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The continental Uruguayan Cenozoic: an overview

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Abstract

Although Quaternary study in Uruguay was started in the 1970s, international diffusion of the results has been limited. This contribution is an updating of the continental aeolian and fluvial Cenozoic period, reinterpreted mostly from a geomorphological perspective. We discuss the limitations in the usage of chronostratigraphic generalizations in the Cenozoic based on a lithostratigraphic interpretation. The upper Pleistocene and the Holocene are reinterpreted through available ^{14}C dates, presenting a comparative preliminary table with the geological formations found in the neighbouring Argentine Provinces of Entre Ríos and Corrientes. © 2000 Elsevier Science Ltd and INQUA. All rights reserved.

1. Introduction

A substantial amount of the past research concerning the Uruguayan Quaternary was carried out in the 1960s, in conjunction with the preparation of an edition of the soil map of Uruguay (Dirección de Suelos y Fertilizantes, 1976), by a multidisciplinary team of pedologists, geologists and geomorphologists based in the Ministry of Agriculture and Fisheries, the University of Uruguay and the collaboration of the ORSTOM (France). The work scales were 1 : 20,000 and 1 : 40,000. This multidisciplinary approach proved to be highly effective in the preparation of the soil map of the country but demonstrably suffered from an excessive reliance on lithological criteria at the expense of genetic approaches and other suitable criteria in the definition and accurate mapping of Cenozoic chronostratigraphic units. Nevertheless, it provided the basis for the development of a widely accepted model for the evolution of the Uruguayan Quaternary (Antón and Goso, 1974; Antón, 1975; Goso, 1985, 1986; Panario, 1988), which is still in use. Since that time, little progress was made concerning Uruguayan Quaternary stratigraphy.

2. Quaternary landscape evolution

2.1. Landscape control

The stratigraphic analysis of the Uruguayan Quaternary requires a combined lithostratigraphic-geomorphological approach. In essence this occurs because: (a) Quaternary erosion in Uruguay resulted in the development of stepped surfaces in areas with high morphogenetic potential; and (b) these surfaces were covered by Quaternary loess deposits in such a way that, at present, the early deposits occur in interfluvial areas (sometimes covered by new ones) while the late deposits, which often incorporate reworked earlier loess, preferentially occur in topographic lows. In contrast, the Quaternary loess deposits in areas with little or no morphogenetic potential (as exemplified by the Argentinean Pampas) form a virtually undisturbed layered sequence that shows little or no evidence of internal reworking and can easily be cross-correlated from area to area. In fact, what all this means is that the study of the Quaternary stratigraphy of Uruguay requires a careful consideration of the geomorphological evolution of the Uruguayan landscape during Cenozoic times.

2.2. The origin of landforms

The origin and development of the main geomorphological features of Uruguay can be traced back to Eocene times (Fig. 1). A widespread Cenozoic planation of the Uruguayan landscape was possible under the

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warm and humid Eocene climate, with deep weathering accompanied by oxisol development and ferricrete formation (Table 1). Eocene ferricretes are known to occur in association with Cretaceous and Precambrian rocks in Uruguay, on basaltic rocks in Corrientes and Misiones in Argentina, and according to Becker (1992) in South Africa (the latter of which presumably had in Eocene times the same climate as Río de la Plata basin). In Uruguay, they also appear as isolated boulders in Jurassic sandstones. Oligocene erosion of the Eocene soils under generally arid conditions resulted in the deposition of alluvial fans of plintite cobbles (Ford, 1988), which pass upwards through a decimetric transition zone into the loess-dominated Fray Bentos Formation (defined by Bossi, 1966) of Oligocene age.

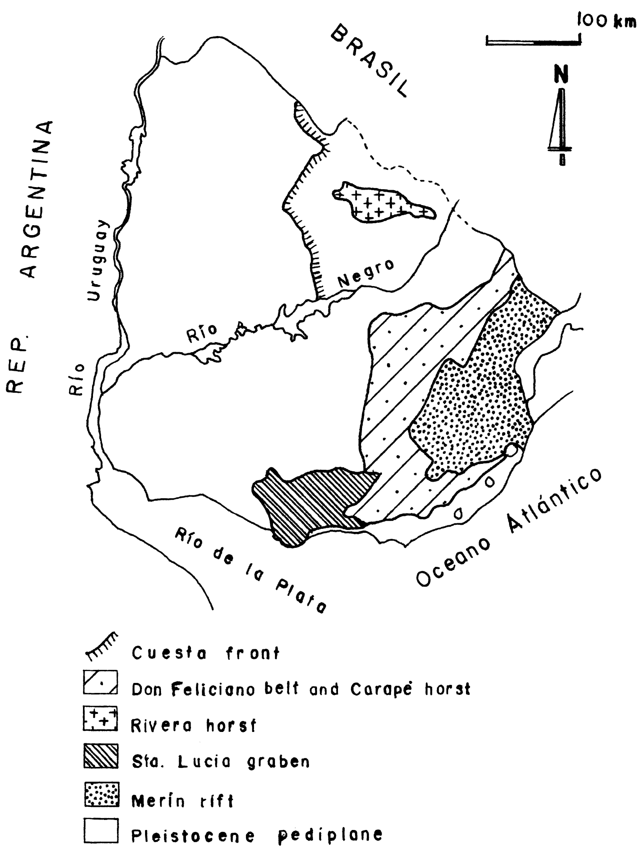

Fig. 1. The main morphostructural features of Uruguay include: the mound and hills systems associated with the Don Feliciano belt and the Carapé horst; the Rivera horst; the basaltic cuesta front; the Cretaceous-Pleistocene Santa Lucia graben; and the Cretaceous-Holocene Merín rift.

In essence, the Oligocene erosion processes were facilitated by the deep Eocene weathering and resulted in the development of extensive planation surfaces in metamorphic, igneous and sedimentary domains. Pliocene erosion, again under generally arid conditions, resulted in the formation of coarse braided river deposits (Raigón Formation; Goso, 1964 in Goso and Bossi, 1966), alluvial fans (Malvín Formation, Antón and Prost, 1974) and probably the Salto Formation (Walther, 1930) associated with the Uruguay River as well as other fluvial sediments in southwest Uruguay comparable to the Ituzaingó Formation defined by De Alba in Argentina (Kröhling and Iriondo, 1998). In the rest of the pedimented landscape a line of cobbles covers the Oligocene erosion surfaces and in places marks the base of the continental aeolian Quaternary sediments of the Libertad I Formation (defined by Goso and Bossi, 1966).

During Quaternary times, humid conditions associated with transgressive periods favoured the dissection of old surfaces while cold and dry conditions associated with regressive periods promoted the formation of new surfaces at lower topographic levels. This resulted in the development of a stepped landscape in which (a) the old surfaces are the highest and contain the early aeolian deposits (which when lying on sufficiently large old surfaces could be buried by late aeolian deposits and

Table 1
Cenozoic correlations, Uruguay — Entre Ríos and Corrientes (Rep. Argentina)

		Slope domain	Fluvial domain	Correlation with Entre Ríos and Corrientes (Rep. Argentina)
Holocene	4000	Aeolian dunes		
	5000	Soils	Meanders	
Pleistocene	Later	Hills slope, loess deposition	Dolores-Sopas Formation	Terraces
		Paso Perico Formation		El Palmar Formation
	Middle	Libertad II Formation (↑?) — Bellaco Formation		Hernandarias Formation
	Early	Libertad I Formation		Alvear Formation
Pliocene		Malvín Formation	Raigón Formation — Salto Formation	Salto Chico Formation — Ituzaingó Formation
Miocene				
Oligocene		Fray Bentos Formation		Fray Bentos Formation
Eocene		Ferricretes Formation		Ferricretes Formation

associated ash falls), and (b) the new surfaces are the lowest and contain reworked early aeolian material, late aeolian material and volcanic ashes, and local rock scree derived from escarpments and slopes (Fig. 2).

2.3. Continental deposits

As mentioned above, the Plio-Pleistocene continental deposits are braided river sediments and alluvial fans. Some of these rivers have been functional from the Pliocene until today (as has the Paraná River, Iriondo, 1987). Others were functional only during the Pliocene, yielding the deposits of the Raigón Formation or the fans of the Malvín Formation. Also, all intermediate situations can be observed. Hence, Quaternarists have had difficulties in agreeing about the age of rivers deposits in the late Cenozoic period.

Besides, the emphasis in lithological definition of deposits becomes an additional source of mistakes, because rivers under similar climatic and energy conditions produce similar sediments, with identical colours and lithology, in different geological times.

When Bossi and Navarro (1988) discuss the Raigón Formation (Pliocene) and identify the different situations in which it appears, one of these represents terraces from the Later Pleistocene (Fig. 3) associated with the present

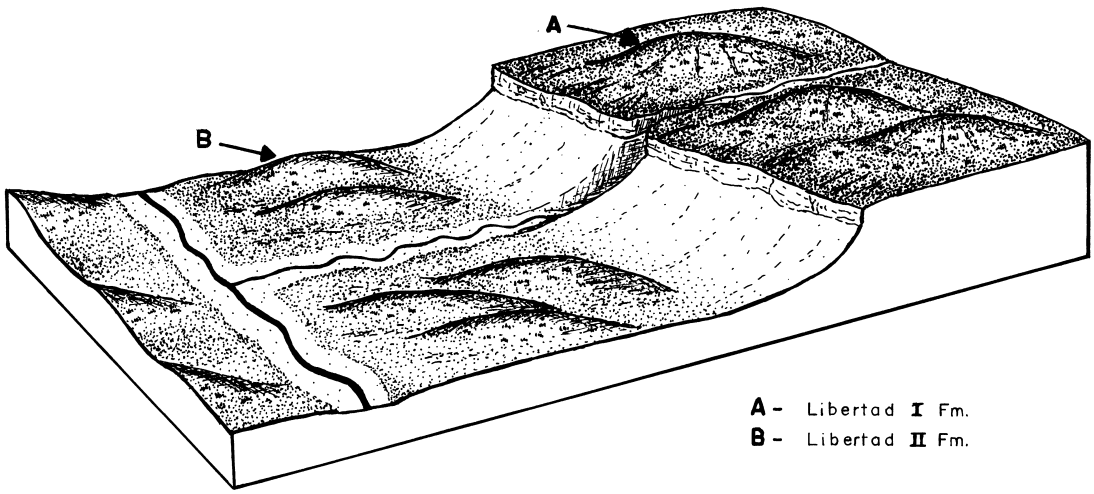

Fig. 2. Schematic representation of the situation of the loessic depositional events, Libertad Formation.

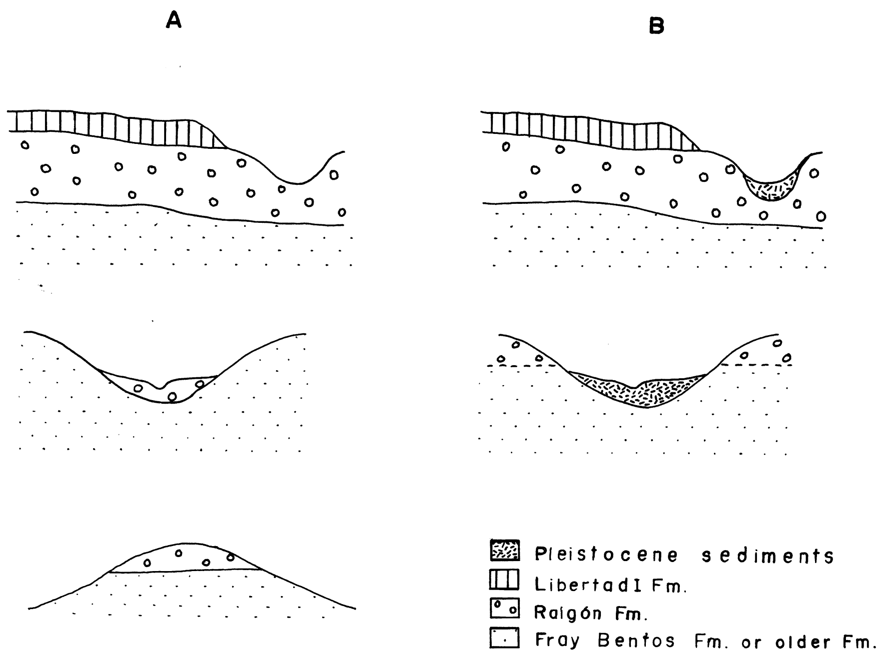

Fig. 3. Stratigraphic interpretations: (A) Bossi and Navarro (1988, Fig. 16.16, p. 848); (B) this paper.

streams. Such is the case of the valley of Arroyo Tarariras, incised in Oligocene deposits. This is the reason why the sediments were considered by them to be of Pliocene age instead of an upper Pleistocene structurally preserved terrace.

It is clear that during all the Quaternary glaciations, climate was cold and more arid than today in Uruguay, but not dry enough to prevent the rivers from flowing during at least sporadic rainfalls. Therefore during all the glacial periods, braided rivers and small alluvial fans produced coarse continental deposits. In the case of small basins, where local material was reworked, it is frequently difficult to discriminate between the reworked and original material.

An extreme example is the 'Oligocene' Fray Bentos Formation, defined in a cliff near the city of Fray Bentos. Within a few meters distance from the type section, sediment clearly identified as a Pleistocene marine deposit containing *Erodona* sp. is interbedded in the lower third of the cliff. A more detailed analysis indicates that the upper section is composed of rounded Fray Bentos loess cobbles in a loessic matrix. This leads to the conclusion that a significant part of the mapped Fray Bentos superficial geological unit is of Upper Pleistocene age, and sediments exposed on the highest surfaces are Lower Pleistocene. The last example of this argument is the case of calcretes crowning the Fray Bentos surface. Formation of this calcrete probably took place in the Early Pleistocene, as suggested by similar processes evident in the Libertad I Formation and, according to Iriondo (1980), in the Alvear Formation (defined by De Alba, 1953, in Herbst, 1971) in Entre Ríos, Argentina.

2.4. Fluvial deposits

Pliocene fluvial deposits (Salto Formation and Raigón Formation), according to sedimentological and palaeontological evidence, are generally coarse and appear in Cenozoic sedimentary basins discordantly overlying Late Miocene marine sediments (Camacho Formation defined by Bossi, 1966), which in turn lie on Oligocene aeolian deposits (Fray Bentos Formation). In the north, deposits of the Uruguay River were separated topographically as the landscape was carved by the river, since the Pliocene (Salto Formation). In the southwest, the same river generated a sequence which probably includes Pliocene sediments at the base and presumed Pleistocene sediments at the top, coloured red due to their origin mostly from the upper basin (a tropical region). The fluvial deposits of this period originating in local basins are generally coarse sediments of braided rivers, and light-brownish and greyish clay from lagoons. Therefore, they are clearly linkable to arid and semiarid climatic conditions. In the downslope area of the Don Feliciano belt, and particularly in Las Animas mounds, continental deposits formed alluvial fans (Malvín Formation) in the Pliocene (Prost, 1982a,b) (Fig. 4).

It is really difficult to establish the chronostratigraphy of Uruguayan Quaternary fluvial sediments without the support of absolute dating techniques. When rivers flowed in the same valley during different geological ages, there are two possibilities: (a) the river deposited material over material in a vertical sequence of layers, as is usual in active rifts; or (b) it shaped a system of stepped terraces, not always well-defined, as can be observed along the rivers Uruguay and Negro. There are two different explanations for the sequences of these deposits. The first (a) suggests the existence of negative tectonic actions (e.g. subsidence). The second (b) implies that during different ages the river had similar depositional patterns, producing stepped terraces in the bed forming processes, which can happen with or without the help of positive tectonic activity (uplift).

Fig. 4. Alluvial fans of the Malvín Formation, Solis de Mataojo (modified from Prost, 1982b).

Near the Uruguay and Negro confluence, the Salto Formation (Preciozzi et al., 1980) appears partially covered by smectitic clays (with gypsum) from the Bellaco Formation (defined by Bossi and Navarro, 1988). This is, as a whole, similar to the Hernandarias Formation (defined by Iriondo, 1980) of Middle Pleistocene age: 0.8 to 1.3 Ma (Bidegain, 1991 in Iriondo, 1996). In this particular case, the sandy materials attributed to the Salto Formation may belong to a second level of the Middle Pleistocene (or earlier) river terraces. Consequently, they are younger than the Salto Formation, or they may have been deposited during the Pliocene, lowered by neotectonics and later covered during the Pleistocene (Fig. 5).

We prefer to attribute the aforementioned fluvial sandy deposits to the Middle or Early Pleistocene, and therefore they would not be equivalent to the Salto Formation as discussed by Bossi and Navarro (1988). Generally, Pliocene alluvial deposits (Salto Formation and Raigón Formation) have not been preserved as morphogenetic structures, and usually appear in the upper part of the highest hills, normally linked to the major rivers (except when related to subsidence zones).

Summing up, not all fluvial sediments which cover Pliocene channels in Uruguay are of that age, since the channels could have been functional during more than one period until they were filled. The Negro River valley and surrounding areas preserve sufficiently complete geomorphological and sedimentological evidence to contribute to an understanding of the evolution of the large rivers of this region since the Pliocene.

2.4.1. Upper terraces

The oldest fluvial deposits of the Negro River (Pliocene) appear at the top of the hills, covering the Fray Bentos Formation under a reworked Quaternary loess, which contains gravel and small rounded cobbles of basaltic origin at the base. In a topographically lower level, the oldest fluvial deposits (with a clearly preserved morphology) appear in the Negro River as sandy bars generally developed in the meandering concavities, 20 or 30 m above the present water level. We consider these deposits as fluvial sands from the Sangamonian period, due to their distribution which follows a more or less meandering pattern, typical of stable flows. This hypothesis is sustained furthermore by (a) the height of the terrace over the mean level of the present river; (b) the pedological development of a deep Ultisol with albic horizons, located under aeolian sand dunes resulting from reworking of part of A1-horizon of the soil; and (c) the mineral composition of the sand (dominance of quartz, secondary feldspar, and lack of dense minerals principally in the soil).

We formally propose here for this entire profile the name "*Paso Perico Formation*". These sediments appear in other rivers, but the Negro has great areas that can be expressed as geological units on maps at a 1 : 100,000 scale or even at smaller scales (Fig. 6).

The type section is located at the right margin of the Negro River, at both sides of the mouth of Arroyo Yapeyú. The succession involves:

- 0.00–1.50 m — A-horizon, sandy (medium-coarse sand) light reddish brown in colour (2.5YR 6/4 of the Munsell Table), in transition to a light grey horizon (A2);
- 1.50–2.10 m — B2-horizon, heavy sandy loam, red in colour (10R 4/8 of the Munsell Table);
- 2.10 m and below — Sandy sediment transition (coarse sand) light grey in colour (5YR 7/1 of the Munsell Table).

A thick sandy sediment with some cobbles and cross stratification lies at the bottom of the soil, as described by Ford et al. (1990) and Morales et al. (1990). Such a layer is characteristic of bar deposits of alluvial origin. These sediments discordantly overlie Tertiary, Cretaceous and

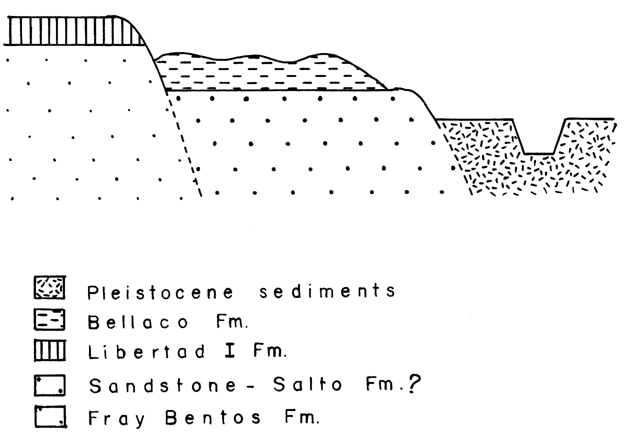

Fig. 5. Stratigraphy of the Cenozoic deposits at the confluence of the Negro and Uruguay Rivers.

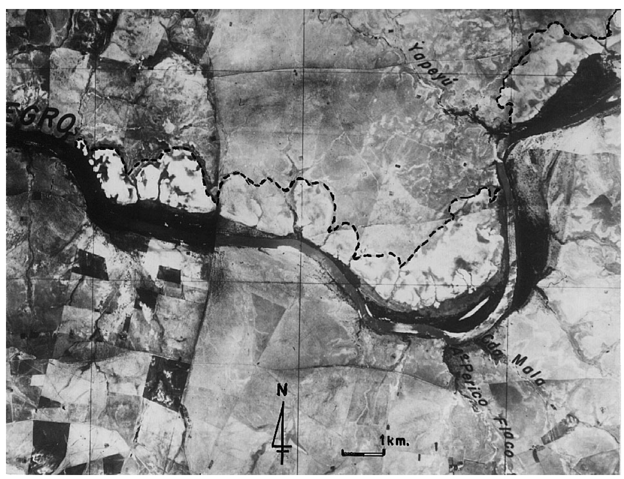

Fig. 6. Upper Pleistocene sandy sediments along the Negro River, Paso Perico Fm.

Precambrian rocks, amongst others, and in parts are more than 7 m thick.

2.4.2. Lower terraces

Sediments in the youngest terraces were defined as the Sopas Formation by Antón (1975) along the rivers of the basaltic area. Correlative terraces were assigned to the "Dolores Formation" along the Negro River (Goso, 1985). All loessic deposits at the bottom of the fluvial valleys, and the flat surfaces and their loessic accumulations of the Quaternary sedimentary basins have been mapped as Dolores Formation. This formation includes colluvial sediments located at the base of the slope, which formed gently sloping inclined plains and alluvial terraces during the Upper Pleistocene.

The Dolores-Sopas Formation includes two members. The basal member is composed of fluvial channel sediments, with included pebbles and cobbles. It is massive in parts, and is either clast-supported or supported by a matrix that can vary from pelitic to sandy. In other areas, basically in the lower course of rivers, it is muddy (reworked loess), more or less consolidated, and includes mastofauna and malacofauna. From the 14C dating reported by Ubilla (1996) for Later Pleistocene terraces we tentatively select only those corresponding to the range 43,000–45,000 BP as the minimum age of this terraces. The five chosen datings were made on wood (3) and shells (2).

The upper member is poorly consolidated, with evidence of pedogenesis, and contains mastofauna, calcareous concretions and, in some cases, calcareous crusts (calcretes). The upper member is a typical paleo-flood-plain deposit, developed under moderately dry climatic conditions and covered by tall grass, that frequently received and retained aeolian dust. Such an environment produced (at the top of the flood plain sediments) a soil in which the last remains of the Lujanense mastofauna frequently appear. Pedogenetic processes make it difficult to discriminate, in this member, the typical loess — directly brought by the wind — from loess reworked and incorporated by water in the flood plain. The available dates for the upper member of the terrace are listed in Table 2.

Table 2
^{14}C dates, upper member Sopas formation

Age (yr BP)	Dated material	Lab number
18,650 ± 160[a]	*Glyptodon* sp. (bones, mineral fraction)	URU-0035
16,460 ± 185[a]	*Cervidae* undetermined (humerus) (bones, mineral fraction)	GX-19272
12,100 ± 140[a]	Undetermined wood	LP-594
11,650 ± 130[a]	Wood (*Prosopis*?)	LP-509
11,200 ± 500[b]	Charcoal	GIF-4412

[a] Ubilla (1996).
[b] Guidon (1989).

During the Holocene, the lower terrace was cut by channels and gullies in different cyclical processes of cut-and-fill. There are two different types of channel sections and infilling processes, attributed to different Holocene ages:

(a) The first is a vertically graded sand deposit, dated from charcoal associated with human bonfires at 9890 ± 75 BP (Austral, 1994). It is covered by grey clays (representing channel abandonment), with medium size desiccation fissures at the top. Fissures are filled with aeolian sand blown from river bars, and are capped by a thin sand layer of similar origin. These sediments are covered by a black vertic soil developed in historical times, that contains remains of European fauna from the colonial period and therefore is younger than the time of cattle introduction in Uruguay, in A.D. 1611.

We estimate an age of around 4000 yr BP for the dry period which produced the desiccation fissures and allowed the transportation of aeolian sand. Calcium carbonate concretions in the north of the country have the same age (4280 ± 50 yr BP, URU-0054, Bracco et al., in press). This period can also be correlated with the time of formation of large dune fields at the Uruguayan coast, with a median grain size around 0.5 mm (1 ∅) (Panario and Piñeiro, 1997; Panario, in press). A 4200 ± 50 BP 14C date exists in this area (López and Iriarte, 1995) at the base of the aeolian deposits.

Channels of this fluvial system are filled by two types of sediment: reworked loess with interbedded laminated cinerite lenses, without clear evidence of pedogenic processes; and palaeosols and peat buried by reworked loessic sediments (Santa Lucia River). In one particular case, in the north of the country, a peat bog developed at the base of a tributary of the Uruguay was dated to 4020 ± 70 BP (URU-0079). The peat is covered by laminated ash lenses approximately 40 cm thick indicating aquatic transport, and by reworked loess. Within the loess, charcoal from human bonfires was 14-C dated at 3880 ± 80 BP (URU-0071) from another similar locality (Castiñeira, 1997).

(b) The second type of channel can be found in the same river and consists of meandering channels filled with black sandy clay deposits. The presence of mammalian bones of living species probably suggests a Hypsithermal age.

3. Quaternary loess

3.1. Origin and distribution

It is clear that the loess in Uruguay has the same origin as that from the Argentine Pampas (particularly that found in the provinces of Entre Ríos and Corrientes), although there are minor differences in grain size and mineralogy, reflecting variation in distance to source areas, climatic conditions at the site of deposition and

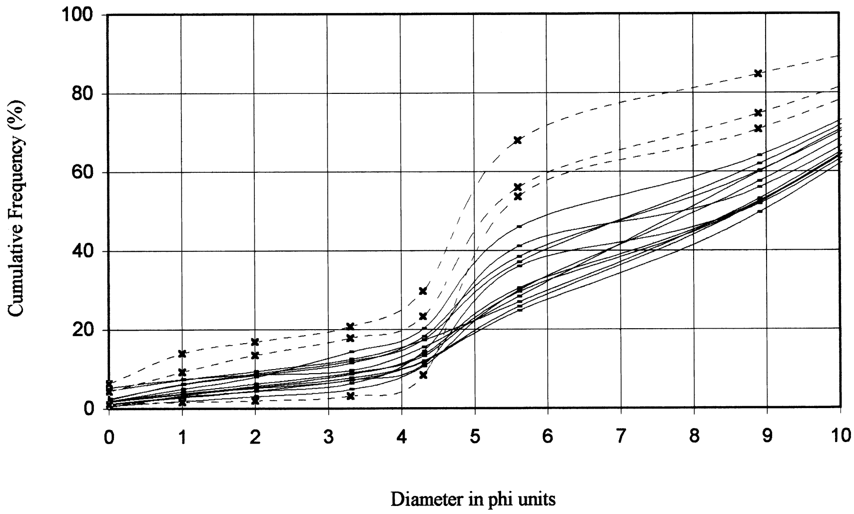

Fig. 7. Cumulative textural curves of loessic sediments, Libertad I Fm and Libertad II Fm. Samples were selected as representative of a total of 120, distributed over a wide geographic area. References: Libertad I Fm. (north and south of Uruguay); — Libertad II Fm. (all the distribution area, see Fig. 8).

its geomorphological potential (Fig. 7). The loess in Uruguay displays a fair degree of lateral variation in grain size and is largely represented by a 1–2 m thick mantle that covers most of the hills. In areas of enough geomorphological potential the thickness of the loess layer is broadly similar to that of the overlying soil layer. In some areas, especially in the south of the country, the loess forms a loessic Litosol (less than 30 cm thick) covering rocks of various ages. It has been included in soil maps but not in geological maps, owing to its small thickness.

The first map showing the distribution of loess in Uruguay was presented by Bossi et al. (1975, in Bossi and Navarro, 1988). A more refined map (Fig. 8) has been produced by including the silty calcimorphic soils (Cca-horizon), that are generally developed on loess and are mapped on the soil map of Uruguay (Dirección de Suelos y Fertilizantes, 1976).

There are two loessic formations, both misleadingly named Libertad: Libertad I Formation and Libertad II Formation. A Lower Pleistocene aeolian material (Libertad I Formation) is a more or less massive and normally strongly calcareous loess, which covers rocks of various ages and occurs on hilltops in stable landscapes. In the Cenozoic sedimentary basins close to the coast of the Rio de la Plata, it normally covers smectitic calcareous sediments lying on top of Pliocene alluvial sediments belonging to the Raigón Formation. According to Bossi and Navarro (1988), the Libertad I Formation is a porous, strongly carbonate, more or less massive loess, and containing illite as the dominant clay mineral. These parameters suggest deposition under dry and cold climatic conditions.

The Libertad II Formation (Goso, 1985) is comparatively enriched in clay minerals, notably montmorillonite. It is not more than 10 m thick, reworked by water, and contains prismatic soil structures, calcareous concretions, clay coats and other features indicative of leaching processes characteristic of B-horizons of soils. The lack of an A-horizon may reflect loess deposition at a rate sufficiently low to allow the evolution of the A-horizon into the B-horizon through eluviation from a new thin

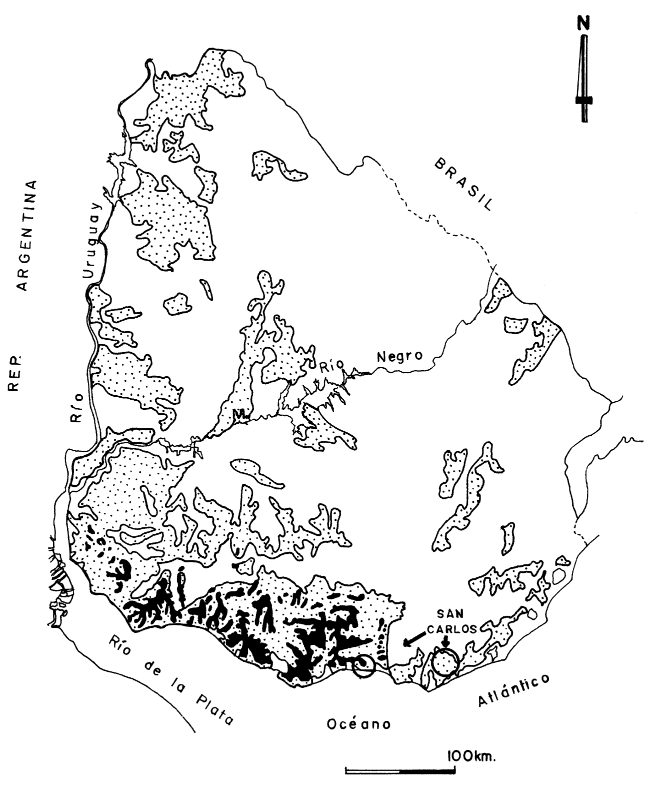

Fig. 8. The distribution of loess reworked loess in Uruguay. Solid pattern: Bossi and Navarro (1988), stippled this paper.

layer that overlaps the A-horizon, as proposed by McDonald and Bussaca (1990) for similar situations.

Mineralogical and textural characteristics of the sediment indicate accumulation under warm and humid conditions, according to Pye and Tsoar (1987, in Derbyshire et al., 1995) and Pye (1995), could also be attributed to Libertad II formation, because, this formation is a loessic material with abundant sponges spicule and includes coarse sand, pebbles and cobbles, and therefore would represent a water reworked loess. The Libertad II Formation can be tentatively correlated with the Hernandarias Formation or younger units in Argentina.

In sedimentary basins, the Libertad II Formation occurs covering typical loess deposits while in low-lying undulated areas it occurs on its own. The typical loess tends to occur on its own on hilltops where it gives rise to leached loessic soils (Argiudol) such as those assigned to the San Carlos unit of the soil map of Uruguay (Dirección de Suelos y Fertilizantes, 1976) (Fig. 8).

The younger Quaternary loessic deposits in the interfluvial areas of the Cuchilla Grande hill in south-central Uruguay occur on granitic rocks of the Precambrian Shield. It is normally covered by calcic montmorillonitic Vertisols, which developed under comparatively warm and seasonally dry climatic conditions, probably associated with transitions from glacial to interglacial periods. These soils occur directly on top of the acidic rocks in some localities. This peculiarity of calcic montmorillonite covering acidic rocks on tops of the hills could be explained by the formation of calcic montmorillonite in the bottom of the valleys within a pedimented landscape. This pediment was cut when the landscape was eroded by the river and the loess removed by erosion. At that time the more resistant pelitic sediments produced a relief inversion. The vertisol, then, appears spatially organized to resemble a fluvial system (Fig. 9).

As previously mentioned, the youngest aeolian material was mainly accumulated on river terraces. At the same time, it must have also been accumulated everywhere as a thin mantle. It seems that such a loess has been rapidly assimilated into soils through biological processes. Therefore, modern silty soils do not appear in Uruguay, as in the neighbouring Entre Ríos Province of Argentina.

4. Stratigraphic summary

In essence, Plio-Pleistocene deposits associated with the main rivers in Uruguay form three levels of terraces. The higher terrace, which is the oldest one and occupies the interfluvial areas of undulated and moderately undulated zones, is composed of comparatively coarse deposits of Pliocene age (Raigón and Salto Formation), covered by Libertad Formation loessic deposits of Pleistocene age (Libertad I Formation and/or Libertad II Formation). The intermediate terrace is a discontinuous sandy terrace of Upper Pliocene age (Paso Perico Formation) while the lower step is an assemblage of channels covered by palaeofloodplains (Dolores-Sopas Formation), which underwent cut and fill processes during Early Holocene and Middle Holocene times.

Reworked loess is one of the main components of loessic deposits in Uruguay. The pelitic component has probably been formed in humid zones under transitional climatic conditions.

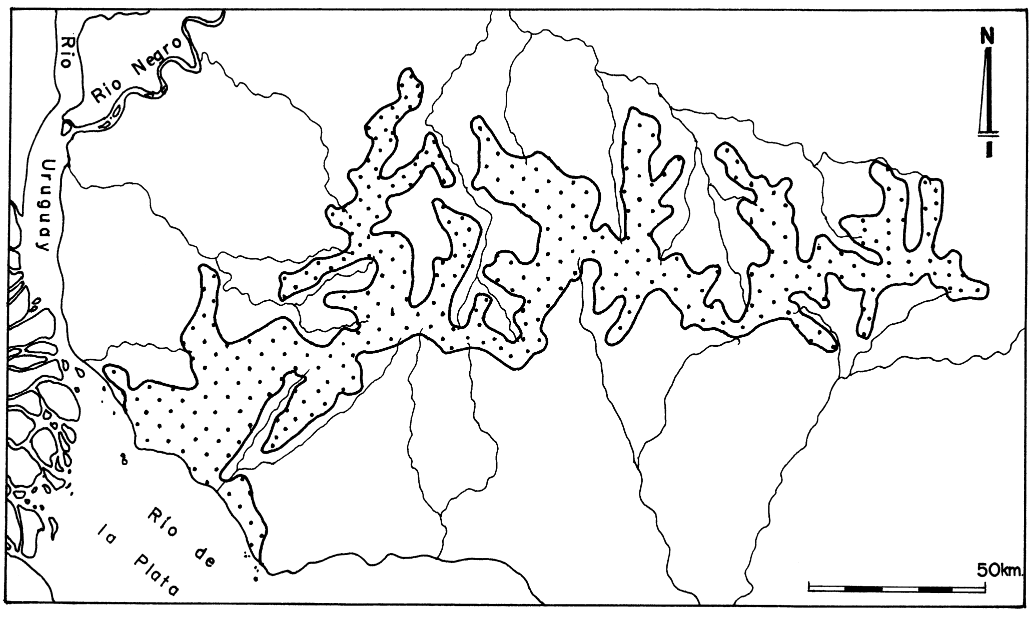

Fig. 9. Vertisols developed on rocks of the Shield. Distribution indicated by stippled area.

Loess deposition occurred at different periods of the Cenozoic. The Quaternary loessic deposits are the most difficult to interpret because, unlike their older counterparts that were accumulated on a pedimented landscape, those that came after that were laid out after the incision of the drainage system over a new surface, which is topographically lower.

In zones of subsiding blocks, loessic deposits consist of three main layers, namely the Libertad I Formation, the Libertad II Formation, and the Dolores-Sopas Formation. In hilly areas, only the Libertad I Formation is generally preserved. In the same topographical level in wide interfluvial areas both Libertad Formation (I and II) are preserved as superposed layers. In the undulating terrain lying below the hilly and interfluvial areas, only the Libertad II Formation appears, mainly as reworked loess, while in the glacis (ramps) or terraces of the drainage systems, there are reworked loessic deposits of Upper Pleistocene age (Dolores-Sopas Formation).

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