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Non-classical types of loess

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Abstract

The purpose of this contribution is to describe the sequence of physical and chemical processes resulting in the sediment-type named loess, a fine-grained sediment deposit of universal occurrence. Owing to historical causes, loess has been (and still is) implicitly linked to glacial/periglacial environments among most naturalists. However it is known today that most eolian dust is deflated from tropical deserts. Hence, that sequence of processes is more comprehensive than the former narrow cold scenario. Six examples of different "non-classical" cases (from South America and Europe) that fit well to the loess definition are developed: 1) volcanic loess in Ecuador: pyroclastic eruptions/valley wind/mountain praire/silica structuring; 2) tropical loess in northeastern Argentina, Brazil and Uruguay: deflation of river and fan splays/savanna/iron sesquioxide structuring; 3) gypsum loess in northern Spain: destruction of anhydrite/gypsiferous layers in a dry climate/valley wind/Saharian shrub peridesert/gypsum structuring; 4) trade-wind deposits in Venezuela and Brazil: deflation in tidal flats/trade wind into the continent/savanna/iron hydroxide structuring; 5) anticyclonic gray loess in Argentina: continental anticyclone on plains/anti-clockwise winds and whirls/steppe/carbonate structuring. All these non-classical types conform to the accepted loess definitions and they also share the most important field characteristics of loess such as grain size, friability, vertical or sub-vertical slopes in outcrops, subfusion and others. Other cases can probably be recognized when systematically scrutinized.

Keywords: Quaternary; South America; Loess; Last Glacial Maximum

1. Introduction

Loess is an eolian sediment dominantly formed by silt or silty loam, which normally generates rich soils; consequently, it is an object of permanent interest in sedimentology and soil science. The world's major loess deposits have correctly been linked to glacial processes (North American and North European loess) or to cold weathering processes (Chinese and Central Asian loess). This predominance of cold environments has influenced the theory of loess formation so strongly, that a general link to glacial action is today almost taken for granted. However, the fact that such an assumption is frequently implicit has hampered the development of knowledge on this issue. Hesse and McTainsh (2003), for example, referred that: "progress in advancing knowledge of loess soils in Australia has been limited by too great a reliance upon "typical" diagnostic characteristics, an approach probably inherited form periglacial loess research…This has led to the misidentification of dust deposits in some instances while other legitimate deposits probably gone undetected". As a result, deposits clearly disconnected to cold systems are "a priori" disregarded by most loess specialists (e.g. Smalley and Vita-Finzi, 1968). Sometimes even non-sedimentological theories have been

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proposed to explain such deposits, e.g. rock alteration, mass movements, etc. Thus, Smalley et al. (2001) state that: "Obruchev (1911) put together the idea of eolian transport and loess deposition and the desert source concept, providing a combination that was later to cause problems".

An undisputed fact is that transport of silt and clay in suspension by wind is a universal process. Observations and measurements of the general movement of atmospheric dust and studies made on Quaternary fine sediments elsewhere suggest that loess is much more ubiquitous than hitherto accepted, and that, in particular, loess also occurs in non-glacial environments.

Thus, transport of dust by wind occurs under all climates, especially in tropical deserts and sub-arid regions. Moreover, measurements of sediment transport indicate that between 90 and 95% of the total load of the world's rivers is composed of silt and clay. Such a statistic is a sound indicator of the present continental dynamics. A somewhat larger time-span of sedimentation can be covered if one considers the surficial deposits of the ocean basins, which represent a period of a few thousand years. Under natural conditions, muds and "clays" in particular, are actually transported as silt-sized particles and aggregates (Kröhling and Iriondo, 2003).

Furthermore, if one superficially looks at the whole Phanerozoic Eon, a dominance of silty deposits is evident. Between 70 and 83% of the computed sedimentary rocks are "lutites", versus 5–14% of sandstones; the remainder corresponding to limestone (Pettijohn et al., 1973). Mean values of the thickness of sediments and sedimentary rocks are 3 km in the oceans and 1.5 km on the continents, 75% of which consist of silt and clay (Kuenen, 1941).

On the other hand, glaciations represent only about 5% of geological time, covering minor portions of continental masses. They can therefore hardly be the only or unique origin of all wind-blown particles. Nahon and Trompette (1982) pointed out that the temporal and spatial occurrence of glaciers and ice sheets is too restricted both in space and time to account for the total volume of silt found within the geological record. In support of this Iriondo (1999a) noted that the lutites of the Jurassic in Argentina are more than 5000 meters thick, a period without any signs of glaciation.

Recently, Wright (2001) and Smith et al. (2002) discussed the existence of non-glacial loess. This issue is picked up in the present contribution, which mainly focuses on South America, the aim being to propose a more comprehensive rationale for the general concept of loess, including scattered information about alternative origins. Some important, recently identified loess deposits cannot be explained by the generally accepted "orthodox" theory (Iriondo and Kröhling, 2004a). With the intention of integrating our theory into the common loess concept, we first discuss the glacially-derived Last Glacial Maximum (LGM) Pampean loess and then use this as a reference against which non-classical occurrences of loess are compared.

2. Definition of loess

There have been many attempts to define loess but no agreement has yet been reached as to which characteristic features are unique to loess. No single definition has been universally accepted (Wright et al., 1998).

Loess is a silt or silty loam deposit of eolian origin, this origin was first proposed by Richthoffen (1882). As in the case of other sediment classifications, there are no clear limits in the definition of loess. The basic agreement on the nature of loess among specialists is expressed in the classical description of Ruhe (1975): "Loess is a wind-deposited sediment that is unconsolidated and is composed mainly of silt-sized particles". Tsoar and Pye (1987) summarize: "loess is a wind-deposited dust with a median grain size of 20–30 μm".

On the other hand, there have been attempts to define a "typical loess" more strictly. For example, Pécsi (1990) listed ten different descriptions. However, some of these, or the combination of two or more of them, is geologically or epistemologically poorly constrained. Several accessory characteristics, although not considered as mandatory by the definitions, are widely used in field studies, e.g. friability, steep slopes, vertical fissures, collapsibility, occurrence of concretions. It is important to note that mineralogy is neither a necessary nor an accessory condition in the logics of the definition or the natural pattern of processes and materials involved.

3. Rationale of loess origin

In order to develop a consistent rationale of loess, a sequence of mandatory processes must be considered. These processes were referred to by Iriondo (1999a) and are in partial agreement with the four major events involved in the formation of a simple loess deposit as proposed by Smalley (1975). Some factors controlling the formation of loess were also reviewed by Pye (1987) and Tsoar and Pye (1987), among others. A general review of the processes involved in the generation of loess is presented below.

3.1. Generation of silt particles

Several natural mechanisms can produce massive volumes of silt-sized particles. Silt-producing mechanisms comprising insolation weathering, glacial grinding, release of particles from siltstones, frost weathering, salt weathering, fluvial comminution, eolian abrasion and attrition, hydration, and crack exploitation by expanding lattice clays have been reviewed by Pye (1987), McTainsh (1987), Smalley (1990), Assallay et al. (1998), and Iriondo (1999a). In addition, Wright et al. (1998) have demonstrated that a range of geomorphic mechanisms are capable of producing quartz silt under laboratory conditions.

One of the most spectacular mechanisms responsible for the production of fines is explosive volcanism, which can eject almost instantaneously millions of cubic meters of particles into the atmosphere. Also, the processes of soil lixiviation or eluviation under humid climates (chemical weathering) provide large amounts of loose silt particles which are then available for deflation during subsequent arid periods. Another quantitatively noteworthy process is the agglomeration of clay and colloidal particles by flocculation during desiccation of water bodies.

Physical weathering represents a very important agent for the production of silt. The most significant appears to be crystal growth (frost and salt weathering). Crystallization of salt, which produces substantial tensile stresses, occurs in rocks and sediments in hot deserts (Goudie, 1985; Pye and Sperling, 1983, among others). Insolation weathering in tropical deserts can also produce sizable amounts of silt particles (Iriondo 1999a).

Fluvial and eolian processes are significant producers of silt particles. Laboratory simulations carried out by Wright et al. (1998) indicate that both processes are highly effective in generating quartz silt over short time periods. Their results indicate that fluvial comminution is likely to be most effective in glacial and semi-arid environments. According to Whalley et al. (1982), grain abrasion and grain rounding produce silt and clay particles, implying that sand and dust storms may have considerable potential for silt production. The favorable environments for such silt production not only include glacial outwash plains, but also fluvio-glacial channels and wadi deposits in hot desert environments (Wright et al., 1998).

In contradiction to the glacial process mechanism as the main sources of silt, results from the glacial grinding simulation experiment reported by Wright et al. (1998) suggest that, although some grain breakage does occur, little material is actually reduced to the required silt size.

3.2. Dust deflation

Wind picks up silt particles from the surface when local humidity of the air is low and its velocity is above the critical shear velocity of 20–40 cm/s (Bagnold, 1941). Dry seasons in all climates and even beaches or low-level wetlands in humid climates are favorable places for deflation. An arid climate is thus not a precondition for this process.

In a rational discourse of the deflation issue, it has to be considered that air is 715 times less dense and 55 times less viscous than water, a properties which explain the "fine-tuned" character of eolian deposits. As is general knowledge, air flows either in laminar or turbulent forms. In all turbulent flows, a thin layer of laminar flow occurs at the contact with the surface, viscosity of this layer controls the deflation process. The layer of laminar flow is known as the "boundary layer" where surface drag acts on the grains and particles. The physical expression of this factor is based on the drag velocity (V_*):

$$V_* = \sqrt{\tau/\rho}$$

with τ as the drag/cm^2 or shear stress, and ρ the density of the air.

The general properties of this phenomenon are rationally described by the Reynolds Number (*Re*):

$$Re = V_* d/v$$

with d as the grain diameter, and v the kinematic viscosity.

The implication of these parameters is that, when *Re* is smaller than 3.5, the surface is "smooth" and the eddies of the turbulence do not reach the clasts. This condition is met when the roughness of the surface (defined by the grain size) is about 100 µm. The drag velocity is then minimal, around 20 cm/s. As a consequence, when the grains become smaller than that value, their entrainment becomes increasingly difficult, even when the particles are cohesionless. As demonstrated in wind tunnels experiments (Bagnold, 1941), the deflation of particles smaller than 30 microns requires as much energy as the entrainment of coarse sand.

In nature, wind incorporates fine sediments by acting on small irregularities in the surface, picking up millimeter-size aggregates which are immediately broken down. After some time, when the surface of the loose particles has become smooth, dust deflation is interrupted.

To reactivate the entrainment of silt (in the simplest theoretical case) a continuous rain of saltating sand grains is required in order to lift particles by impact. Where sand is not available, deflation does not occur until some other mechanism destroys the surface. One such mechanisms can be observed in the field when herds of big animals or a number of vehicles move across a loessic plain and temporarily raise clouds of dust. Indeed, almost any small animal and plant shaken by the wind will mobilize particles in a more general, though less visible way. One can hence conclude that dust entrainment into the atmosphere is to a significant degree biogenically triggered.

Another effective deflation mechanism has a meteorological origin. Small-scale convective vortices (tens of meters in diameter) are numerous under certain weather conditions on the Argentine plains. Characterized by a high concentration of energy, such vortices raise visible columns of dust in the atmosphere. Numerous circular deflation hollows have been excavated by this mechanism in the Pampa during the Little Ice Age. Observations made in the Sahara (Bücher, 1989) confirm that dust storms may occur at both low and high wind velocities, depending on "high temperature and turbulence", rather than on wind velocity alone.

Several authors have contributed to recent progress on the question of particle deflation. According to Shao et al. (1993), interparticle bonds are not easily broken by aerodynamic forces but may be disrupted by the impacts of saltating sand grains. Iversen et al. (1987), among others, found that the critical wind shear velocity can also be modified by the relative importance of surface density effects and the strength of interparticle forces. Nickling (1988) outlined the complicating effects of grain size, shape, and packing on grain entrainment threshold; according to this author, despite the importance of the bombardment process, field studies indicate that even relatively small changes in surface conditions (soil moisture, aggregate content and stability, soluble salt content, and development of a lag cover during erosion events) play a significant role in the temporal and spatial variability of dust emissions at a given site.

3.3. Transport of dust

The areas with conditions favorable for the transport of large amounts of fine sediments in suspension are the arid and semiarid regions of the Globe, which cover approximately 35% of the total continental surface. The most important of these are the tropical-subtropical high pressure belts of both hemispheres. These belts are formed by a series of anticyclones which generate almost permanent dry winds in their gyres (Trade-winds, Harmattan wind, and others) with the capacity to convey dust over thousands of kilometers (Bücher, 1989; Prospero, 1999).

The modeling results of Tegen and Miller (1998) indicate that the relative importance of source versus transport variability varies with time and distance from the dust source regions. The results also suggest that transport variability becomes increasingly more important as the distance from the dust source increases.

Large amounts of atmospheric dust are transported annually over long distances by the major wind systems of the earth. Considering the present global pattern, the major dust transport systems can be grouped into four different types:

- Systems directly linked to the general atmospheric circulation pattern: Trade-winds, Harmattan winds and equivalents are active systems located in tropical regions, and generally produce red and yellow tropical loess.
- Monsoon transport: The difference in radiation between the ocean and the large continental masses in the Northern Hemisphere generates high pressure cells over Siberia and Canada during winter. This condition produces strong ocean-ward winds, which can produce "dust storms" in Asia and in the Great Plains of North America. Such phenomena tend to result in classical loess deposits.

Obruchev (1958) suggested that the loess in China was distributed in areas where the oceanic monsoon meets the continental monsoon, and he emphasized the function of the atmospheric vertical turbulent currents. Also, Liu et al. (1985) described the transport and accumulation of dust produced by the winter monsoon.

- Transport by winds generated in continental anticyclones: Continental anticyclones are typical of the Southern Hemisphere. In comparison with the major oceanic anticyclones, they are second-order systems covering tropical and subtropical latitudes. At present, the largest one is located in Australia and the weakest one in South America. These anticyclones are characterized by dry air, rare cloudiness and gentle winds circulating in an anti-clockwise direction (Preston-White and Tyson, 1993; Iriondo, 1999b). In normal years, the South American anticyclone reaches the ground only sporadically during a few days and then fades out, but during abnormally dry years, and during dry periods of the past, it remains on the surface for months (Iriondo, 1990). In summertime, such anticyclones are characterized by the occurrence of numerous whirls in the hot, early afternoons. Already in the 1930s, stressed the role of anticyclonic activity in the transport and sedimentation of loess material in the Northern Hemisphere.

- Dust transport by meso-scale regional winds: In some regions, particularly in broad valleys of tectonic origin, regional low winds flow in wide corridors flanked by high mountains. Such regional patterns have generated particular types of loess, for example the cases in Ecuador and Spain described in this article.

The Sahara is the world's largest area of contemporary dust storm activity. The Sahara system is a special case as it integrates two or more of the above types of dust transport forming a complex system of dust movement. As a consequence, the Sahara exports its aerosols to Europe in the north, to North and South America in the west, as well as to Central Asia and Equatorial Africa, i.e. over an area that covers 25% of the Earth's surface.

According to TOMS data (Total Ozone Mapping Spectrometer), the material in the world`s four most important dust deposits (Sahara, Arabia, China, and Thar) originates from the Sahara region. Thus, 200 million tons of Saharan dust are deposited annually in the Caribbean (Shlatter, 1995). The most important source area of Saharan dust is the Bodélé Depression between Tibesti and Lake Chad. Saharan dust sediments precipitated over Southern Europe have been reported by Bücher and Lucas (1984), among others.

3.4. Subaereal sedimentation of dust

The accumulation of silt particles on subaereal surfaces is a necessary condition in all definitions of loess. Tsoar and Pye (1987) indicate that there is a critical rate of deposition of dust in order to accumulate as loess (0.5 mm/yr); below this critical value, all the deposited dust is mixed into the soil by bioturbation and leaching by rain.

Two basic mechanisms of sedimentation were observed in eolian dust: one induced by rain, the other by *Gramineae* and other grasses acting as sediment traps. The former is the most frequently observed, although loess deposits primarily form as a result of sediment-trapping.

The accumulation mechanism is most effective when the dust particles reach areas covered by grass. Wind speed and turbulence cease almost completely in the interior of the foliage, i.e. near its surface, several decimeters above the ground. The suspended particles are trapped and accumulate on the surface. Accumulation rates have rarely been estimated; in extreme cases the rates range from 740 to 1640 kg/ha/yr (Herrmann et al., 1996), which results in accumulation of about 8 cm/1000 yr, a figure acceptable for several Pleistocene loess deposits in South America. Some of the typical characteristics of most loess, such as high porosity and collapsibility, suggest that this is the main mechanism of accumulation. Also, Tsoar and Pye (1987) state that, in a global context, the absence of more widespread peridesertic loess is largely due to a lack of adequate vegetation traps for dust.

The particles of atmospheric dust act as nucleii for the condensation of water vapor, forming rain droplets. It is a widely observed phenomenon, which has been registered and studied in the Mediterranean countries of Europe (Bücher, 1989) where "dirty rain" occurs. Also, wet deposition is produced by incorporation of dust into rain droplets during precipitation events.

According to field observations and palynological registers, regions most prone to accumulate dust are large grass biomes: steppe, savanna and prairie. Besides the existence of efficient sediment traps formed by the grass, the climate in such regions has a marked seasonality with clearly defined dry and humid periods, thereby favoring both transport and sedimentation of silt.

3.5. Weak epigenesis

There is general agreement among specialists that loess is not simply an accumulation of loose silt, but a deposit with a particular degree of cohesion and a (very open) texture. Relevant field features such as the aptitude to form stable vertical cliffs and large sub-vertical fissures derive from a weak cementation. Such a cementation is produced by precipitation of dissolved salts during the infiltration of water into the soil down to the water table. This process incorporates several field diagnostic characteristics of loess such as vertical disjunction, friability, vertical slopes in outcrops, subfusion, and others.

The most common dissolved salts are bicarbonates, ferric hydroxides and silica. Each of these is mobilized and precipitated within a specific climatic regime determined by the annual precipitation. In that particular interval of precipitation, the mineral precipitates are re-dissolved and eventually again precipitated. The general movement of water in this process is vertical, infiltration to the phreatic level, and capillary rise to evaporation. The result is the generation of weak cohesion and the appearance of vertical structures in loess. The dynamics

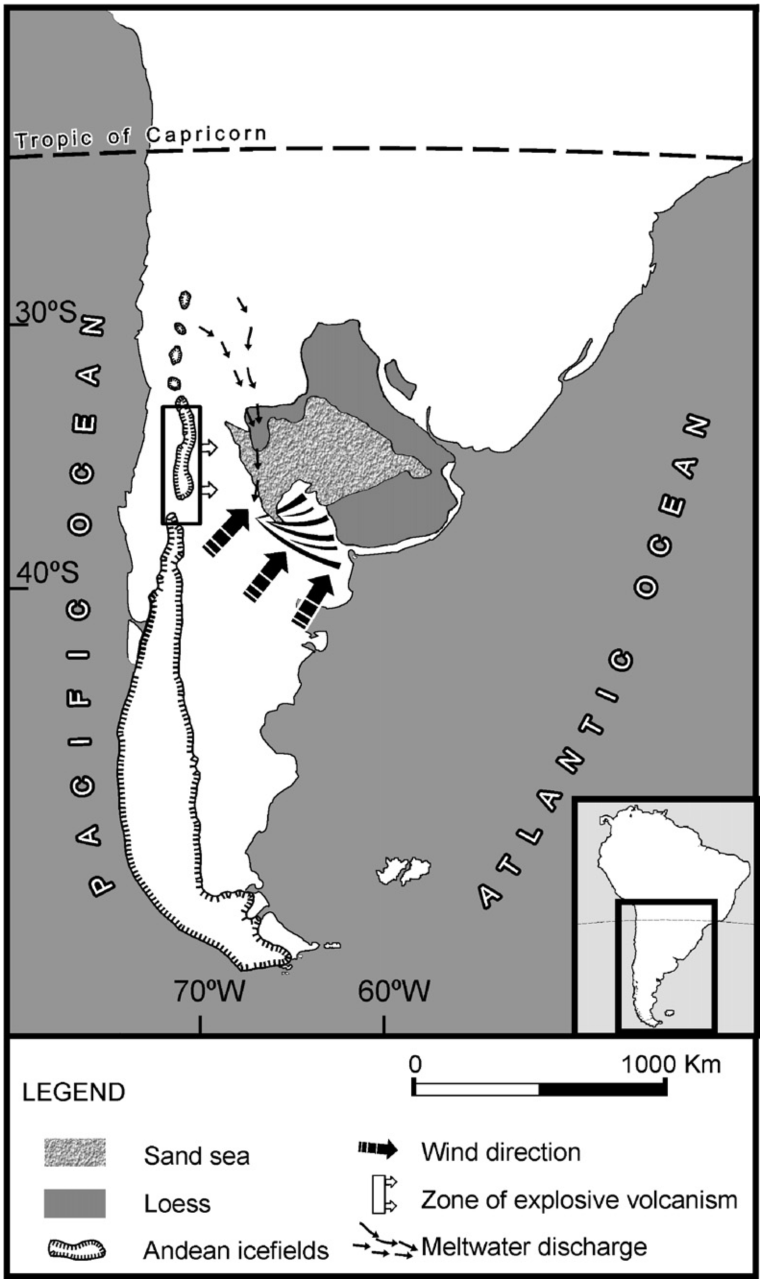

Fig. 1. General pattern of the Pampean Eolian System during the Last Glacial Maximum (after Iriondo, 1988).

of carbonates dominates in semiarid climates (300–700 mm/yr); the generalized mobilization of iron occurs under savanna climates (more than 2000 mm/yr of precipitation and above 20 °C air temperature (Maignien, 1964); silica is dissolved under humid hot climates (Chalcraft and Pye, 1984). Gypsum can be the cementing mineral in deserts, with precipitations under 300 mm/yr. An excess of cementing minerals frequently segregates by the formation of centimeter-long concretions and nodules.

4. The typical loess of South America

The Pampean Eolian System is the most representative Quaternary eolian system of South America, covering more than 600,000 km^2 in the central Argentine plains. Its northern part comprises a loess belt, 2000 km long and a mean width of 300 km, that borders a large sand sea to the southwest (Fig. 1; Iriondo, 1988). The Pampean loess is the most widespread of the Southern

Hemisphere and, according to recent research (Kröhling, 2003), is among the thickest loess deposits in the world.

According to Iriondo (1987, 1988), the Pampean Eolian System evolved during the Last Glacial Maximum. The Andean Cordillera ice-field covered a large area south of 28°S, allowing a strong influence of the South Pacific anticyclone and producing katabatic winds blowing to the NNE. The primary source of the eolian materials of the LGM loess are silt, clay and very fine sand generated by physical weathering in a periglacial environment in the Andean Cordillera north of 28° S. These materials were transported by meltwaters to the south along the Cordilleran piedmont by the Bermejo–Desaguadero–Salado fluvial system. This fluvial basin covers 248,000 km^2 in western Argentina from 28°30′ to 37°30′ S and is fed by major Cordilleran tributaries draining substantial periglacial areas in their Andean source regions, which are composed of Tertiary volcanic rocks. Their products, originating from seasonal discharges and accumulated in moraines and large piedmont fans, are rich in silt and fine sand fractions.

Significant volumes of sediments were accumulated in wide floodplains at latitudes of 37° to 38° S. Such deposits, transported and accumulated by glacio-fluvial systems, constitute the direct source of fine sediments, which were deflated by SSW winds blowing from the North Patagonian icefield. In that region, located near the northern border of Patagonia, strong gradient winds transported sand by saltation and surface creep on the plains more affected by a cold desert environment to form an extensive sand sea. The longitudinal dune fields show an anticlockwise deviation, coherent with the anticyclonic main circulation. More to the northeast, the climate was peridesertic, promoting sedimentation of windblown dust in a steppe environment to form the loess mantle. Approximately 300 km farther to the northeast (south of Chaco region), the typical loess grades into a loessic fringe deposit, sedimented in swampy environments under a sub-humid climate.

Extensive stratigraphic, granulometric and mineralogic studies of the LGM loess were performed on the North Pampa (e.g. Iriondo, 1997; Kröhling, 1999; Kemp et al., 2004; Kröhling and Iriondo, 2003). The loess unit, 6 to 10 m thick on average, is a silty loam deposit, light brown in color (7.5YR 6/4), which is homogeneous, porous, friable, and has frequent segregations of $CaCO_3$. It has stable steep walls which, in part, are altered by subcutaneous subfusion and shaped by columnar disjunction.

The mineralogic composition of the very-fine sand fraction is dominated by three forms of quartz (polycrystalline, micro-agglomerates, and monocrystalline quartz), with acidic volcanic glass, volcanic lithics, and plagioclases as accessories. The silt fraction is predominantly composed of quartz with feldspars as a minor component. Illite is the dominant clay mineral. The minerals constitute a mixture of two different sources. The main mineralogical association is represented by Andean volcaniclastic materials, with a secondary source derived from the crystalline basement of the Pampa Ranges. Volcanic ashfall sources are subordinate. The presence of micro-agglomerates of silt particles forming fine sand clasts in the Pampean loess has been cited by us and also other authors. Kemp et al. (2004) described micro-morphological features of the LGM loess of the North Pampa and referred to the occurrence of rounded "embedded aggregates", suggesting a faunal origin.

Kröhling and Orfeo (2002) deduced from detailed sedimentological analysis in the LGM of the North Pampa, that the loess mainly originated from eolian suspension, which represents 70 to 90% of the identified transport. This dominant mechanism transported the fine sediments over distances of 700 to 1100 km from their source area. The data indicate that between 22 to 58% of the material were mobilized in dust storms, composed of particles with diameters smaller than fine silt (<16 μm), and were transported by long-term suspension (cf. Tsoar and Pye, 1987). Short-term suspension involved coarse/mean silt (63–16 μm), which is present in variable proportions of 37 to 60%.

A research borehole, drilled by the authors in a relatively elevated flat area of the North Pampa (covering 17,800 km^2), showed that this area only experienced eolian influence during the Quaternary. The borehole revealed 54 m of typical loess which begins at the surface. A Quaternary paludal clayey unit (between 54 and 60.3 m depths) separates the loess from a Miocene littoral unit. The thick loessic profile consists of three primary (not reworked) loess units and is predominantly composed of silt with scarce fine sand and abundant segregations of $CaCO_3$, light brown in color (Kröhling, 2003).

5. Some cases of non-classical loess in South America

The following non-classical types of loess in South America comply with the accepted loess definitions and share the most important field characteristics:

5.1. The tropical loess

Eolian fine-grained sedimentary deposits, dark red in color and bounded at the base by erosive discordances,

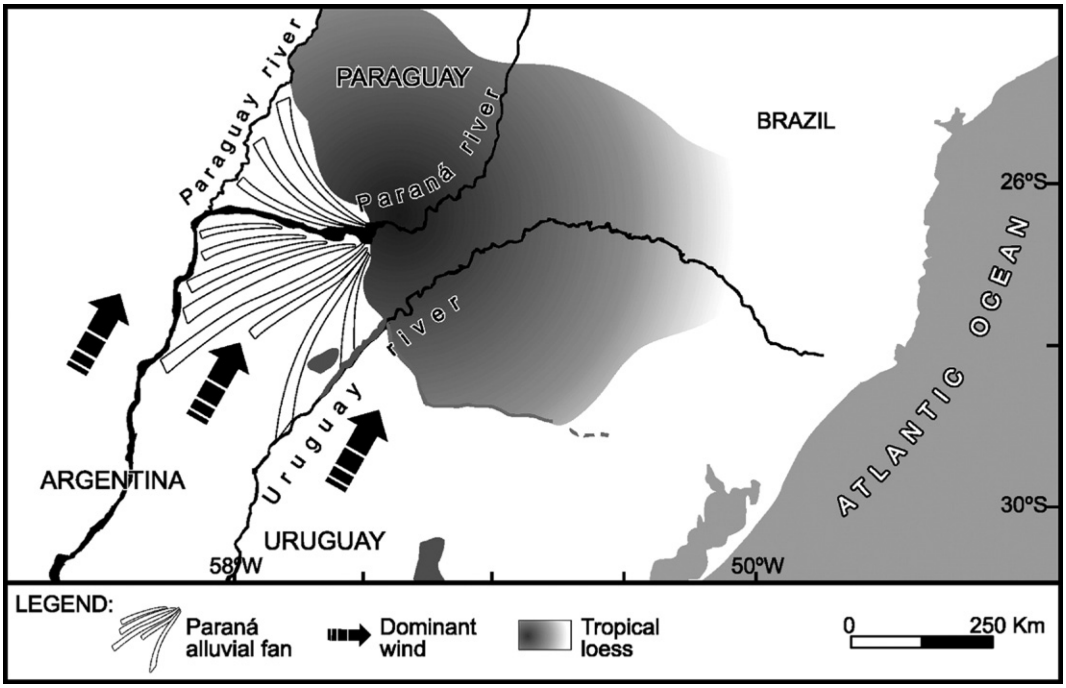

Fig. 2. Formation of tropical loess in Northeastern Argentina and neighboring regions (modified after Iriondo and Kröhling, 1997).

mantle the landscape of large areas in tropical South America (the hills of northeastern Argentina, southeastern Brazil, eastern Paraguay, northern Uruguay and the lowlands of Bolivia; Fig. 2). Such deposits were defined as "tropical loess" (Iriondo, 1996; Iriondo and Kröhling, 1997, 2001).

The field characteristics of the tropical loess are: loam to silty loam, powdery, friable, porous and massive with a dark red color (10R 3/6). It forms steep slopes in gullies with columnar disjunctions. It lies in an erosive unconformity on the Cretaceous basalts and sandstones, ferricretes and Tertiary rocks, and has a typical thickness between 3 and 8 m. The mobilization of iron is dominant throughout the profile. Fine to medium ferri-manganiferous concretions and nodules are frequent. Subfusion processes are frequent in some areas, for example in the Northwestern Paraná state of Brazil (Nóbrega, 2004).

The mineralogy of the modal sand fraction of the tropical loess in northeastern Argentina is dominated by subrounded to well rounded quartz, with scarce volcanic glass, alterites and amorphous silica. Heavy minerals of the very fine sand fraction is dominated by magnetite and ilmenite. The clay fraction is composed of kaolinite and quartz, with subordinate hematite and gibbsite. Grain-size and mineralogy indicate that the tropical loess was generated by the accumulation of silt-sized particles and aggregates mainly deflated from the alluvial plains of large rivers (Paraná, Paraguay and Uruguay) during the LGM (Iriondo et al., 1997). After the dust accumulation, a savanna environment established in the region, promoting the percolation of iron. A buried soil (Ultisol) is preserved in the middle section of the outcrops (Iriondo and Kröhling, 2004b).

Tropical loess has been included in the so-called "red earths", erroneously ascribed to other types of tropical products (such as laterites or colluvium). Nevertheless, an eolian origin for this type of deposit has been suggested earlier by some authors. Among them, Macar (1957) indicates a loessic origin for the fine-grained deposits of southeastern Brazil. For this region, Lichte and Behling (1999) postulated an allochthonous origin, with significant eolian participation, of the fine sediments mantling the top of the hills.

Tropical loess composed of particles of volcanic origin were found in the Amazonian lowlands of Ecuador and neighboring regions of Peru and Colombia. There, a layer of fine sediments, reddish ochre to yellowish ochre and brown in color, 1.5 to 4 m thick, covers a landscape of rounded hills, fluvial terraces and other geomorphological units in the form of a conspicuous mantle. Being composed of a mass of altered silicates and clays, with quartz and opaque minerals in the silt fraction, it correlates with the typical volcanic loess located in the Interandean Valley of Ecuador (Iriondo and Kröhling, 1997).

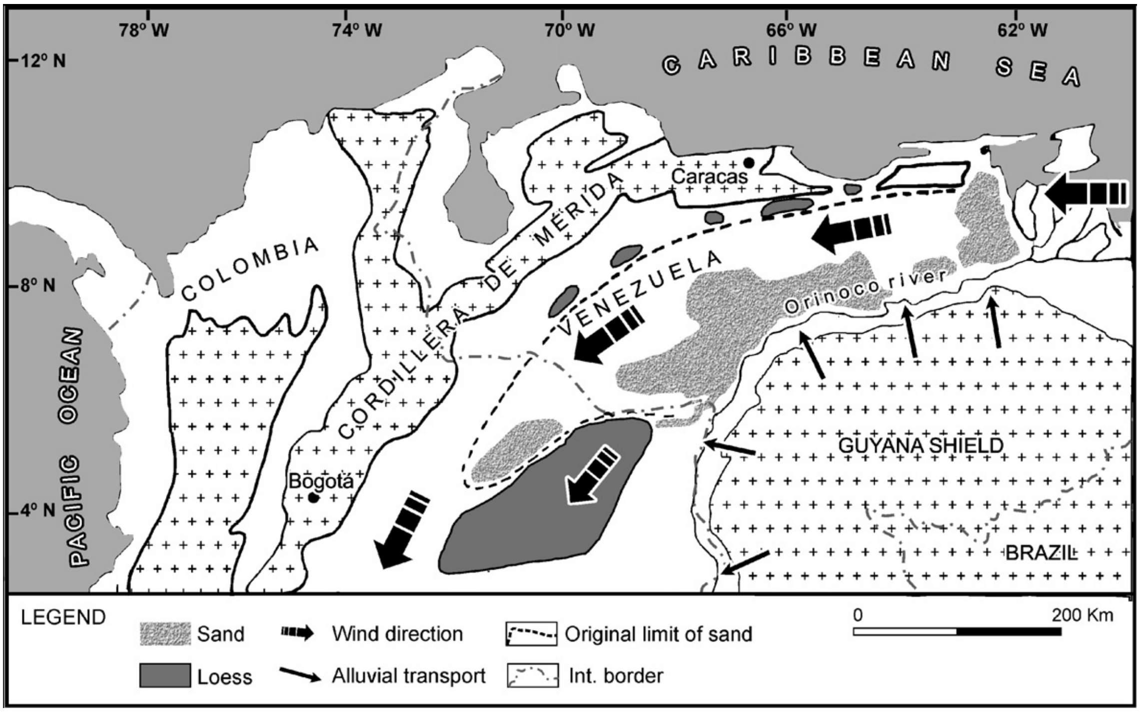

Fig. 3. Trade-wind eolian system in Northern South America (after Iriondo, 1997).

Continuous Holocene deposition of eolian dust has been registered along the coastal region of Brazil from 5° to 20°S and extending up to 300 km into the interior (Gouveia et al., 2002). The rate of accumulation ranges from 0.16 to 0.40 mm/yr, figures that are somewhat lower than the minimum sedimentation rates suggested by Tsoar and Pye (1987).

5.2. Trade-wind loess

Trade-winds are prominent components of the Global Circulation System of the atmosphere. In fact, trade winds are generated by the oceanic tropical anticyclones in their low-latitude sectors (Strahler and Strahler, 1979). Owing to the Coriolis force (which influences each Hemisphere in an opposite sense), trade winds blow in an east–west direction on both sides of the Equator, and thereby impinge on the eastern sides of the continents. In South America there are extensive deposits of loess generated by trade-winds. The North Trade-Winds, for example, are responsible for eolian deposition in the Orinoco valley of Colombia and Venezuela (Iriondo, 1999c).

The Los Llanos is a tectonic depression located between the Andean Cordillera and the Guyana Shield in Venezuela and Colombia, covering approximately 800,000 km^2. The climate of the region is dominated by the North Trade-Winds and by the north–south migration of the ITCZ. The Orinoco delta along the Atlantic coast and the central region of the depression are covered by large dune fields, which were interpreted as indicators of a past desert climate by Khobzy (1981), among other authors. The sands of the dune fields are very fine to fine-grained, being almost entirely composed of quartz grains. Geochemical studies indicate that the sediments were supplied from two areas: the Guyana Shield and the Atlantic coast, but not from the neighboring Cordillera. On the lee-side, and in contact with the sand field, a silt deposit is developed. This deposit, which mantles an area of 50,000 km^2 in the Colombian Llanos, was considered by Gossen (1971) to be a loess (Fig. 3).

The global importance of this type of loess lies in the permanent action of the trade-winds along a wide latitudinal front and in the oscillation of the ITCZ in the tropical belt. Trade-winds permanently blow into the Orinoco Llanos during the dry season of the year, directions being controlled by the main topographical features (cordillera and shield). They enter the region with strong force, crossing the Orinoco delta from east to west and shifting into the interior of the system towards the southwest. It is assumed that during the LGM these weather conditions were enhanced, thereby generating the eolian system, which comprises a main sand body with peripheral loess along frontal and lateral positions (Iriondo, 1997).

The loess is composed of an association of quartz and kaolinite. According to Gossen (1971), the grain size of the loess ranges from sandy loam near the Orinoco river to sandy clay loam along the southwestern fringe of the plains, with a predominance of loamy silt to silty loam, yellow in color (10YR 7/8); it is powdery, friable and structured in steep walls. The main epigenetic agent was iron hydroxide. In the lateral parts of the system, it occurs in discontinuous bodies 50 to 300 m long and 0.80 to 3 m thick in topographically protected locations of the "High Llanos". Vertical slopes with vertical disjunctions and small angular blocks of friable sandy loam are typical in that area. A torrential deposit formed by sandy gravel appears at the base. The sand fraction of the loess is dominated by very fine sand composed of very poorly rounded quartz grains, some of them broken. Some 15% of the grains consist of dark siliceous lithics of moderate roundness and with smooth surfaces. Between 5 and 10% of the grains are kaolinized feldspars. Fines form hard silt-sized agglomerates. Scarce and translucent limonite films cover the vertical fissures. The sediment mass is friable and powdery. Macropores are coarse and irregular, having formed during accumulation (not by roots), and action occupying 20 to 30% of the total volume.

Another case of non-classical loess in South America is generated by the action of the South Trade-Winds. It occurs in northeastern Brazil where a number of loess deposits were identified (Iriondo and Molinas, 2000). The South Trade-Winds reach the Brazilian northeast coast along a wide front between the latitudes of 5° and 17°S. The coast there is flanked by a wide belt of coastal dunes with a general tendency of westward migration. Two generations of dunes have been described in the region of Natal, located at the easternmost tip of South America. The older dunes, estimated to have an LGM age, are fixed by vegetation and are ochre in color, whereas the younger dunes (whitish in color) were mobilized in the late Holocene, and are at present not covered by vegetation (Passos Costa, 1980).

Iriondo and Molinas (2000) described two loess units in the interior, which correlate with the coastal sand dunes. The older deposit (Cariutaba Formation) is a dark red, friable, porous, powdery and massive tropical loess. The thickness varies between 1 and 6 m. It occurs in numerous localities of Ceará and Río Grande do Norte States. The Cariutaba Fm is composed of 95 to 99% quartz in the very fine sand fraction. Minor components are K-feldspars, lithics and heavy minerals. Kaolinite is the clay mineral present. In spite of its strong red color, the content of iron hydroxide is only 4%. The unit correlates with the older dunes of Natal. Thermoluminescence (TL) datings indicate ages of 21 ka BP at the base, and 9 ka BP at the top. According to the datings, the rate of accumulation is similar to that measured in Niger (Africa) by Herrmann et al. (1996), in the order of 20 centimeters per century.

The younger loess (Porteiras Formation) is light gray in color and occurs in association with patches of eolian fine sand. It is up to 3 m thick, loam to sandy loam in grain size, massive, powdery, friable, with vertical disjunction and subfusion processes. The quartz content is not as high as in the Cariutaba Fm, feldspars and mica being also present in substantial proportions. Clay minerals (kaolinite, montmorillonite and inter-stratified clays) have a low crystallinity. The cementation was produced by $CaCO_3$. Such features suggest a semiarid climate similar to the present one during the epigenesis. The age is late Holocene, with TL datings of 2 ka BP in different localities. It correlates with the younger dunes of Natal.

5.3. Volcanic loess

The origin of the silt particles in some loessic deposits is from explosive volcanism. Layers of cinerites and modest proportions of volcanic glass, and volcanic minerals, are widespread in many typical loess deposits. In some cases the presence of such components is important, as in certain areas of eastern Argentina and in volcanic regions, as for example the Central Valley of Chile, the Ecuadorian Andes or the Volcanic Belt of México where particles of pyroclastic origin are absolutely dominant. In this particular type of loess, rapid wind-driven accumulation must be assumed, because simple ash fall would have resulted in the formation of tephras.

Strong explosive volcanism under a montane climate produces a different type of loess. The "cangahua" of Ecuador is considered here as the best example of volcanic loess (Baldock, 1982). Field geologists working in the region have persistently compared this deposit with, or simply defined it as loess (Sauer, 1965; Clapperton, 1993). The cangahua is a loose ash deposit which was reworked by wind and fixed under a humid prairie climate, covering 20,000 km^2 of the Interandean Corridor and adjacent slopes in northern Ecuador and in southern Colombia (Iriondo, 1994; Fig. 4). It forms vertical slopes in gullies and valleys, shows scarce resistance to deep linear erosion and undergoes subfusion processes. Prismatic columnar jointing is common in outcrops. Typical thicknesses vary from 10 to 30 m.

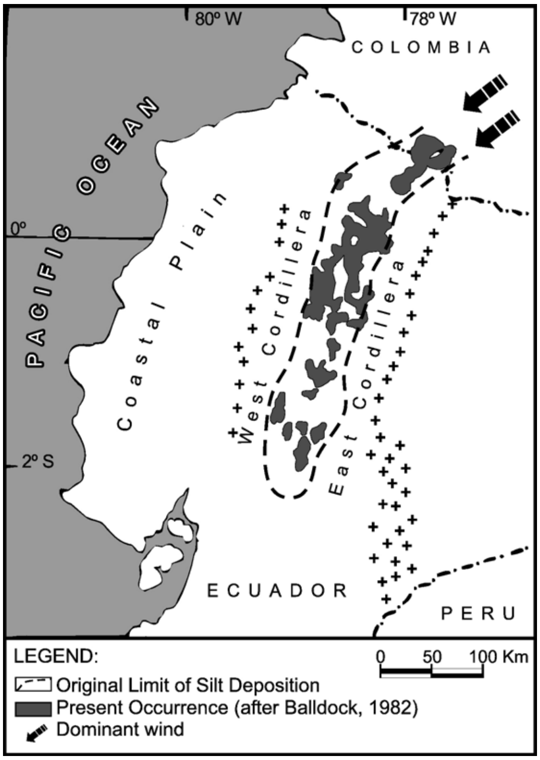

Fig. 4. Volcanic loess ("cangahua") in Ecuador (after Iriondo, 1994).

The sediment is formed by silt-and very fine sand-sized clasts, with a general andesitic composition (plagioclases, hornblende, augite and biotite, with scarce quartz; Clapperton, 1993). The color is gray to ochre and it shows a weak degree of cohesion produced by silica precipitates. The segregation of silica has also formed nodules and rounded large concretions dispersed in the sediment mass. Northerly winds forced by topography along the Interandean Corridor were responsible for the dispersion of particles. On the basis of ichnofossils of the beetle *Deltochinum deltipes* found in the deposit and segregations of limonite, a humid climate is assumed for the epigenesis.

There are probably other cases of this type of loess in Latin America. Specifically in the Central Valley of Chile all intergrades from volcanic ash, through retransported ash, up to non-volcanic sediments form the valley infill (Iriondo, 1999a). Preliminary observations made in the Volcanic Belt of Mexico by the authors of this paper resulted in the recognition of frequent loess-like profiles in vertical gullies, intercalated with particular cemented horizons locally named "tepetates". Furthermore, a pre-Quaternary loess has been described from northern Patagonia by Spalletti and Fiazzoni (1979).

5.4. Loess generated by continental anticyclones

Continental anticyclones strengthened and shifted towards the equator during the LGM, covering large areas of the southern continents (Preston-White and Tyson, 1993; Iriondo, 1999b), and favoring wind erosion and deposition. Another case, not linked to glaciation, has been described for a non-glacial condition in South America (Iriondo, 1990). This loess category has been named "desert loess" by colleagues working in North Africa.

In normal years at present, a seasonal anticyclonic structure occurs above the Bolivian High Plateau; in dry years this anticyclone grows strongly in size and reaches the land surface, covering a wide area of the Argentine plains and surrounding regions. According to measurements of paleowind directions, such a condition was the normal weather during the late Holocene between 3.5 ka BP and 1.4 ka BP (Fig. 5; Iriondo, 1997).

A mantle of eolian silt, 20–80 cm thick, occurs on the surface of the Pampa Plain of Argentina and in the Chaco Plain of Bolivia, Paraguay and Argentina, as well as surrounding regions of Brazil and Uruguay (1,600,000 km^2). It homogeneously covers the local forms of the landscape, being composed of coarse and medium silt, with minor contributions of clay and very fine sand. The deposit is loose, friable and porous, brownish gray in color (10YR 5/1), and moderately structured in very coarse prisms. The epigenetic agent is silica. Light minerals of the fine sand fraction are mainly quartz and plagioclases, with minor additions of volcanic glass and K-feldspars. According to the mineralogical indicators, the sediment has basically had local sources.

Scattered sand fields of the same age occur across this rather large area. The sand fields are characterized by parabolic dunes which, together with the orientation of elliptical deflation hollows in the loess area, provide robust indicators of paleowind directions. The geographic pattern of the paleowinds reveals an anticyclonic circulation 600–800 km in radius, which is typical for anticyclones of the Southern Hemisphere. This climatic structure was dominant during a dry period (basically warm and semiarid) in the late Holocene (Iriondo, 1990). The general distribution of isoplethic curves of both LGM loess and Late Holocene loess maps of the North Pampa demonstrate that the younger loessic unit was supplied by local sources (Kröhling, 1999).

6. A European case of non-classical loess

The geology of parts of northern Spain is characterized by a lack of silici-clastic rocks, being instead

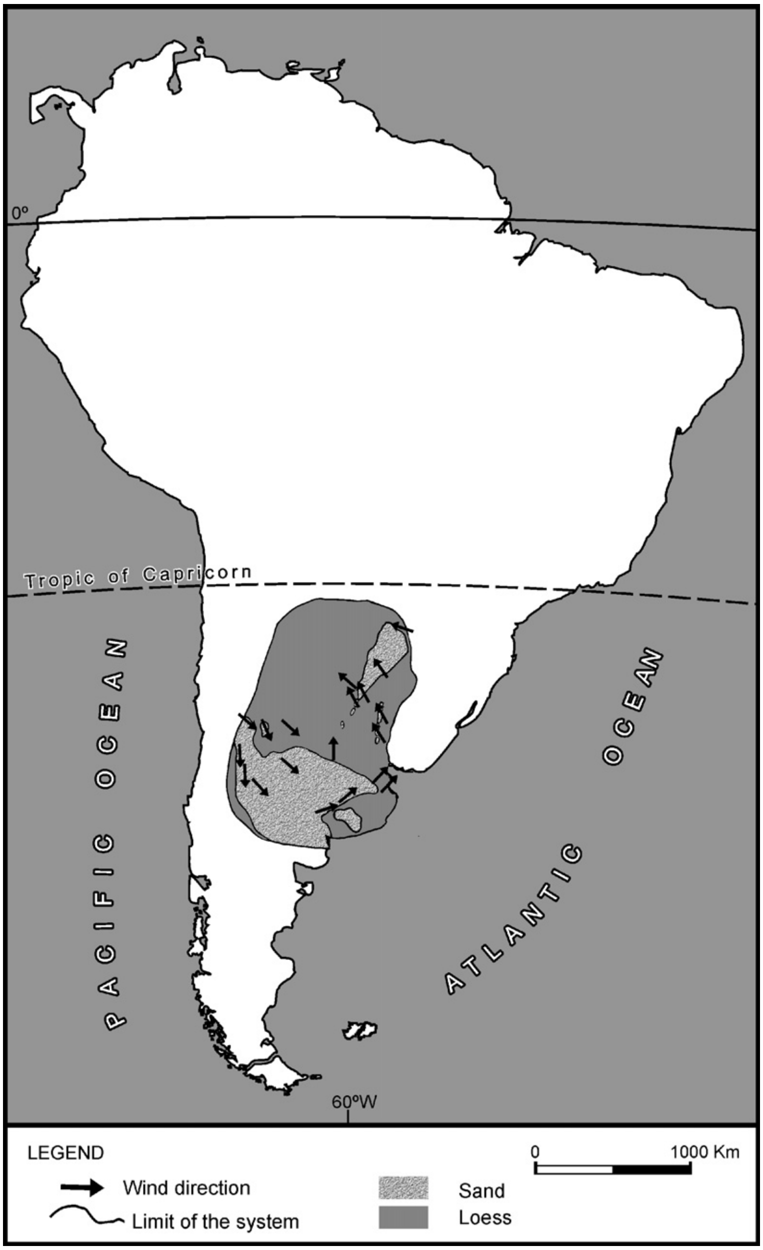

Fig. 5. Subtropical anticyclonic pattern of a Late Holocene eolian system in central Argentine and neighboring regions (after Iriondo, 1990).

dominated by gypsiferous Tertiary formations. The action of the former mentioned loess-forming factors in that region originated a fine eolian sediment which fulfill all the requirements of the definition of loess. Such a loess is mainly composed of silt-sized particles of anhydrite and gypsum. It occurs in the Ebro basin, which forms a wide eolian corridor linking the North Atlantic Ocean with the Mediterranean Sea (Fig. 6). The loess discontinuously covers Tertiary fluvial terraces, alluvial fans and glacis of the Ebro basin.

The sediment consists of silty loam, light yellowish brown to very pale brown in color (10YR 6/4 – 7/4), and is massive and friable. The loess has a typical thickness of 6 m, outcrops in steep profiles with vertical disjunctions and conspicuous subfusion holes. The segregated epigenetic mineral is gypsum, together with $CaCO_3$.

According to Iriondo and Kröhling (2004c), the mineralogic composition of the modal sand fraction of the loess (very fine sand) is represented by three different populations of anhydrite (typical anhydrite, a micro-

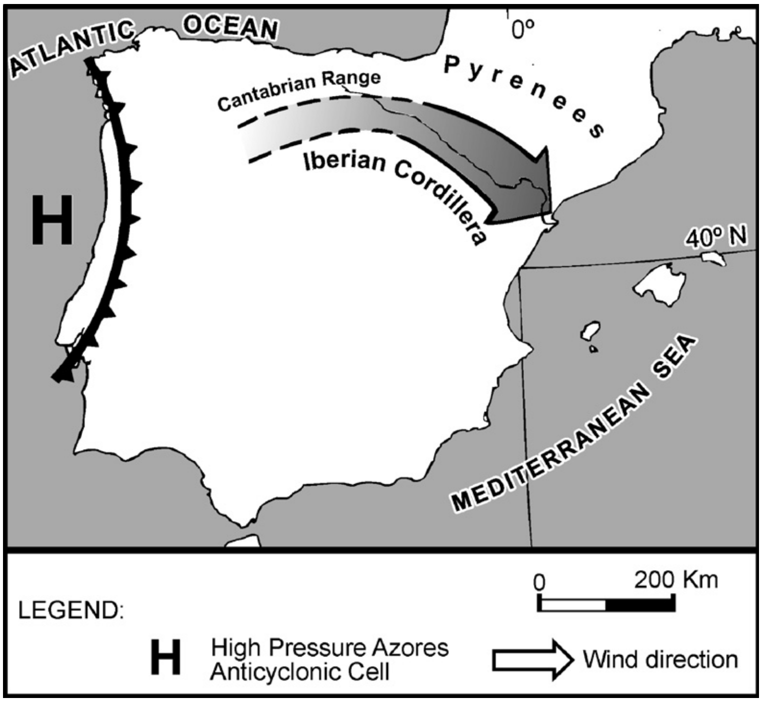

Fig. 6. Sketch of the wind circulation during the loess material sedimentation (the gray area indicates the region with scattered gypsiferous loess fields) (after Iriondo and Kröhling, 2004c).

cryptocrystalline variety, and anhydrite with significant alterations to gypsum) and gypsum, with quartz as accessory mineral. Gypsum and anhydrite grains are rounded to subrounded, with subordinate tabular clasts of gypsum with broken borders. The quartz grains are equant, rounded to subrounded and clean. Other mineralogical criteria also indicate that the gypsiferous formations dominating the area are the source of the clasts.

The probable scenario for the genesis of the loess is the following: Air masses derived from the Azores anticyclone generate a regional wind named "cierzo" after crossing the mountains in Northeastern Spain (Llaugé Dausá, 1986). This wind is dry and strong, and blows along the wide Ebro valley towards the Mediterranean Sea. The region crossed by the wind is a Cenozoic continental basin composed of thick layers of lacustrine gypsum and anhydrite formations. According to TL datings, the sedimentation of this loess occurred from 12 ka BP to 7 ka BP (late Pleistocene–early Holocene). These ages agree with C14 datings (12.15 ka BP and 6.12 ka BP) of sandy paleosols interbedded in eolian sands of the southern area of the Duero Tertiary Basin, located westward (Garcia Hidalgo et al., 2004). The wind influence under an expanded peri-saharian environment resulted in physical weathering of the gypsiferous sediments. Infiltration of water resulting from episodic rainfall events on a surface sparsely covered by Stipa hard grass caused the vertical mobilization of sulphates and carbonates under subtropical temperatures (Iriondo and Kröhling, 2004c).

Of particular interest here is the process of generation of silt-sized particles of anhydrite and gypsum by desertic physical weathering. The remainder of the sequential processes are "normal": dominant northwesterly wind action under a dry climate along an eolian corridor, and fixation of the particles by sparse vegetation.

In earlier papers, Llamas Madurga (1962), Torras Foulon and Riba Arderieu (1968), and van Zuidam (1980) deduced a possible eolian origin for the gypsiferous silty deposits of the central Ebro basin. Also, Brunnacker and Lozec (1969) suggested the importance of eolian processes in the generation of silty deposits in eastern Spain. A similar scenario as that proposed above was elaborated by Brosche and Walther (1977) for the origin of the silty sediments along the northern coast of Spain.

7. Discussion

The classical and generalized concept that loess is in all cases linked to glacial/cold weathering processes is not necessarily true. On the other hand, the definition of loess, simple and sound as it is, is also much more comprehensive. The accumulation of wind-borne materials produces loess deposits, which are described as structured loams or loamy silts. Different types of fine eolian sediments, which clearly belong to the definition of loess, can be found in several regions of the Earth. Their typical loessic characteristics, such as grain size, structures, subfusion properties, etc., are produced by agents homologous (but different) than those already described for North Eurasia and temperate North America. Various examples of loess deposits identified in South America such as "tropical loess", "volcanic loess", "trade-wind loess", "loess generated by continental anticyclones", include other scenarios. Therefore, it is indispensable to consider the sequence of processes necessary for the generation of loess besides the known frost/cathabatic wind/steppe process, but also the homologous conditions. The necessary sequence for loess generation is: a) production of silt particles, which can occur in explosive volcanism, formation of A-horizons in soils, rainforest weathering, nival processes and others, b) deflation and transportation of dust occur in periglacial environments, tropical deserts, flood-plains, dry lakes, etc., c) dust accumulation in steppes, savannas and other grass communities, and d) weak epigenesis produced by incomplete percolation of carbonates, iron hydroxides, anhydrite and similar salts. From a global view, the major conveyance systems of atmospheric dust are trade-winds, winter monsoons, continental anticyclones and regional mesoscale winds.

Although generally ignored by the mainstream of the loess community, isolated studies of loess not related with cold conditions are scattered in the international literature. Porter (1997) studied an important volcanic loess field located at the northwestern flank of the Mauna Kea volcano in Hawaii. Such sediment was already known and defined as loess by geologists (Porter, 1975; Wolfe et al., 1997 among others). Crossing the Atlantic, a number of papers written by different authors describe loess occurrences in Libya and Israel (Rathjens, 1928; Yaalon and Dan, 1974; Yaalon, 1987; Assallay et al., 1996), a general scenario that points to a large rotational system around the Eastern Sahara. The loess near the Western Sahara–Tunisia, Morocco, Canary Islands, Nigeria (see Coudé-Gaussen, 1987, 1991; Rognon and Coudé-Gaussen, 1987; Zöller et al., 2003; McTainsh, 1987) is probably linked to the Harmattan wind.

Another case, produced by a continental anticyclone, was studied in Australia by Hesse and McTainsh (2003). It is interesting to note here that these authors suggest implicitly that the study of the Australian loess has been hindered by the theory that this sediment is necessarily linked to a glacial source, something impossible in Australia. However, loess research is developing in that continent since Crocker (1946), who reported calcareous loess in South Australia, derived from deflation of extensive calcareous dunes and beach ridges that, in turn, were the result of deflation on the continental shelf exposed during low sea level stands. Clay rich, calcareous loess was identified by Butler (1956) at the inland basins of SE Australia. The author considered that the loess was derived by wind erosion of soils during arid climatic phases of Late Quaternary. Hesse and McTainsh (2003) cited several authors who reported loess deposits very similar to classical loess at the Eastern Highlands of Australia. According to the authors, the widespread gypseous and calcareous soils of the southern arid zone at the Inland ranges were identified by Jessup (1961) as being at least partly the result of several episodes of dust deposition. Bowler (1976) studied the dust paths in Australia, which are conveyed by easterly-moving frontal systems within the zonal westerly winds in the south and the easterly Trade-Winds in the north.

Other references on loess occurrences, a volcanic type in this case, were collected by Eden and Hammond (2003) for the North Island of New Zealand. In particular, Pullar (1967) considered it formed from the eolian reworking of tephra deposits. Pillans (1988) indicates that the yellowish brown loess of the North Island may consist of non-volcanic minerals with a weak structure. Also, Goudie et al. (2000) studied "desert loess" in the United Arab Emirates.

Hence, the general conclusion is that fine-grained eolian deposits not related with glaciations are common in all continents and authors with different backgrounds tend to name them "loess".

8. Conclusions

As a result of the above analysis, the following main conclusions can be drawn:

a) Eolian transport of fine sediment in suspension is a universal phenomenon, being particularly important in all dry climates. The accumulations of such material are named loess.
b) As a sediment, loess is a silt or loam of eolian origin deposited in subaerial environments.
c) The genesis of loess requires a succession of several specific mechanisms: generation of particles (several processes), deflation (physical and biological), eolian transport (long or short distances), accumulation (sediment traps or rain), and weak epigenesis by infiltration.
d) Besides the "classical loess" (silt/loam with carbonate linked to glacial processes), new loess types can

be defined by following the same rationale outlined above.

e) A preliminary list of other loess types in South America includes tropical loess, trade-wind loess, volcanic loess, and loess generated by continental anticyclones.

f) “New” types of loess cover large areas in South America and Europe: trade-wind deposits in Venezuela, Colombia, and Brazil; tropical loess in Argentina, Brazil, and Uruguay; loess sedimented by tropical – subtropical anticyclones in Argentina; volcanic loess in Ecuador; and gypsiferous loess in Spain. The last two cases are associated with mesoscale regional winds.

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