Sand Sea: volcaniclastic particles (volcanic glass shards, polycrystalline quartz, alterites, lithic artefacts) followed by quartz and feldspar from the Sierras Pampeanas of Córdoba	Volcaniclastic material
Tucumán (4)	*Tafí del Valle Formation* (sand fraction): quartz, K-feldspar, plagioclase and volcanic glass, ≪tourmaline, zircon, apatite and epidote *Silt fraction*: ≫plagioclase and volcanic *Clay minerals*: illite, kaolinite smectite, quartz, feldspars	Volcaniclastic material
Chaco (Salta province) (5)	*Urundel Formation*: quartz (60/80%), hornblende, altered plagioclases; no volcanic glass shards	Bolivian Andes rocks
Chaco (northern Santa Fé) (7)	*Western area (loess)*: volcanic glass shards, pyroxenes (augite mostly), garnet, decreasing content eastward	Andean source Volcanic ashfalls
	Eastern area (loessoid): ⋙quartz, estaurolite, tourmaline cyanite, zircon, rutile increasing content eastward	Alluvial sediment Paraná basin Volcanic ashfalls

Arena (Sand Sea) of Iriondo (1990a, 1997). Along the piedmont of the Sierras Pampeanas (Pampean Ranges) of Córdoba and San Luis provinces (Fig. 1b), it has been reported that several alluvial fans are partially interbedded with and covered by loess deposits (Cantú and Degiovanni, 1984; Carignano, 1999). Also, large alluvial fans several hundred kilometres long have been noted in the Paraguayan and northern Argentinean Chaco (Iriondo, 1990a; Clapperton, 1993; Sayago, 1995). In the eastern Chaco plain of northern Santa Fé province, mineralogical analysis of modern soils (Table 1) has clearly revealed the occurrence of both aeolian (loess) and alluvial sediments, the latter becoming more dominant eastward (Bertoldi de Pomar, 1969; Morrás and Delaune, 1985).

Apart from the classic deposits of the Chaco–Pampean plains, loess has been reported in mountain environments, including the mountain valleys of Tucumán (Sayago, 1995), the highland plains of the Sierras Pampeanas of Córdoba and San Luis provinces (Manzur, 1997), and along parts of the Sierras sub-Andinas (sub-Andean ranges) of Northwestern Argentina and Bolivia (Iriondo, 1997). Loess was also identified in the Catamarca mountain area (Kuhn, 1913 in Frenguelli, 1955) and along the eastern Andean piedmont of Mendoza province (Polanski, 1963) (Fig. 2).

No loess deposits have been reported from Patagonia, the localized deposits of the Valdés Península, originally described as loess (Frenguelli, 1955) being aeolian sands (Bouza, 2001, pers. comm.). In Tierra del Fuego, aeolian deposits are restricted to relatively a thin (10–120 cm thick) silty sheet interpreted as loess deposited during the Late Pleistocene blanketing the landscape of the semiarid and subarid areas of the island (Frederiksen, 1988). Late Holocene sand mantles and sand dunes are reported in the area of Bahía Sebastián (Favier Dubois, 2001).

In neighbouring countries, loess has been reported in Paraguay (Bender, 1995 in Sayago, 1995), and southern Brazil (Rio Grande do Sul State) (Bombin, 1976). In Uruguay, an extensive, surficial loess of Late Pleistocene age blankets the landscape, constituting the parent material of the present soils (Argiudoll) on hilltops and river terraces (Panario and Gutiéerrez, 1999) (Fig. 2).

From a regional perspective, and considering the general geographical distribution of loess in areas with different climatic conditions, a subdivision into Neotropical and Pampean loess has recently been proposed (Sayago, 1995; Zinck and Sayago, 1999). The Neotropical loess (including both primary and reworked loess) extends between 20°S and 30°S, in the present-day subtropical area of the Chaco plain and the pre-Andean mountains and intermountain valleys to the west, while the Pampean loess covers the temperate region south of 30°S (Sayago, 1995). Using similar reasoning, Iriondo and Kröhling (1997) proposed the term tropical loess in a reinterpretation of the sediments overlying basaltic rocks in northeastern Argentina (northern Corrientes and Misiones provinces) and large areas of Brazil (Fig. 2). However, this explanation of the source of the surficial sediments in northeastern Argentina is controversial, and conflicts with current interpretations by soil scientists (INTA, 1979) and geologists (Gentili and Rimoldi, 1980) regarding these materials as soil-weathering products.

3. Loess deposits older than Late Pleistocene

The beginning of the loessoid sedimentation cycle has been related to a phase of Late Miocene (ca 10 Ma) orogeny in the Andes resulting in the elevation of the Cordillera, which acted as a barrier to moisture-laden Pacific winds. This initiated, "the desertification of Patagonia caused by the rain shadow while precocious Pampas environments probably came into prominence at about this time" (Patterson and Pascual, 1972 in Marshall et al., 1983, p. 68). As a result, accumulations of sinorogenic sediments several hundred metres thick, derived from erosion of the uplifted Cordillera, were deposited during the Late Miocene and the Pliocene (Ramos, 1999) over extensive areas of the southern Pampas (Fidalgo et al., 1975), along the Andes piedmont of Mendoza (33–34°S) (Polanski, 1963), and in northwestern Argentina (Sierras Pampeanas of Catamarca, La Rioja and Tucumán provinces (Caminos, 1980; Muruaga, 1999) (Fig. 3). Sedimentation earlier than the Late Miocene was predominantly pyroclastic, whereas the Late Miocene to Pleistocene/Holocene units are predominantly clastic in type (silt, sands, loess: Marshall et al., 1983). The composition of these Late Cenozoic sediments varies from north to south. Feldspar and quartz are dominant in the deposits of the northern Sierras Pampeanas (Caminos, 1980), while the sediments described as loess or loessic in the southern Pampas are mostly composed of volcaniclastic, fine sandy silts similar to the Pleistocene aeolian deposits (De Francesco and Nuccetelli, 1990).

The Uruguayan loess is mainly represented by a 1–2 m thick mantle with a composition similar to the loess of the Northern Pampas (Entre Ríos and Corrientes provinces). Loess deposition occurred at various intervals during the Cenozoic, and two main loessoid units (Libertad I and Libertad II) of Early and Middle Pleistocene age, respectively, have been identified. The lower unit (Libertad I Formation) is composed of calcareous loess containing illite as the dominant clay mineral. The upper Libertad II Formation is enriched in clay minerals, notably montmorillonite, and shows evidence of water reworking and pedogenic modification (Panario and Gutiéerrez, 1999).

The loess–loessoid record for the last 3–5 Ma is well exposed along the Mar del Plata sea-cliffs and the Paraná River. The long exposures, running for 35 km along the Mar del Plata sea-cliffs, are mainly composed of loessoid sediments, with primary loess facies clearly documented by the uppermost Late Pleistocene–Holocene aeolian mantle and relatively thin layers (2–3 m thick) of Late Gilbert age and Early Gauss magnetic age. The very limited amount of primary loess in the Late Cenozoic record is explained by its low stratigraphic preservation potential, being susceptible to reworking and redeposition by hydrological processes (Zárate, 1989). Pedogenesis has also greatly modified the deposits, while faunal activity (both invertebrate and vertebrate) has played a significant role in the bioturbation of the original material (Kemp and Zárate, 2000). The occurrence of both palaeosols, laterally traceable along several kilometres, and erosional unconformities suggests a discontinuous stratigraphy (Zárate, 1989). The age control is mostly based on vertebrate assemblages (land-mammal ages, stage ages) (Tonni et al., 1992) and magnetostratigraphy (Orgeira and Valencio, 1984; Orgeira, 1988; Ruocco, 1989). Numerical ages have recently been obtained only at a key stratigraphic layer of Late Pliocene age (Schultz et al., 1998).

In the Pampa Ondulada area of northern Buenos Aires (Fig. 4; see below for explanation), a broad spectrum of studies covering magnetostratigraphy (Bobbio et al., 1986; Nabel et al., 1993; Bidegain, 1998), palaeopedology (Teruggi and Imbellone, 1987; Imbellone and Teruggi, 1993; Zárate et al., 2002), environmental magnetism (Orgeira et al., 1998; Nabel et al., 1999), geochemistry (Morrás et al., 1999) and vertebrate palaeontology (Tonni et al., 1999) have been carried out. Magnetostratigraphy and fossil-mammal

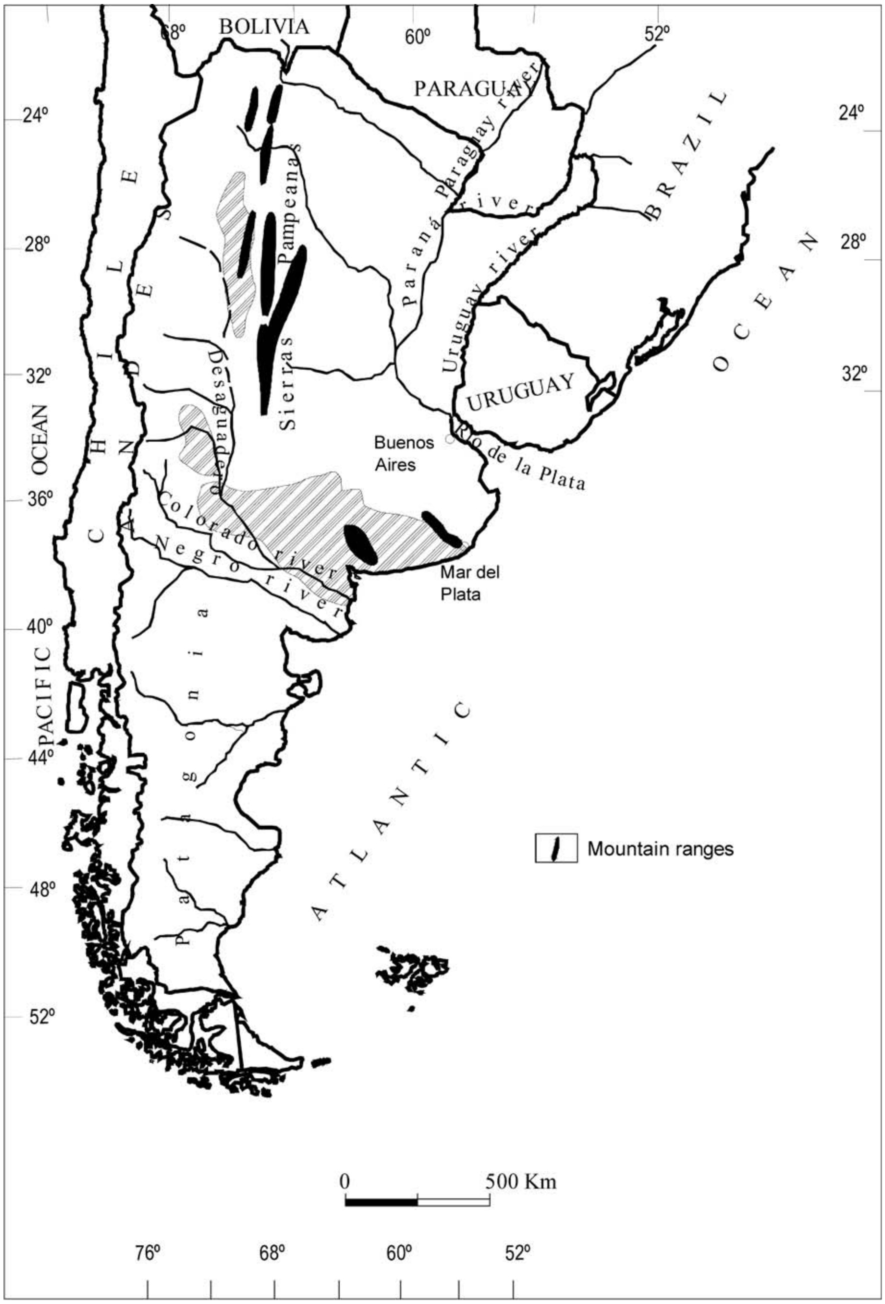

Fig. 3. Distribution of late Tertiary loessoid sediments. Modified after Fidalgo et al. (1975), Polanski (1963) and Caminos (1980).

assemblages were used to calibrate the sequences chronologically, with no numerical ages being available for pre-Late Pleistocene records. At several localities, the Brunhes-Matuyama boundary is recorded stratigraphically above a regional palaeosol 7–10 m below the modern surface (Nabel et al., 1993; Bidegain, 1998; Tonni et al., 1999).

In the La Plata area, palaeosols have been identified on the basis of both macromorphological and micromorphological features (Teruggi and Imbellone, 1987), which suggest a polygenetic origin that involved welding of subjacent palaeosols through shallow thicknesses of intervening loess-like sediments. Recent micromorphological analysis generally supports this interpretation, suggesting a complex pedosedimentary history of welding with some degree of water reworking (Zárate et al., 2002).

4. Late Pleistocene–Holocene loess

Late Pleistocene–Holocene loess deposits of variable thickness cover the region, and constitute the parent material of the modern cultivated soils. Considering the

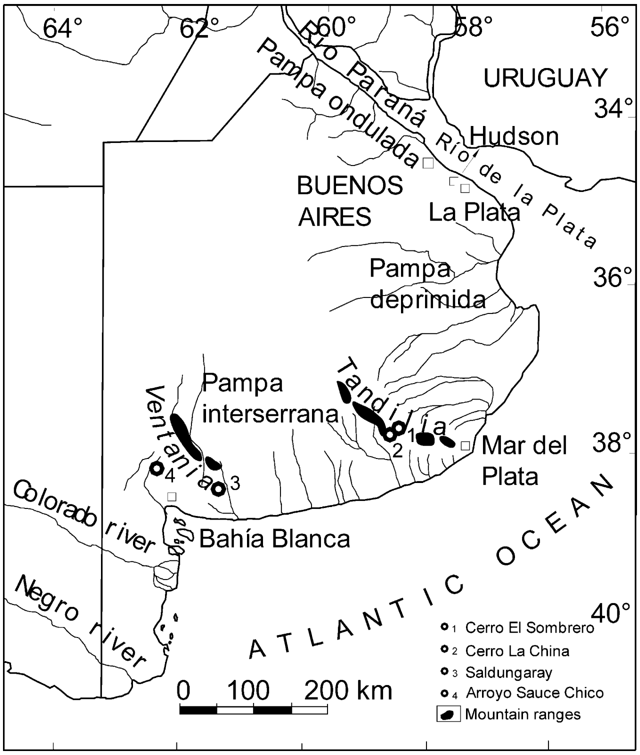

Fig. 4. Southern and northern Pampas of Buenos Aires Province, showing main geographical domains.

areas where most studies have been carried out, the region is divided for practical reasons into four main geographical domains (southern Pampas, northern Pampas, Chaco, and the Tucumán mountain valleys (Fig. 1a); their boundaries are transitional and are specified according to current geographical subdivisions.

4.1. The southern Pampas

The southern Pampas comprises the southern part of Buenos Aires province including the so-called Pampa Interserrana (Interrange Pampa) or Llanura interserrana (interrange plain) between the Ventania and Tandilia ranges and most of la Pampa province (Fig. 4). The Late Pleistocene–Early Holocene loess and aeolian sands form a continuous mantle across the Pampa Interserrana, reaching altitudes of around 220 m in Tandilia and ca 400 m in Ventania. An average thickness of 1.5–2 m is found on interfluvial surfaces, varying between 5 and 10 m in the intermontane valleys of Tandilia and the upper fluvial basins draining the Ventania range. Westward and southwestward, the loess deposits are surrounded by the large and complex sand dune systems of central Argentina. The deposits are coarse textured. In the Bahia Blanca area (Fig 4), the average sand–silt–clay content is 44%, 26% and 24%, respectively, the maximum sand content (mostly very fine sand) being ca 80%. The great majority of these sediments have been classified as sandy loess followed by silty clayey sands and a very limited number of cases of clayey loess, typical loess and sandy silty clay facies (Bidart, 1996).

Along the Tandilia range and around Mar del Plata, sandy loess facies are dominant, with 60–80% very fine sand and coarse silt and <13% clay, except in the uppermost parts of sections modified by recent soil formation (Zárate and Blasi, 1991).

The sandy loess deposits are of volcaniclastic composition (Table 1). Particles are very fresh and usually well rounded (volcanic rocks, magnetite, pyroxenes) or subrounded to subangular (clinopyroxenes, orthoclase, plagioclase) (Camilión, 1984; Zárate and Blasi, 1991). Illite is the dominant clay mineral (Camilión, 1993).

The aeolian deposits have been stratigraphically grouped under several different names (Médano Invasor, Tapia, 1938; La Postrera Formation, Fidalgo and Tonni, 1981; Saavedra Alloformation, Rabassa, 1989) and divided into two (Bidart, 1996), three (Fidalgo and Tonni, 1981) or four subunits (Rabassa, 1989; Zárate and Blasi, 1991), interpreted as indicating different aeolian episodes. Radiocarbon dates on both fossil bones (Figini et al., 1987), charcoal from archaeological sites (Zárate and Flegenheimer, 1991), and TL dates (Rodbell, 1995, written communication) indicate a Late Glacial–Early Holocene age for the uppermost part of the lower section (Table 2). The sedimentation rate notably decreased regionally at around 10 ka, and modern soils began to develop on top of the sandy loess mantle at some time between 11–10 and 9 ka BP (Zárate and Blasi, 1991).

During the Middle Holocene, between 4000 and 5000 yr BP, aeolian deposition was reactivated at some localities (Table 2) and soils were locally truncated. An uppermost and very thin aeolian unit, usually containing remains of European fauna, and postdating the Hispanic arrival in the 16th century, has been reported by several authors. It was formerly believed that sediments in the Bahia Blanca were deposited under arid conditions synchronous with the Little Ice Age (Rabassa et al., 1985). However, at some localities, this topmost aeolian unit has been reinterpreted as road dust accumulated on top of the modern soil (Bidart, 1992).

4.2. The northern Pampas

The northern Pampas consist of the Pampa Deprimida (low Pampa) and the Pampa Ondulada (undulating Pampa) of Buenos Aires province as well as south central Santa Fé, eastern Córdoba and Entre Ríos provinces (Fig. 1a and b).

4.2.1. Pampa Deprimida

The Pampa Deprimida, bounded on the south by the Tandilia range and on the north by the Pampa Ondulada (Fig 4), is a very flat plain, extending across the tectonically subsident Salado fluvial basin. In this

Table 2
Numerical ages (^{14}C and TL) obtained at selected localities on the southern Pampas where these dating techniques were used and at Hudson locality (Pampa Ondulada)

Locality	Stratigraphy	TL dates Rodbell (1995), (*) = Zárate and Flegenheimer (1991)	^{14}C dates	
			Material	Numerical age
Hudson quarry (Isla et al., 2000)	Upper loess	20.9±2.1 ka		
	Lower loess Marine deposits	61.2±5.3 ka		
Cerro La China (Flegenheimer and Zárate, 1997)	Unit 4	4.5±0.6 ka (*)		
	Unit 3		Unit 3: charcoal	Unit 3: 10,730±150; 10,790±120; 10,745±75; 10,804±75; 10,525±75; 11,150±135; 10,560±75 ka
	Unit 2	14.6±1.6 ka		
Cerro El Sombrero (this paper)	Upper loess	9.5±0.8 ka		
	Lower loess	21.5±3.2 ka		
Saldungaray (Bidart, 1996)	Upper loess Lower loess	9.8±1.0 ka 10.8±1.0 ka		
Sauce Chico (Prieto, 1996)	Upper loess Buried soil	4.4±0.3 ka	 Organic matter	 6.2±0.1 ka

area, Tricart (1969, 1973) identified two Late Pleistocene–Holocene aeolian units, named E3 and E1.

The E3 unit consists of sandy loess grading northeastward into typical loess. A Brunizem soil (Argiudoll) developed on top of the E3 loess and was later partially eroded. A relatively thin (up to 0.6 m thick) aeolian silt of loessoid appearance (E1) accumulated on the truncated Brunizem soil surface (Tricart, 1973).

The E3 loess forms longitudinal landforms, several kilometres long, 1–1.5 m high, and some hundreds of metres wide, as well as parabolic dunes located on the NE margin of deflation basins (Tricart, 1969). North of Mar del Plata, well-preserved, W–E oriented aeolian landforms superposed on a SW–NE aeolian system have recently been identified (Martínez, 1998; Martínez et al., 2000). Tricart (1973) pointed out that the general direction of the landforms suggested WSW winds, particularly during E1 deposition, which represents less intense and much more localized aeolian activity than the E3 episode, affecting only swampy depressions and valley bottoms.

No numerical ages have been obtained from the E3 loess which grades southward into the Late Glacial loess of the Pampa Interserrana. The E1 aeolian silts represent a Holocene depositional episode, tentatively placed between the mid-Holocene (not older than 5000 yr BP) and the Late Holocene, using regional stratigraphic correlation (Fidalgo and Tonni, 1981; Zárate, and Blasi, 1991). Martínez et al. (2000) obtained an OSL date (700±150 yr) for the lower part of the modern A horizon (equivalent to the E1 of Tricart), and attributed this upper unit to the Little Ice Age.

4.2.2. *Pampa Ondulada*

The Pampa Ondulada is a gently rolling landscape, drained by several minor tributaries of the Paraná River and the Río de La Plata (Fig. 4). In general, recent contributions have not specifically focused on the Late Pleistocene/Holocene record, but have encompassed broader time intervals (0.75 to 1.5–2.0 Ma). Regional stratigraphic correlation suggests that the Late Pleistocene/Holocene loess is recorded by the uppermost 3–5 m of these sequences. This assumption is supported by two TL dates, between 20 and 60 ka BP (Table 2) (Rodbell, 1995; written communication), derived from loess and loess-like deposits overlying marine sediments of last interglacial age (marine isotope stage 5: Isla et al., 2000).

The deposits are classified as clayey loess (González Bonorino, 1965), with a low sand content (<5%) and high percentages of silt and clay (Teruggi and Imbellone, 1987; Nabel et al., 1999; Blasi et al., 2001). Grain-size analysis from soil studies also reveal

Table 3
Stratigraphic scheme for south central Santa Fe Province (lower Carcaraña River basin). After Kröhling (1999b)

Marine isotope stages	Stratigraphy	Aeolian deposits	Palaeosols	Numerical ages TL (*) = ^{14}C ka BP
	San Guillermo Formation	Loess		2050 ± 100
1			Hypsithermal soil	1320 ± 120
				454 ± 550
	Tezano Pintos Formation	Loess		9390 ± 630
				15,000 (*)
2				31,690 ± 1620
				35,890 ± 1030
			—Palaeosol—	
3	Carcaraña Formation	Aeolian fine sands		52,310 ± 1200
4	Sand Sea	Sand dune fields		

fine-textured sediments composed of up to 70% silt (2–50 μm), a minimum of 20% clay, with only 5–15% of particles being > 50 μm (INTA, 1989). Regionally, Morrás and Cruzate (2000) recognized a decreasing grain-size trend from SW to NE, which determines three successive belts consisting of sandy loess, typical loess and clayey loess, the latter lying close to the Paraná–Rio de La Plata axis.

The mineralogical composition varies throughout the sections, and includes metamorphic and igneous rock particles, as well as stratigraphic levels with a high content of volcanic glass shards. Illite and smectite are the dominant clay minerals (Table 1).

4.2.3. Southern Santa Fé –eastern Córdoba

This gently rolling area, dissected by several tributaries of the Paraná River, has been thoroughly studied by Iriondo and collaborators (e.g., Iriondo and García, 1993; Iriondo, 1997, 1999; Kröhling, 1999a, b; Kröhling and Iriondo, 1999). Information obtained at different localities on the general composition (grain size and mineralogy), stratigraphy, geomorphology, and geochronology of the deposits has been summarized in a combined stratigraphic sequence correlated with the marine isotope stages and the Holocene climatic oscillations (Table 3).

During marine oxygen isotope stage (MOIS) 3, aeolian silty fine sands, generally non-calcareous (Carcarañá Formation) were deposited. This unit, mainly of aeolian origin, is the result of reworking by erosion of a dunefield in the Pampean Sand Sea attributed to MOIS 4; paludal and alluvial facies are locally present. A TL date from the middle of a representative section yielded an age of 52,310 ± 1200 yr BP (Kröhling, 1999a).

The Tezanos Pintos Formation unconformably overlies the Carcarañá Formation. Southwestward, it is partially replaced by aeolian sands belonging to the Pampean Sand Sea that were remobilized during MOIS 2. The unit is composed of calcareous aeolian silts (silt, 71–81%; clay 13–29%; sand 1–6%), generally 2–4 m thick, but up to 6–8 m thick in interfluvial areas. The very fine sand fraction is dominantly composed of volcaniclastic grains followed by particles from the Sierras Pampeanas of Córdoba (Table 1). TL dates yielded ages between 31 and 32 ka BP (Table 3) at a depth of 4 m below the upper limit of the unit. Paludal and nodule bearing facies have also been identified (Kröhling, 1999b).

The uppermost part of the Tezano Pintos Formation and the aeolian sands were modified by Holocene pedogenesis and, in turn, by formation of the Hypsithermal palaeosol, typically represented by a Bt horizon. The interval of soil formation is placed between 8.5 and 3.5 ka, after which it was partially truncated by erosion and buried by the San Guillermo Formation (Kröhling, 1999a, b).

The San Guillermo Formation is described as a continuous mantle of aeolian grey silts covering the Hypsithermal palaeosol. It was formed by the deflation of the A horizon of the underlying palaeosol and subsequent dust deposition. The deposition of this unit is believed to have occurred during a dry interval between 3.5 and 1.4 ka BP (Iriondo, 1990a).

4.2.4. Córdoba

The Córdoba area consists of a flat plain dissected by fluvial systems that drain the Sierras Pampeanas. Several researchers studied the loess around Córdoba during the Early 20th century (Doering, 1907; Frenguelli, 1918). More recently, it has attracted the attention of soil scientists who have provided information on its composition and age (among others, Sanabria and Argüello (1999) and Argüello and Sanabria (2000)).

The deposits are classified as typical loess with a grain size dominated by coarse silt. From the upper 5 m of the deposits, TL dating yielded ages between 3 and 6 ka (3.20 ± 0.14; 5.59 ± 0.81, 5.76 ± 0.17; 6.26 ± 1.79 ka yr BP). Based on these numerical ages and the weakly developed soils (A, AC, Ck horizon sequence), Sanabria and Argüello (1999) attributed a mid- to Late Holocene age to this upper loess. Another Holocene aeolian episode has been reported in Córdoba, coinciding with the Little Ice Age, an event that gave way to the development of dunes and deflation basins (Cioccale, 1999) as well as the partial deflation of dunefields formed by the reworking of fluvial sands (Kröhling, 1999b).

Two hundred kilometres southward, in the area of Río Cuarto (33–34°S; 63–65°W), two Late Pleistocene–Holocene aeolian units have been identified, the La Invernada Formation loess (Late Pleistocene) and the Late Holocene/modern dunes (Cantú, 1992).

At a regional scale, covering the entire Córdoba province, Carignano (1999) proposed a scheme for the last 100 ka, consisting of several intervals correlated with the Marine Isotope Stages that essentially constitutes an extrapolation of the stratigraphic scheme and climatic interpretation proposed in Santa Fé by Iriondo. The chronology attributed to the episodes of loess deposition, palaeosol formation, and accumulation of alluvial sediments is inferred on the basis of general stratigraphic correlations and palaeoclimatic assumptions.

4.3. The Tucumán mountain valleys

In the mountainous environments of northwestern Argentina, Sayago (1995) and Zinck and Sayago (1999) reported the occurrence of very thick loess sequences along the intermontane fluvial valley of the Tafi River, between the Cumbres Calchaquíes–Mala Mala ranges to the east and the Sierras de Aconquija to the west (Northwestern Sierras Pampeanas). Primary loess and reworked loess cover the valley floor and the lower slopes of the surrounding mountains. Fluvial erosion has exposed the loess–palaeosol sequences grouped together as the Tafi del Valle Formation, within which sections have been analysed in detail.

The Zanja del Chivo section (26°56′40″S; 65°40′40″W), located at an altitude of 1800 m, consists of 18 m of loess including five palaeosols. A conventional radiocarbon date on bones exhumed at a depth of 11–12 m (ca 8.6 kyr BP), suggests a Holocene age for the upper half of the section (Zinck and Sayago, 1999).

The La Mesada section (26°57′15″S; 65°45′30″W), lying at 2280 m, is 42 m thick and contains 28 palaeosols interbedded with 26 loess layers. The average grain size consists of 33% sand, 58% silt and only 9% clay. Conventional radiocarbon dating of organic sediments yielded ages of ca 17.6 ka yr BP at 5.2 m to 27.7 ka yr BP at 42.3 m depth. It was suggested that this dated part of the sequence, including 20 palaeosols (Bt/C horizon pairs), indicate a climatic change every 500 yr from drier and cooler (loess deposition) to moister and warmer (palaeosol formation) conditions. This pattern might have been related to recurrent northward shifts of the polar front accompanied by a weakening of the South Pacific anticyclone (Zinck and Sayago, 2001).

The basal part of the 42 m loess–paleosol sequence at La Mesada has recently been re-examined using a combination of micromorphology and optically stimulated luminescence (OSL) dating (Kemp et al. 2003). The three OSL age assays obtained from between 34 and 40 m depth range from ca 150 to 195 ka BP, suggesting that the whole sequence is significantly older than any of the radiocarbon dates. The interfluves in this gullied landscape are well rounded, suggestive of erosional stripping of unknown extent. Although no ages are known for the upper part of this section, recent and as yet unpublished OSL determinations at a 70 m section at El Lambedero, in similarly rounded ridge terrain about 12 km NE of La Mesada, have a bearing on this question. A near-surface (0.6 m depth) age of 33 ± 2 ka BP at El Lambedero (P. Toms, pers. comm.) would be consistent with both a generally greater age for the Tafi del Valle loess and a substantial amount of late Quaternary erosion. Indication of a much greater age for the loess in this basin is also suggested by a recent magnetostratigraphical study of the 50 m thick Las Carrera section, situated a short distance north of La Mesada. Schellenberger et al. (2003) detected the Brunhes-Matuyama boundary (MBB) at 26.7 m depth, and the Jaramillo subchron between 38.7 and 44.9 m, using linear extrapolation to estimate a minimum age of 1.15 Ma for the basal loess, making Las Carreras one of the longest Quaternary terrestrial palaeoclimatic records in the southern hemisphere. They estimate that depositional rates decreased from 6.3 cm ka^{-1} below the MBB to 3.4 cm ka^{-1} within the Brunhes chron, yielding accumulation rates comparable to those on the Loess Plateau of China.

4.4. The Chaco plain

The Chaco plain, generally the least studied of the four geographical regions, extends across northern Argentina, southeastern Bolivia and Paraguay. The boundary between the Chaco and the Pampean plains is a transitional belt located around latitude 30°S. Most of the available information is related to the distribution and some aspects of loess composition. In northern Santa Fé, included in the transitional belt, several papers primarily concerned with mineralogical aspects demonstrate a significant proportion of volcanic shards (Bertoldi de Pomar, 1969; Morrás and Delaune, 1985; Morrás, 1994).

Northwestward, loess deposits were grouped under the name of the Urundel Formation (Iriondo, 1990b), a unit some 18 m thick. In Bolivia this is found in several localities from Santa Cruz to the Argentinean border. Extensive areas of the western Chaco of Salta and Chaco provinces are blanketed by this silty to sandy loess, which was later eroded by Holocene alluvial fan formation across large areas, resulting in reworked loess deposits (Iriondo, 1997). Here, the loess is mainly composed of quartz with no volcanic glass shards. One numerical age for this unit consists of a ^{14}C date (16,900 ± 270 yr BP) on wood collected in the middle of a section (Iriondo, 1997).

A general model (Chaco model) of loess deposition has been proposed by Iriondo (1997). In essentials, this is similar in its chronological and environmental aspects to the Pampean model of Santa Fe province, i.e. it consists of intervals of alternating soil formation and loess accumulation. Accordingly, during the Last Glacial Maximum loess was deposited along the sub-Andean ranges and the Chaco plain of Argentina, while sand fields of parabolic dunes were formed in the Bolivia–Paraguay low plains. During the Early and Middle Holocene, a soil developed on top of this unit under humid conditions. Eventually, in the Late Holocene, large dune fields were formed during a dry interval between 3.5 and 1.4 ka in SE Bolivia and NW Paraguay (Parapetí dunefield at the Bolivia–Paraguay border).

5. Discussion

5.1. Loess source areas and the transport mechanism

Northern Patagonia had been regarded as a potential source area of Pampean loess since the Early 20th century (Bayley Willis 1912 in Roth, 1920; Frenguelli, 1957). However, Teruggi (1957) was the first to provide a comprehensive explanation of loess source areas, transport and depositional mechanisms. His interpretation, essentially derived from the analysis of selected samples of Plio-Pleistocene age collected along the Mar del Plata sea-cliffs (Teruggi, 1957), was later extrapolated by other authors to the entire Chaco–Pampean plains. This resulted in an oversimplified loess model.

A much more complex scenario is now envisaged. This consists of several loess and loessoid domains across the region, and involves a multistage transport mechanism related to source areas other than the classic ones (northern Patagonia or Mendoza province and the Andean piedmont), situated westward and northward of the Chaco–Pampean plains (Table 4). Current interpretations involve a fluvial transport stage prior to sediment deflation. Iriondo (1990a) pointed out the Salado–Desaguadero–Curacó rivers were the potential source area of the Pampean loess and the sand dune fields. This large fluvial system extends between latitudes 28°S and 38°S, east of the Andes piedmont and west of the Sierras Pampeanas of Tucumán, Córdoba and San Luis (Figs. 1a and 5). At present, it is basically inactive and partially covered by alluvial fans and Holocene sand dunes fields (Iriondo, 1990a). During the glacial stages, the headstreams of the numerous tributaries drained the glaciated valleys of the Cordillera. Thus, it was suggested that the floodplain was deflated by SSW

Table 4
Main characteristics of the late Pleistocene-Holocene loess record across the region

Area	Aeolian deposit	Mineralogical composition	Source area	Inferred transport–wind systems
Southern Pampas (Pampa Interserrana)	Sandy loess–loessial sands, sand mantles	Volcaniclastic ≪(quartzitic and metamorphic rocks)	Northern Patagonia; Andes (34–38°S)	South-southwesterly winds
			Tandilia and Ventania (local)	*Holocene*: westerly winds
Northern Pampas (Pampa Deprimida)	Sandy loess (WSW) grading to typical loess (ENE)	Volcaniclastic ENE area: not determined	Northern Patagonia; Andes (34–38°S)	South-southwesterly winds
			Sierras Pampeanas (?)	*Holocene*: westerly winds
Northern Pampas (Pampa Ondulada, southern Santa Fé, Córdoba)	Typical loess/clayey loess	Metamorphic + igneous rocks + volcaniclastic material	Andes Cordillera Sierras; Pampeanas, Paraná basin, Uruguayan shield	South-southwesterly winds
			Altiplano (?)	(?)North/northeasterly winds (?)Tropospheric from Altiplano
Southern Pampa and northern Pampas	Sand dune fields, Sand mantles	Volcaniclastic composition + metamorphic rocks	Northern Patagonia, Andes (34–38°S)	South-southwesterly winds
			Sierras Pampeanas	*Holocene*: westerly winds
Mountain valleys of Tucumán	Typical loess	Volcaniclastic	Northern Patagonia Western Andean sources (?)	Southerly winds Westerly winds (?)
Western Chaco	Typical loess	Dominant quartz composition	Bolivian Andes	Northerly winds

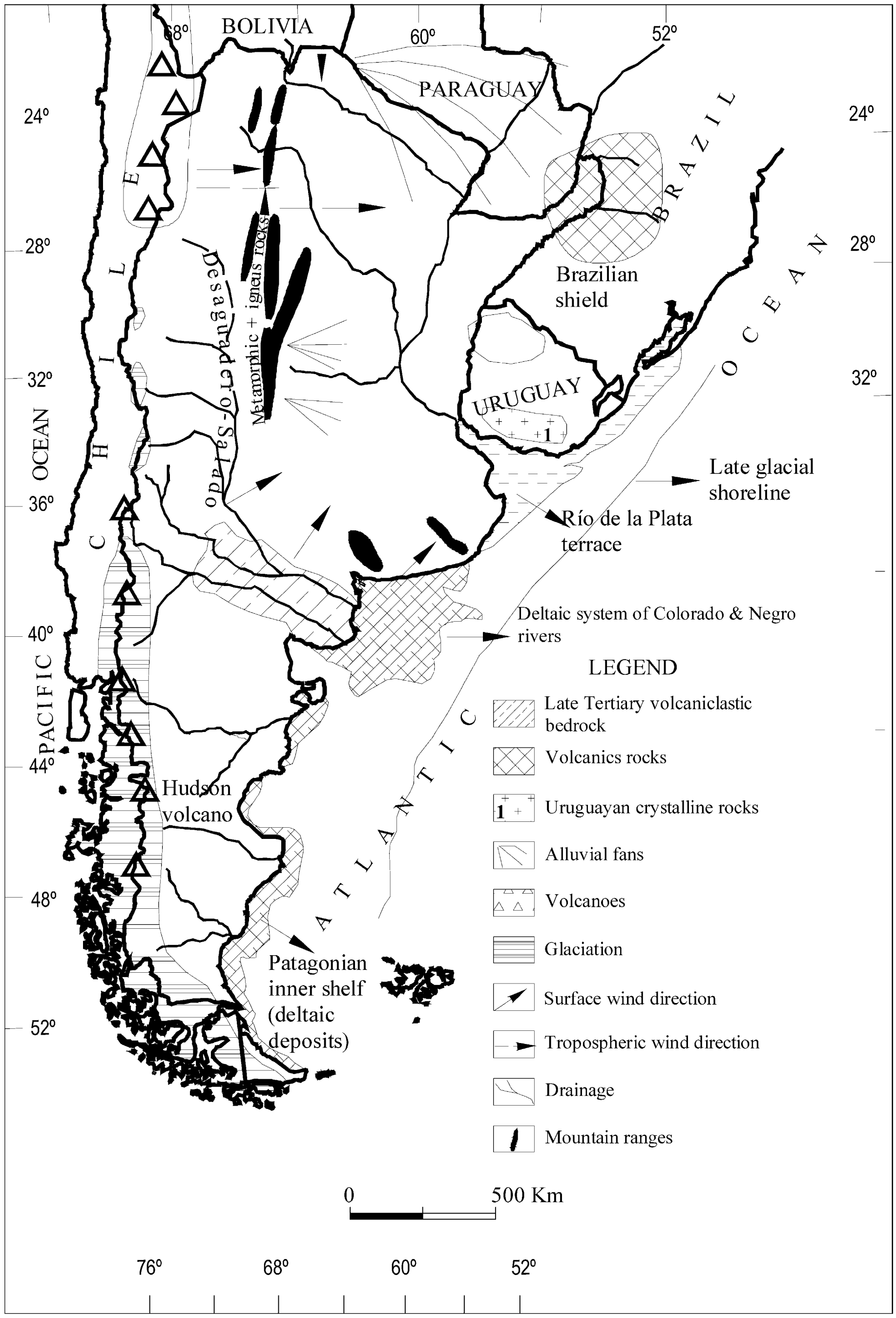

Fig. 5. Source areas of loess and aeolian sands.

winds, driving northeastward to form the extensive sand dune systems and sand dune fields (Sand Sea) of central Argentina and the loess mantle further northeast (Iriondo, 1990a, 1997; Clapperton, 1993). In the Chaco region, Iriondo (1997) also proposed that loess deposits (the Urundel Formation) were deflated by northerly winds emanating from the floodplains of the Parapetí, Pilcomayo and Bermejo fluvial systems that drain the Andes.

In the southern Pampas it was inferred that loess particles were fluvially transported and deposited along the extensive alluvial plains of the Colorado and Negro rivers (Zárate and Blasi, 1993). These streams derived their loads from erosion of Late Tertiary volcaniclastic deposits, as suggested by the very well-rounded mineral grains found in the loess (Teruggi, 1957; Zárate and Blasi, 1991). Material was deflated from the alluvial environments and deposited in the southern Pampas. It was proposed that the distinct grain-size zonation of alluvial material presently observed along the Colorado River might have shifted eastwards, so controlling the west–east grain-size zonation of the aeolian material in the area (Zárate and Blasi, 1993). During glacial stages, the floodplains extended along the continental shelf forming a large and complex deltaic system (Parker et al., 1996), very close to southern Buenos Aires (Fig. 5), which may explain the thick and coarse-textured loess (proximal facies) and the aeolian sands present in this area.

Concerning the provenance of the Chaco–Pampean sediments, rocks from northern Patagonia and the Andes piedmont of Mendoza seem to have contributed to the loess and sand deposits in the southern Pampas. The Ventania and Tandilia ranges provided minor amounts of material found in soils and loessic sediments of the areas immediately surrounding these two mountain systems (Table 4).

Morrás (1997) pointed out that this sedimentological model of an Andean-derived loess explains fairly well the origin of the southern Pampas aeolian deposits, but is not consistent with the compositional differences and variations found in the northern Pampas and Chaco. According to the existing Andean model, a homogeneous composition (volcaniclastic) was attributed to the loess and loessoid material of this area, while the differences found in the clay mineralogy of the soils, for example, were interpreted as resulting from more intense weathering related to increasing rainfall to the east. Instead, Morrás inferred a heterogeneous composition for the surface material based on mineralogical and geochemical data. Morrás used soil phosphorus content to demarcate several areas, and their characteristics and limits were correlated with sedimentological and mineralogical information from surface materials. The results obtained permitted the inference that sediments had been derived from three different provenances (Andes Cordillera, Sierras Pampeanas, and the Paraná River basin) (Morrás, 1999).

The relative input from these source areas varies across the region (Kröhling 1999b; Morrás, 1999; Blasi et al., 2001). In southern Santa Fé, the Andean volcaniclastic material is dominant (Kröhling, 1999b), it being believed that it was deflated from the floodplains of northern Patagonia by SSW winds (Iriondo, 1990a). Also, in the Pampa Ondulada close to Buenos Aires city, a significant Andean contribution is suggested by the Nd isotopic composition of the loess (Gallet et al., 1998). The Sierras Pampeanas apparently constituted a secondary source area providing particles of metamorphic and igneous rocks (Cantú and Degiovanni, 1984; Cantú, 1992; Kröhling, 1999b). The entrainment and transport mechanism of the aeolian sediments is not explained. It can be speculated that the dominant SSW winds during glacial stages might have deflated material from the floodplains and alluvial fans of the eastern piedmont of the Pampean ranges (Table 4).

The occurrence of variable amounts of material derived from the Paraná basin (Fig. 5) in the loess deposits of Santa Fé, and the Pampa Ondulada of northern Buenos Aires, is not fully understood. The present drainage system flow across the Early mid-Pleistocene stratigraphic units (the Ensenadense beds) composed of material derived from this source area (González Bonorino, 1965). These streams, tributaries of the Paraná River, have cut into the Ensenadense beds and, assuming that SSW winds were the single dominant transport mechanism, it might be speculated that material was deflated and later deposited and mixed with particles coming from other areas. Considering the proximity of potential source areas of metamorphic and igneous rocks cropping out on the Uruguayan margin of the Río de La Plata (50 km away), as well as the presence of the extensive alluvial plain of the Paraná River carrying sediments from southern Brazil, raises an alternative and plausible explanation involving loess transport by other wind systems (north? northeast?) (Table 4).

The origin of the loess particles derived from the Tandilia range and Sierras Pampeanas, in addition to those potentially contributed by the Uruguayan shield, might be related to the soil-weathering profiles developed on the granitic and metamorphic rocks recently reported at numerous localities along Tandilia (Rabassa et al., 1995), the Precambrian bedrock of Uruguay (Panario, 2000, pers. comm.) and the Pampean ranges of Córdoba and San Luis (Kirschbaum et al., 2000). According to González Bonorino (1966) kaolinite, commonly found as traces in the loess deposits, is derived from altered rocks of the Sierras Pampeanas.

Apart from the source areas previously mentioned, Bloom (1990) assumed that aeolian dust released by weathering processes on the Altiplano (Fig. 5) were entrained by slope winds and carried aloft and eastward by tropospheric winds, eventually being deposited across the eastern plains. How much of the Altiplano material, rich in volcaniclastic material, contributed to the loess of the northern Pampas and also the Chaco, still remains untested, however.

It is believed that the loess in the mountain valleys of Tucumán was transported by southerly winds from northern Patagonia, and deposited in the mountain environment in accordance with the general sedimentological model discussed above. The grain size and mineralogical differences between this loess and the Pampean loess are interpreted as a result of contrasting environmental conditions in the two areas (Sayago, 1995). In neighbouring areas to the west, earlier reports suggested that local winds might have deposited loess along the dry mountain slopes of the northern Sierras Pampeanas of Catamarca (Kuhn, 1913, referred to in Frenguelli, 1955).

5.1.1. Volcanic ashfalls

Volcanic ash falls constitute another significant contributor to the southern South American loess, Andean eruptions generating this direct input of material. Discrete tephra layers, as well as high percentages of fresh volcanic material within individual loess units have been reported from a number of different localities across the region (Imbellone and Camilión, 1988; Morrás, 1994). In an attempt to quantify the role played by this process, Teruggi et al. (1957) estimated that at least 5–10 m of pyroclastic material accumulated directly from volcanic ash falls in the last million years. This assumed one volcanic eruption each century of similar magnitude to the eruption of the Quiza Pú volcano, which deposited an average of 0.5–1 mm of volcanic material in eastern Buenos Aires in April 1932. Using mineralogical data, Zárate and Blasi (1993) estimated that around 10% of the Late Pleistocene–Holocene loess in the southern Pampas was generated by direct volcanic ash falls.

The locations of the volcanic eruptions that generated the discrete tephra layers and the pyroclastic admixtures in the loess are unknown. From the three volcanic districts (Central Volcanic Zone, Southern Volcanic Zone and Austral Volcanic Zone) present along the Andean Cordillera south of the Equator (Clapperton, 1993), the first two probably played a significant role. Until now, the volcanic segment between latitudes ca 34°S and 40°S (volcanoes of Neuquén and Mendoza provinces) has been almost the only source of volcanic ash falls referred to as a potential contributor to the Pampean loess. This is probably because most of the major eruptions that affected the Pampas during the XXth century (Quiza-Pú, Descabezado volcanoes) occurred in this area. More recently, ash from the Hudson Volcano eruption in 1991 (located in the Southern Volcanic Zone, Patagonian Andes: Fig. 5) was deflated and re-suspended several times, reaching the southern Pampas on several occasions. Nothing is known about the Altiplano volcanic district (pertaining to the Central Volcanic Zone), another potential source of the tephra layers found in the loess of the Chaco and the Pampas.

5.2. Southern South American dust and Antarctic ice-core dust

The isotopic ratios ($^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$) of four loess samples from the southern Pampas of Buenos Aires (38°S 59′W; 37.5°S 57′W) regarded as having come from Patagonia, suggest a South American origin for the dusts of the Late Glacial Maximum found at Dome C in East Antarctica (Grousset et al., 1992). Basile et al. (1997) broadened this study to include seven samples from the Argentine continental shelf between the Rio de La Plata (35.67°S; 56.57°W) and a marine core at 54.17°S; 64.97°W, as well as three other soil samples from Tierra del Fuego. The results confirm that the Argentine source contains two main isotopic signatures (from Patagonia and the continental shelf). Of these two sources, the dust deposited at both Vostok and Dome C during glacial stages 2, 4 and 6 fit best with the Patagonian potential source area (Basile et al., 1997), supporting previous interpretations.

Some questions arise with respect to southern South America as a potential source area for Antarctic dust. Was dust deflated only from the region between 39°S and 52°S (Patagonia)? Did Tierra del Fuego play a role as a dust source? Did dust come from the Pampas, north of latitude 39°S, where loess and aeolian sands are extensive? Were both Patagonia and the Pampa prone to deflation? Did the newly exposed continental shelf contribute nothing to the Antarctic dust? These questions are briefly explored below.

For geographical convenience, Basile et al. (1997) used the term Patagonia to refer to the whole desert/arid/semiarid continental area of southern South America east of the Andes including, in this broad sense, the Chaco–Pampean plains. However, Patagonia and the Chaco–Pampean plains have geomorphic, climatic and biogeographical characteristics that clearly differ from each other. Thus the two areas cannot be considered as a single, uniform region likely to have provided identical environmental responses during glacial stages. Extensive loess deposits of last glacial age are located north of latitude 39°S (Chaco–Pampean plains), with no records south of 39°S (Patagonia), except for local areas with some aeolian sands.

Basile et al. (1997) envisaged Patagonia as a large, arid and elevated, outwash-covered plateau. In reality it is not a single tableland, but a complex landscape consisting of several different geomorphological surfaces, the oldest of which is probably Late Tertiary in age. During the most recent glacial periods, and particularly in MOIS 2, 4 and 6, outwash plains of the Patagonian fluvial systems that drained the glaciated cordillera, were limited to relatively narrow valleys excavated into the Patagonian plateaus. These rivers extended across the continental shelf, where outwash plains probably formed. It is likely that the outwash plains on the continental shelf had high sediment availability. With regard to potential dust sources other than fluvial environments, Iriondo (2000) hypothesized that the numerous deflation hollows and depressions scattered throughout the high Patagonian plateau were subject to deflation. However, the potential sediment availability from these environments, if any, must have been very restricted compared to the floodplains. The role played by the high Patagonian plateau as a potential source area is unknown and should be considered within the context of the environmental conditions that probably prevailed during glacial stages when the region was affected by permafrost (Trombotto, 2000).

Following Basile et al. (1997), distinctive isotopic signatures in the marine deposits make it unlikely that the extensive continental shelf exposed during the last glaciation was the source of the Antarctic dust. Rather, the very extensive exposed continental shelf would probably have been a more humid environment because of its proximity to the ocean. This would have promoted lush vegetation growth and soil development, conditions that are not conducive to deflation (Basile et al., 1997). This hypothetical scenario remains untested. However, the environment of the present-day Patagonian shoreline south of 39°S is quite similar to the inland plateau, except for a narrow littoral zone or local coastal settings. During glacial stages the shelf was more than 300 km wide in some latitudes, but the littoral environmental conditions were probably restricted to a narrow coastal fringe, as they are today. It has also been proposed that this shelf acted as a source for the loess and aeolian sand mantles of southern Buenos Aires province at 38°S, with specific sources in the lower reaches of the Río Negro and Río Colorado (Zárate and Blasi, 1993).

The locations of the samples used for isotopic analysis require some comment. Of the three soil samples that, according to Basile et al. (1997), come from Tierra del Fuego, only one (Punta Arenas, 54°S 69°W) is actually from the island itself. The second sample comes from south of Puerto Natales, in the Chilean fiord district (Ushuaia, 52°S 73°W) and the third (51.5°S 69°W) comes from southernmost extra-Andean Patagonia northward of Rio Gallegos, Argentina. The geological and geomorphological settings of these three samples are quite different. The Punta Arenas and the Ushuaia samples were taken from an area covered by glacial ice until the Last Glacial Maximum, and the Rio Gallegos samples derive from a periglacial region associated with the glaciation; soils in this area are developed in Holocene sediments (Coronato, 2002, written communication). On the other hand, the upper horizons of the modern surface soils in the region include volcanic ashes from eruptions of southern Patagonian volcanoes. Volcanic ash input to soils occurred throughout the Holocene and ash is found in almost all the modern surface soils of Argentina, to some degree or other. Thus, a volcanic ash contribution might influence the isotopic signature obtained from several soil samples, yielding similar ratios in Patagonia, the Pampas or Tierra del Fuego. Finally, on the basis of rare-earth-element and Sr-Nd isotopic data from a suite of loess samples, Smith et al. (2003) have recently concluded that the region north of 37°S in Argentina played no significant role as a dust supply source for Antarctica during the last glaciation. Their evidence suggests a mainly Andean source for the northern Argentine loess, thus casting doubt on earlier views favouring a substantial northward shift in the climatic belts at the last glacial maximum.

6. Concluding remarks

Several aspects of the classic model of the southern South American loess need to be reconsidered. The last 5–3 Ma record, ante-dating the last glacial cycle, is mostly known from sections exposed in the southern Pampas and the Pampa Ondulada area of northern Buenos Aires province. Described as sequences composed of alternating loess and palaeosol units, there is general agreement on their relationship to cyclical climatic fluctuations, alternating between arid and cold (loess deposition) and warm and humid intervals (palaeosol development). However, the sequences are much more complicated than this simple model suggests, consisting of a complex succession of mostly reworked loess facies (loessoid sediments), welded palaeosols, and several erosional unconformities. Where detailed studies have been carried out, pedogenesis seems to have been active throughout the sedimentation process, and palaeosols are not always discrete entities. Changes in the sediment supply (grain-size variations) have also occurred; these, together with the variable degree of reworking (bioturbation and aqueous transport) displayed by the sediments, mask palaeosol boundaries. Chronologically, these sequences still cannot be correlated with the marine oxygen isotope stages, except with respect to some time intervals (Late Pliocene) where numerical ages have been obtained.

The Late Pleistocene–Holocene record reveals an aeolian sequence with a heterogeneous composition as a result of derivation from three main source areas, namely the Andes, the Sierras Pampeanas and the Paraná River basin, with relative contributions varying across the region. The Andean source, present in all the geographical domains considered, is prevalent in the southern Pampas. It has also been suggested that the mountain valley loess of Tucumán is derived from a southern Andean source. Material from the two other sources is found in the northern Pampas and the eastern Chaco. However, more research is needed to elucidate the role played by the Paraná basin as well as the areas located immediately westward of the northern Sierras Pampeanas.

The establishment of a regional model of climatic changes is hindered by several factors. First, few numerical ages are available, which preclude the correlation of type sections in each area. Second, the region encompasses a wide variety of geomorphological settings, characterized by very different conditions of topography and bedrock lithology, which must have exerted some control on environmental responses to climatic fluctuations. Hence, local versus regional changes, as yet undifferentiated, may lie at the heart of some disagreements. These factors also pose great difficulties in any attempt to calculate loess mean accumulation rates, an exercise that must await improved dating and more certain discrimination of strictly aeolian units in a greater number of sections across this extensive region.

Current interpretations based on palynological records (Markgraf, 1983, Prieto, 1996), and general reconstructions derived from the aeolian deposits (Sayago, 1995; Iriondo, 1999; Zinck and Sayago, 2001) agree in relating palaeoenvironmental changes to latitudinal shifts in atmospheric circulation anomalies (Pacific and Atlantic anticyclone cells). Inferred westerly and southwesterly transport directions for the last glacial aeolian sands and loess accord with westerly palaeowind simulations derived from climate models (Muhs and Zárate, 2000). However, the role played by westerly tropospheric and northerly winds remains to be established. Also, more work is needed if more light is to be shed on past climatic gradients across this region.

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