

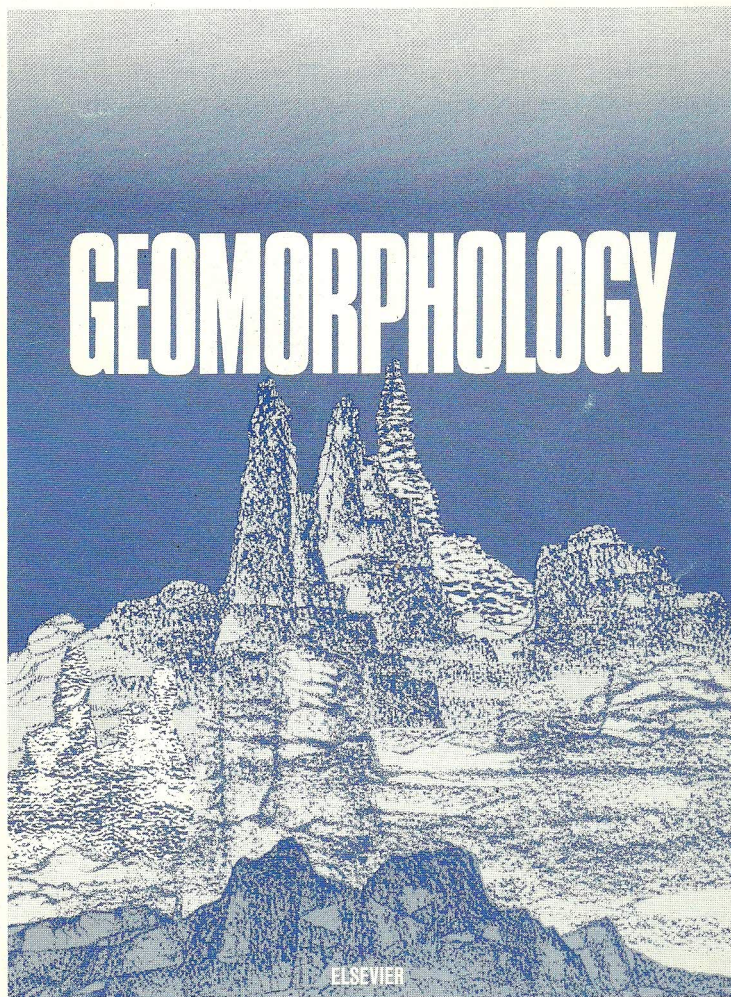
Geomorphology and late Quaternary of the Chaco (South America)

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ABSTRACT

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The Chaco is a large tropical plain located in the interior of South America, consisting of parts of Argentina, Paraguay and Bolivia. It is 840,000 km² in area and is characterized by forests, savannas and extensive swamps, which give it a marked climatic and biogeographic identity. It encompasses five huge alluvial fans built by the major rivers which cross the region: Salado, Bermejo, Pilcomayo, Parapetí and Grande. The fans are composed of several sedimentary units, deposited during different times of the late Quaternary under diverse climates. Two fluvial terraces appear at the apex of each fan; the older one is probably late Pleistocene in age, the second was formed in postglacial times. Humid climates, such as the present one, favoured the generation of soils and stable fluvial belts; drier climates led to widespread sedimentation along small ephemeral channels and large spill-outs. During two intervals, on in the late Quaternary glacial maximum and the late Holocene dry climates occurred in the region, leading to the formation of dune fields and loess mantles.

Introduction

The Chaco is a large, uninhabited, and poorly known plain that covers 840,000 km² in the tropical heart of South America. In spite of its strong climatic, biogeographic and geologic identity, it has not interested scientific investigators as much as Amazonia or Patagonia. It forms the tropical region located between the Pampas and the Amazonic lowlands, limited to the west by the Andes Cordillera and Subandean Sierras, and to the east by the humid Brazilian Planalto (Fig. 1).

The Chaco is characterized by forests, tall grass savannas and large swamps. The rare rivers have gentle longitudinal profiles; in consequence, extensive floods frequently cover the ground for several months each year. Interan-

nual climatic variations are also large.

The Chaco lies within three countries: Argentina, Paraguay and Bolivia; the political diversity has been a factor in hindering the acquisition of knowledge about the region. The present paper is a synthesis of the geomorphology and evolution of the area during the late Quaternary. After previous surveys briefly described elsewhere (Iriondo, 1984), the author has mapped the Chaco for the Geomorphology and Quaternary of South America Project, sponsored by the National Geographic Society of USA (Grant 4127/89) and the National Research Council of Argentina (CONICET, PID 951/88). The four year long research effort was based on remote sensing interpretation and field work in the three countries; mineralogic and granulometric analysis were carried out for a general characterization of the large fluvial and aeolian systems.

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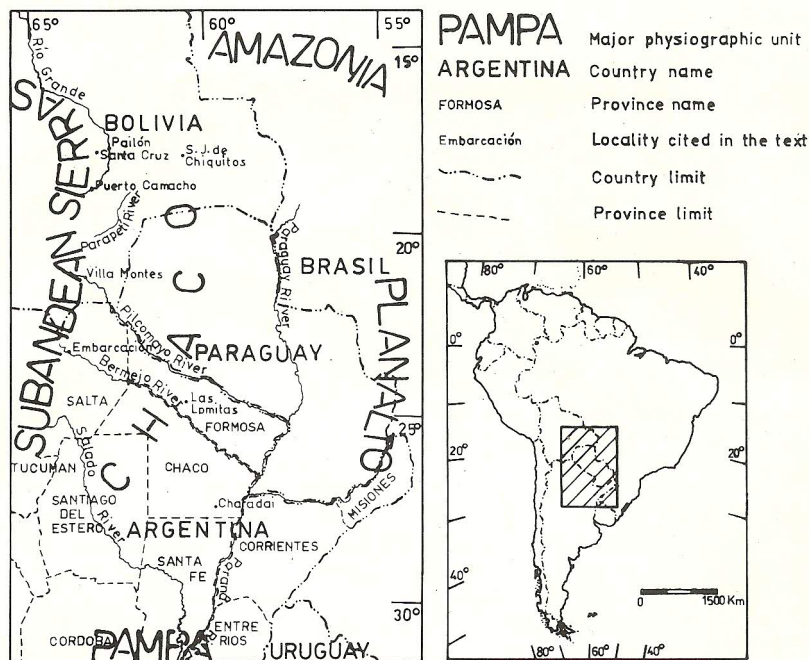


Fig. 1. General map of the Chaco, with political divisions and the five main rivers. Localities cited in the text are shown.

Climate and biogeography

The Chaco has a particular climatic and biogeographic identity in South America. The climate is tropical semi-arid to tropical humid; it is characterized by a permanent interchange of tropical and cold austral air masses. During periods of northerly winds the temperature can rise to 40°C or more in one hour, even during the cold months of August and September. Rains are intense; two types of rain occur: frontal, associated with northward-advancing cold fronts, which cover large areas; and convective, produced by severe thunderstorms which form within the tropical humid air masses and affect limited areas with intense precipitation. The mean annual rainfall in the Chaco ranges from 400 mm in the west to 1200 mm in the east (Schmieder, 1980). The rainy season begins in October and ends in March; winters are dry.

The mean temperatures vary between 24°C and 30°C in the summer, with maxima exceeding 40°C every year. Diurnal amplitudes

are large in the west, reaching 15 to 20°C; radiative cooling during the night is important in the west, which produces frost in the dry winters. Conditions are milder in the east because of higher humidity of the air (Schmieder, 1980).

The vegetation is characterized by forests, savannas and swamp associations. In the eastern Chaco, forests have a high species diversity, and large swamps covered by paludal and floating plants are frequent. As a consequence of the climatic gradient, in the semi-arid west the vegetation is represented by only ten species of xerophytic trees, cactus and hard grass (Cabrera and Willnick, 1980). At a local level, the vegetative cover depends simply on the character and relative altitude of the substratum: diversified forest on levees and other elevated surfaces, palm trees at intermediate elevations, tall grass in depressions, etc.

The Chaco is a homogeneous, highly defined biogeographic province of the Chaco Dominion, which is a major biogeographic level covering a large portion of South America. The

Chaco province is characterized by a scarce number of endemic forms at the family level; Leguminosa, Mimosoidea and Caesalpinoidea are typical. Neotropical vertebrates of the Chaco are Edentata, Chiropterae, Tinamidae, and a lung-fish (*Lepidosiren paradoxa*). Among insects, ants (*Atta*) and termites (*Cornitermes*) are abundant (Cabrera and Willnick, 1980).

In my opinion, from an evolutionary point of view, the Chaco Dominion can be interpreted as a secondary environment, evolutioned by the interaction of the Neotropical poles: Patagonia and Amazonia. Considering that the present geologic and climatic patterns of South America were broadly established during the Miocene (and consequently the Amazonian and Patagonian Dominions), one can postulate a Pliocene age for the Chaco biogeographic identity.

Western Chaco

The Western Chaco (Fig. 2) is dominated by the fluvial dynamics of allochthonous rivers flowing from the humid Sierras Subandinas (Fig. 1). The rivers cross the mountains through deep transverse canyons and carry well-sorted, fine quartz sands. In spite of the high transport capacity of the rivers, coarse sediments are absent from the fluvial deposits. The only exception to this sedimentological pattern is the Bermejo river, which carries large pebbles and boulders in its upper reach. The fluvial systems have developed two terraces on the eastern slope of the Sierras.

Large rivers cross the region to the east along complex alluvial belts composed of long old channels, oxbow lakes, swamps and other minor landforms built by the channel and related geomorphic agents. Occasionally, a major avulsion occurs. About 100 years ago, the Bermejo river abandoned its former channel and shifted to a different location along a stretch of 200 kilometers (Iriondo, 1974). The Pilcomayo river has been undergoing a similar pro-

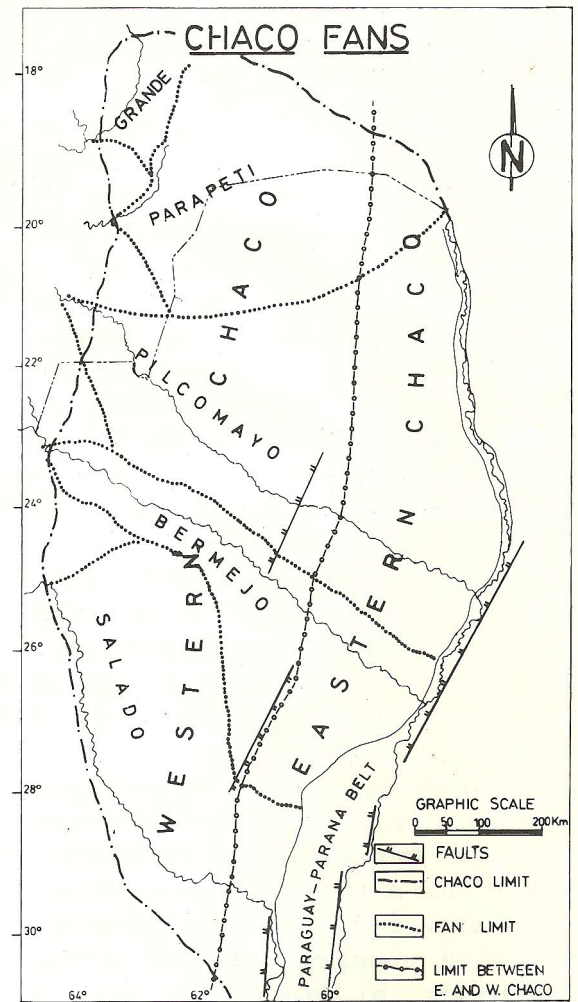


Fig. 2. The five main alluvial fan systems and the present climatic division of the Chaco into a semi-arid (west) and a humid (east) region.

cess since 1980. Such types of avulsion take several years until completed.

During past dry climates the Chaco rivers were smaller and less stable than they are at present. Numerous small paleochannels can be observed in the plain, forming large-scale distributary patterns, especially evident in the Pilcomayo and Salado systems. Two arid episodes occurred in the late Quaternary, during which strong, dry northern winds formed dune fields and loess mantles in western Chaco.

Eastern Chaco

The eastern Chaco is formed by the distal areas of the alluvial fans of the major rivers: they are basically swamp environments, crossed by old fluvial belts of the rivers. The climate is subhumid to humid, and the floods of the allochthonous rivers discharge large volumes of water across the landscape. Infiltration is practically nil, because the terrain is composed of 12 to 20 m thick impervious silty clays. The extremely low regional slope does not favor runoff of the water excess. As a consequence, permanent and ephemeral swamps, densely covered by floating and paludal vegetation, cover broad areas of the region.

Evapotranspiration in the swamps is several times higher than the potential evaporation, and organic matter accumulates in the anaerobic environment at the base of the swamps. Neiff (1986) described two types of swamp: (a) Temporary swamps ("bañados") are formed by rainwater and do not accumulate sediments, water remains periodically for several months, forming a 30–40 cm deep layer on the surface of the plain. A short period of oxygen deficiency appears at the beginning of the flooding, originated by the decomposition of vegetation. (b) Permanent swamps ("esteros") have well defined borders and are larger and deeper. The roots of the vegetation are adapted to survive anaerobic conditions for long periods of time. A natural mechanism in the swamp is the periodic occurrence of fires. Production of organic matter is high in these tropical wet environment, estimated at 20 ton $\text{ha}^{-1} \text{yr}^{-1}$ (dry weight) according to Neiff (1986). Approximately 70% of the organic matter accumulates at the bottom, forming a peat horizon which degrades very slowly, due to the oxygen deficiency and to a low C/N ratio.

The major swamps, 100–200 km long and 3–10 km wide, are typically less than 1 m deep. The central area of the swamp is often free of vegetation and forms an irregular belt of slowly

flowing water (Iriondo, 1989). The Quaternary paludal deposits and present swamps cover an area of 125,000 km^2 in the Bermejo and Pilcomayo fans.

Large swamps are the headwaters of local river networks, which have developed on the large fans during the present humid climate. The collectors of such systems are small tortuous channels, 2 to 5 m wide (Orfeo, 1986). They flow along abandoned channels of the major allochthonous rivers, which are normally bordered by levees. They are a special type of underfit rivers (Cucchi, 1973; Iriondo, 1974), with the former channel belonging to a river basin several times larger than the present one. When major floods cover the whole region, only the old levees remain above the water level.

A significant percentage of the sedimentary load of local rivers are colloids, which form as much as 75% of the total weight of some samples. Pedrozo and Orfeo (1986), in their study of several river systems, found between 40 and 52% of suspended solids composed of particles with diameters ranging from 1.2 to 0.45 μm . Colloids are composed of clay minerals and organic matter in different stages of degradation, probably resulting in the formation of organic-clay complexes.

The Paraguay-Paraná belt

The eastern fringe of the Chaco is formed by deposits of the Paraná and Paraguay rivers. Both rivers developed a well-defined belt of sediments and landforms during the Quaternary, which are clearly different from the rest of the Chaco (Iriondo, 1987a). The primary component of the sediments is clean, fine grained quartz sand, whose origin is from Cretaceous sandstones of southern Brazil and Paraguay. Silt and illitic and montmorillonitic clays are found in minor proportions. Sedimentary deposits are formed of coarse strata of channel sand extending to several tens of meters in depth. Local relief is moderate to low,

in contrast to the very flat surfaces of the fans.

The belt is broad in the south, reaching more than 100 km in width in the province of Santa Fe (see Figs. 1 and 2). Local rivers cross it along well-defined channels, with relatively high runoff (Iriondo, 1987a). To the north, in Paraguay, the belt is much narrower, only 5 to 10 km in width. There it consists of two components: (1) the present river flood-plain, and (2) a massive 4 m high terrace composed of montmorillonitic greenish-gray plastic mud and remains of paleochannel meanders.

The alluvial fans

The large alluvial fans of the Chaco rivers are complex systems composed of numerous sedimentary and geomorphological units, which formed at different times and under different climatic conditions. Although their general characteristics are similar, each of them shows unique features. From south to north, the fans are the following (Fig. 2): Salado, Bermejo, Pilcomayo, Parapetí and Grande.

The Salado alluvial fan system

The Salado alluvial fan system is 650 km long and 150 km wide in its distal region. It is composed of several minor subsystems: minor fans, fluvial belts, lacustrine and swamp deposits (Fig. 3). Silt, illite clay and fine sand are the more important clastic sediments; chlorites dominate among the soluble salts. The minor fans were formed during dry periods on tectonically sunken blocks. Such blocks have surfaces several thousand square kilometers in area (Iriondo, 1987b).

The uppermost fan of the Salado system is located in the provinces of Salta and Chaco (Argentina). It is formed by a series of small, well preserved paleochannels, cutting across late Pleistocene loess deposits of the western Chaco, without accumulation of significant volumes of sediments. The most probable age for the fan development is late Holocene, be-

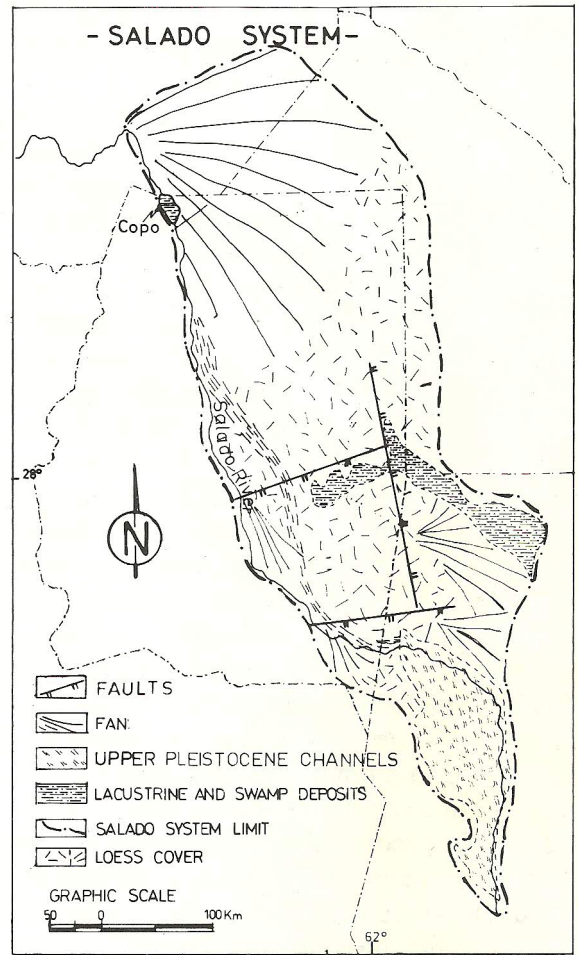


Fig. 3. Map of the Salado river system showing minor alluvial fans, alluvial belts, lacustrine deposits and a loess cover.

cause channels erode the late Pleistocene loess, and the early Holocene was characterized by channel stability in the region. At present, the Salado river which crosses the region is a permanent, well defined channel until it reaches the latitude of 25°40'S, where it debouches into a large swamp (Bañado de Copo, 300 km² in area).

The large swamp affects the general characteristics of the Salado system. Evapotranspiration reduces water discharge by 50%, causing the sediments to diminish in grain size from a coarse silt upstream to a fine grained silt at the edge of the swamp, where the river lives the

depression. Downstream, the river is reconstituted by the successive addition of small channels, that originate inside the swamp.

The southeastern corner of the distal region of the Salado alluvial fan system, located in the province of Santa Fe (Fig. 1), is composed of a series of large, stable paleochannels, formed during a late Pleistocene humid period. The channels are buried by a 6–8 m thick loess carpet; however, they are still visible in the field and in aerial photographs. Their primary features are a well sorted sand content, marked tortuosity, and a width of up to 200 m. Paleochannels of different ages and directions can be seen partially superimposed and crossed in an irregular pattern. The sands in the paleochannels are reservoirs of groundwater with low salinity, a fact of high significance in a region with serious water shortage.

The rest of the distal region is formed by clayey swamp silts which contain a high percentage of colloids. The area is flooded for several months in humid years. The only features emerging in a very flat, tall grass landscape are small surfaces covered by dense forest, names "isletas" (islands). Such mounds are built by the biological activity of ants (gen. *Atta*). A colony of *Atta* ants can build a mound several meters wide, with a system of chambers and galleries reaching as much as 3 m under the surface (Bonetto, 1959). The volume of sediment removed and altered in each ant hill can total several cubic meters, resulting in soft and damp material, composed of rounded clods smaller than 2 mm in diameter and with high porosity. The accretion of successive colonies can result in 40 to 80 m long landforms, providing a very good substratum for trees and shrubs.

The Bermejo alluvial fan system

The apex of the Bermejo fan is located near Embarcación, in Bolivia (Fig. 1); the system extends 650 km to the east and southeast, as far as the Paraguay–Paraná belt. In the west-

ern and central Chaco, a large number of Holocene paleochannels can be observed in the plain. Their general orientation is northwest to southeast. In the south, a large spillout lobe reaches the province of Santa Fe (Fig. 1). Farther east, in Charadai, swamps cover the region and have probably done so since Pleistocene times. Six to twelve meters of thick silty clays, greenish-gray and reddish-brown in colour, were deposited in a depression formed by a tectonically sunken block of 5000 km².

Several local fluvial networks were developed in the eastern region of the Bermejo alluvial fan system: Tapenagá, El Rey, Los Amores, Negro, all having similar characteristics. The Los Amores river will be described as typical (Fig. 4): Its upper basin, approximately 600 km² in area, is a part of the western Chaco. The area is underlain by pervious

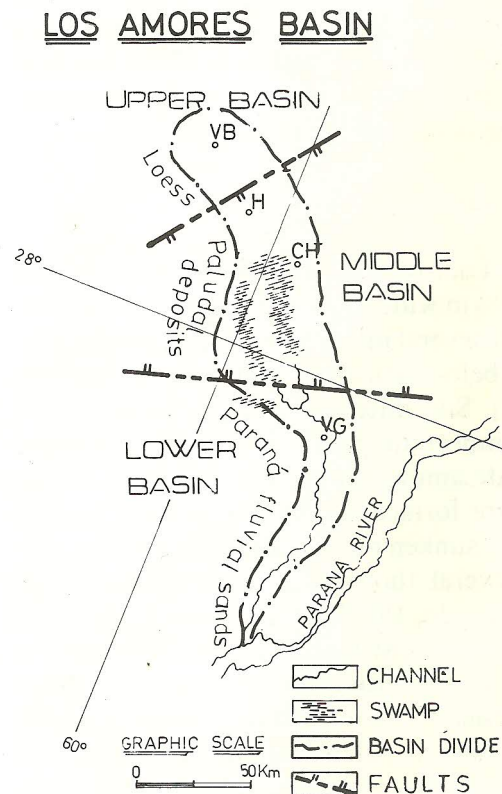


Fig. 4. Map of Los Amores basin, a local underfit river located in the middle and distal section of the Bermejo fan and neighboring Paraná belt.

brown loess. Because it is dominated by infiltration, with little runoff, there is virtually no contribution of sediment to the channels. The middle basin is located in the eastern Chaco. It covers an area of 4000 km², consisting of hard, impervious, grayish-green and reddish-brown clays, paludal in origin. It is a slightly sunken block, covered by large permanent swamps and dense vegetation. Runoff is very slow, resulting in a generalized accumulation of organic matter and development of tropical peat in some places. The region does not contribute clastic sediments to the channels, but the volume of colloids entering the system is large.

The lower basin of Los Amores, 3500 km² in area, is a sector of the Paraguay-Paraná belt shown in Fig. 2. The relief is moderate to low, and the fluvial system is composed of a comparatively well developed net of tributaries and an active collector channel. The runoff is high, with bank erosion and sediment transport (Iriondo, 1987a). Figure 4 is a general map of the Los Amores basin.

The Bermejo river flows at present in a several kilometer wide belt, which at Las Lomitas (Fig. 1) is discontinuous and 10 km in width. It is characterized by numerous minor abandoned channels in different degrees of preservation. The oldest ones are hardly visible, obliterated with overlying sediments. Several deflation depressions are present at the central line in such paleochannels. The youngest channels are well preserved, 3 to 4 m deep, and transport water during floods. A hard reddish clayey silt, composed of quartz and illite, forms the substratum of the belt. The young deposits are formed of loose brown clayey silt, with the same mineralogical composition as the substratum. The paleochannels described here are formed in 1 to 2 km wide fringes, composed of young deposits and separated from each other by areas of reddish substratum.

In that area the river is actively eroding a 4 m high bank, in which the local sedimentary column is well exposed. The upper section of the bank is composed of sand bars deposited

during floods, and paleochannels filled with dark clayey silt containing 15 to 25% of very fine laminated sand. The silt is rich in decomposed organic matter and leaf molds. Strata are plane, concordant, 0.40 to 1 m thick and 50 to 300 m long. The lower section outcrops less than 1 m above the mean water level. It is composed of reddish silty sand, more compact than the upper section, with gray mottles and black patches of manganese minerals; it probably represents the substratum of the present fluvial belt.

The river flows through a very tortuous 1 km wide channel, with a high load of suspended sediments and very fine sand transported as bedload. The sand accumulates in planar bars, several hundred meters long; numerous trunks and branches of "palo bobo" (*Tessaria integrifolia*) are included in the sand mass. Large dessication polygons, to 1 m in diameter and similar depth, appear in the sand when dry. Such contraction structures, common in all Chaco rivers, are probably caused by the high percentage of colloids in the sediments. Such colloids are probably composed of clay-organic complexes.

The Pilcomayo alluvial fan system

The Pilcomayo river constructed the most important alluvial fan in the Chaco. It is the almost unique case of an active alluvial fan of a major South American river (Fig. 5). Its total surface area is 210,000 km². The river originates in a large mountain basin in the Cordillera Oriental and Sierras Subandinas in Bolivia. The valley crosses the mountains to the east forming large incised meanders, in a clear antecedent relationship. Hence, a Tertiary age, probably early Pliocene, can be proposed for the Pilcomayo river. The Subandean tributaries on the contrary, are subsequent, young and scarcely developed.

The river reaches the plain at Villa Montes (Fig. 1), forming the fan apex (Fig. 5). The

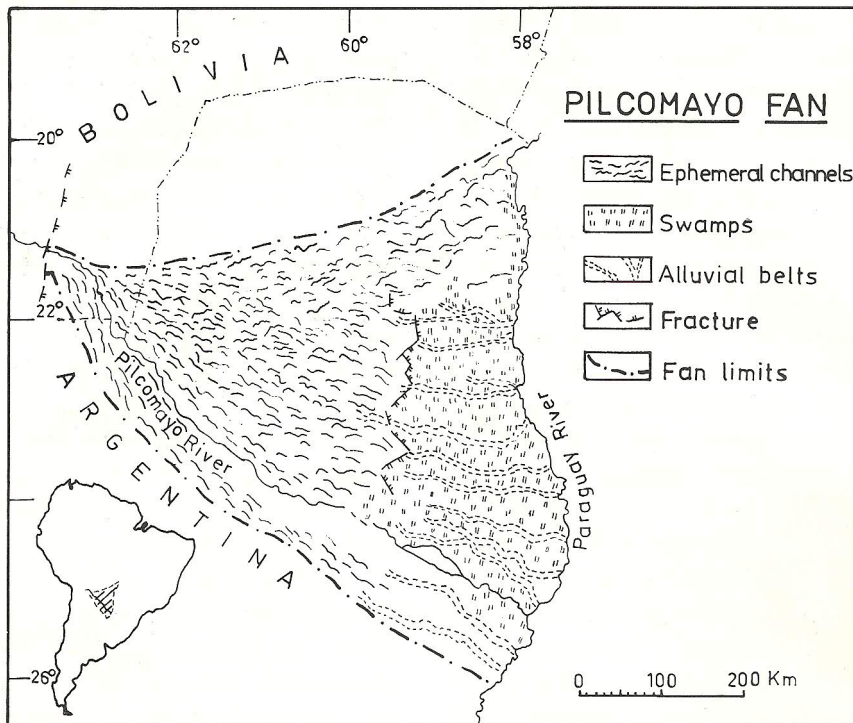


Fig. 5. Map of the Pilcomayo fan showing its major internal elements: channels, swamps, fluvial belts and fractures.

fluvial deposits of the area are preserved in two terraces. The older one has a variable altitude above the present channel (40 meters in the upstream valley and 20 meters in the piedmont); it is covered by a 3 m thick reddish aeolian silt that has a well developed soil. The younger terrace covers a large surface in the region. In the upstream valley, near the road bridge (5 km from Villa Montes), it is 6 m thick and composed of two units. The lower one is composed of pebbles and blocks, gray in colour; the upper unit of the section is composed of smaller pebbles and boulders in a red sandy matrix.

Downstream, in the piedmont area, the lower terrace is 2 m high. It is formed by coarse and very coarse planar strata, with sharp contacts. The continuous surface of the terrace extends farther to the east, forming a wide area in the western Chaco. In western Formosa (Fig. 1), 300 to 400 km to the southeast, an older unit is present; it contains quartz silt and very fine

quartz sand. The grains are covered by hematite and large plates of illite (Fig. 6). The sediment is yellowish brown in colour, moderately plastic and compact. It is characterized geomorphologically by numerous ephemeral channels, 5 to 15 km in visible length and with an irregular pattern. This unit extends to 60° W longitude, forming a regional fan pattern.

An older sedimentary unit, probably equivalent to the upper terrace in Villa Montes, appears on the surface to the east. It is composed of 10 to 20 m thick paludal silty clay, covered at the present-time by temporary and permanent swamps. Fluvial belts, formed by paleochannels and levees, cross the area in west to east, and northwest to southeast directions; they transport waters of local fluvial basins (Monte Lindo, Pilagá, Melo and others) (Cucchi, 1973; Iriondo, 1974), whose main features are similar to those described for the Los Amores basin (Fig. 4). Such a unit composes the whole distal region of the Pilcomayo

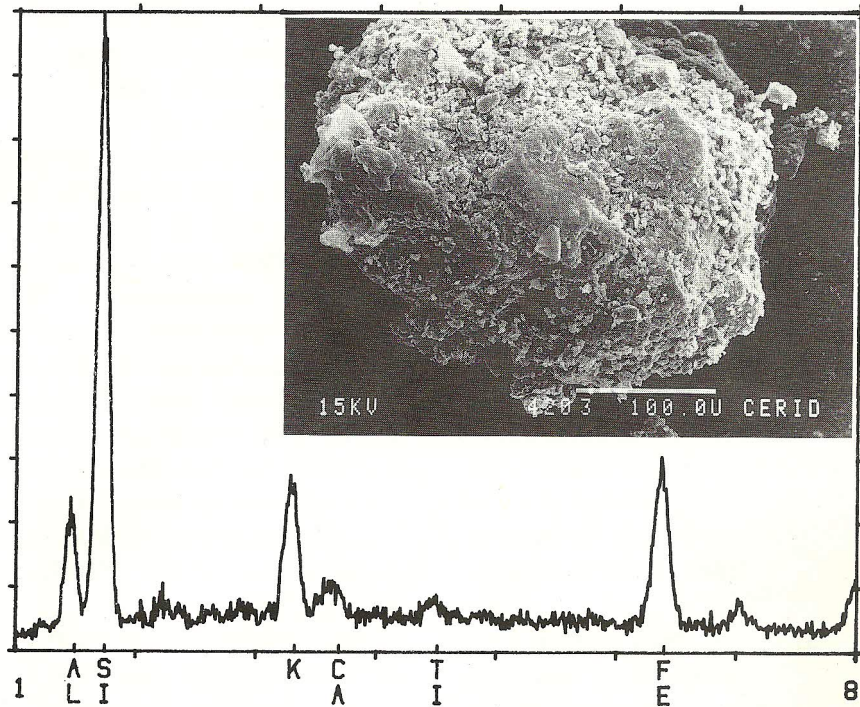


Fig. 6. Typical sand grain of the Pilcomayo system, covered by large illite plates. The composition curve at the bottom indicates high contents of potassium (in the clay) and iron (as coat of the quartz grain).

fan, limited by the Paraguay–Paraná belt along 650 km.

The Pilcomayo river at present transports a very fine gray quartz sand at Villa Montes. The sand accumulates in large bars, which also include small deposits of isolated rounded pebbles. The maximum discharge of the channel is $800 \text{ m}^3/\text{s}$, 45 times higher than the minimum. In western Chaco the Pilcomayo river has changed its channel several times during the present humid climate. Abandoned channels are filled with fine silty sand, without clay of coarse clastics. Its internal relief is about 1 m. In some cases, the channel conveys considerable quantities of water during the rainy season (Rabicaluc, 1986).

During the last four or five centuries the upper Pilcomayo river discharged its water into a $15,000 \text{ km}^2$ tectonic depression, the Estero Patiño, located at the border of Argentina and Paraguay, 250 km upstream from the confluence with the Paraguay river (Cordini, 1947).

The Pilcomayo deposited huge volumes of silt and very fine sand in the area. Cordini measured high concentrations of suspended solids during floods (up to 40,000 ppm). Dikes of vegetative debris that accumulate during periods of high water acted as sediment traps, building up plugs of silt and sand, which frequently caused channels to shift. Eventually, the wood and leaves disappear through oxidation, resulting in a collapse of the overlying sand. Such a process produces a landscape of “hoyales” (holes), which is characterized by numerous pits up to 5 m in diameter and 1.5 m in depth.

In 1980 the river completed a century-long sedimentation process by entirely filling the depression. Consequently, the Pilcomayo began an avulsion process, depositing fine sand and silt in the lower reach of its channel, and with water overflowing into the surrounding plain. In successive years the area of channel filling and water overflowing migrated up-

stream, leaving behind a rapidly enlarging sector abandoned by the main stream. The velocity of retreat is 10 to 35 km/yr, with a total of 160 km in seven years. The overflowing water in Argentina formed a swamp 250 km long and 7 to 12 km wide, with paludal dynamics and geomorphology. Approximately the same volume of water spilled over into Paraguay, forming a similar swamp.

A few well preserved paleochannels, cutting the general surface of the region, were mapped in western Formosa (Fig. 1). A well drilled in one of them showed that the channel fill is composed of well-sorted very fine quartz sand, reddish in colour. It is most probable that the same sedimentary process active at present times in the Pilcomayo filled the former channels during the Holocene.

As a first approximation, the Pilcomayo alluvial fan system was produced by two contrasting processes: (a) development of stable fluvial belts during humid periods, such as the present one, and (b) generalized sedimentation by spillouts and ephemeral channels during periods of dry climate. In both cases, swamps formed in tectonically sunken blocks.

The Parapetí alluvial fan system

The Parapetí river has formed an alluvial fan in Bolivia and Paraguay, which has a surface area of several tens of thousands square kilometers (Fig. 7). Part of it is located in the Paraná basin, the remainder lies within the Amazon basin. At present, the permanent channel flows into the Izozog swamp, and eventually into the Mamoré river, a tributary of the Amazon. During the rainy season an important water transfluence occurs, forming the Timané river, which flows into the Paraguay river.

According to Huamán et al. (1975), four different units compose the surface of the Parapetí alluvial fan in Bolivia: (a) old alluvial deposits; (b) the aeolian plain; (c) the present

alluvial belt of the river; and (d) the Izozog swamp. Two terraces were formed at the fan apex, equivalent to those of the Pilcomayo system in Villa Montes.

The old alluvial deposits form a large plain with slopes less than 1%, located between 62°15'W and 62°30'W longitudes. Water drains very slowly. The surface is crossed by numerous paleochannels. The sediment is clayey to sandy loam, composed of quartz and illite. In general, soils on this unit are deep and well developed, with a Bt horizon; in the subsoil CaCO₃ precipitates form pseudomicelia and small patches. The sediment has been partially affected by local deflation. The old alluvial deposits are equivalent to the western Formosa surface of the Pilcomayo alluvial fan system (Table 1).

The aeolian sand plain covers a surface area of 25,000 km² in eastern Bolivia and northwestern Paraguay. It is composed of large parabolic dunes oriented in a north-south direction. The individual dunes range up to 10 km in length and are composed of fine sand (98% quartz, 2% feldspars). The unit was formed during a general aeolian mobilization in the late Holocene, between 3400 yr BP and 1400 yr BP (Servant et al., 1981).

The present alluvial belt of the Parapetí river is formed by the river channel and a series of old channels abandoned by avulsion. It is 10 km wide at 63°W longitude, where it turns to the north. When it reaches the Izozog swamp, its width has increased to 20 km. The wind forms sand shadows and small mounds at the southern bank of the channels during the dry season. The unit is discordant with the aeolian plain; hence, it is younger than 1400 yr.

The Izozog swamp is an area of 6800 km² located on a tectonic depression. As the river enters into the swamp its channel divides into numerous distributaries flanked by levees. The sedimentary load of the Parapetí river is deposited in the swamp, where it is locally redistributed by the wind during the dry winter. Most of the water infiltrates and is lost by eva-

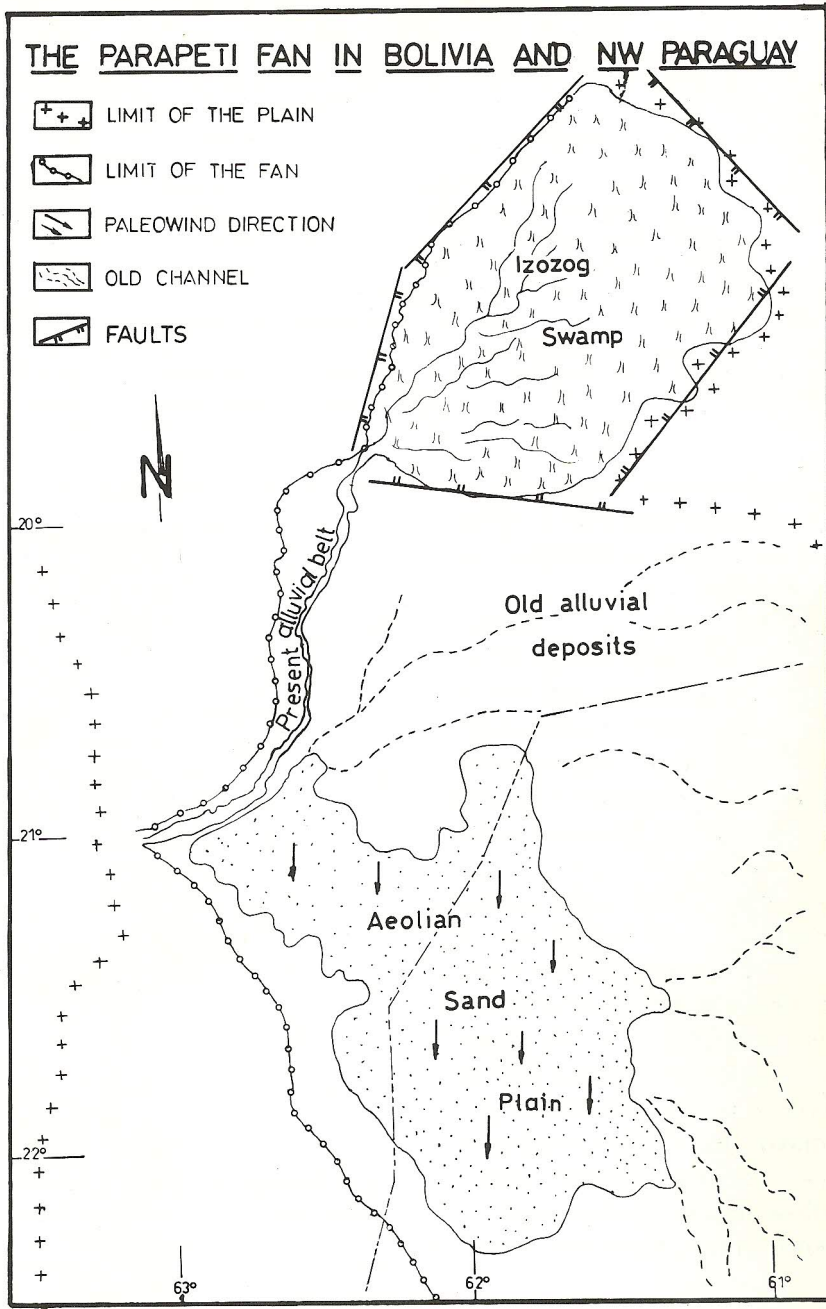


Fig. 7. Major internal units of the Parapetí fan: old alluvial deposits of Glacial age, Aeolian san plain formed in the upper Holocene, and the (present) Izozog swamp.

potranspiration; the rest slowly migrates to the Amazon river. In local depressions, the sedimentary fill is composed of fine-grained stratified mud. The levees are composed of coarser particles.

The Río Grande alluvial fan system

The Río Grande alluvial fan system enters the plain at Puerto Camacho (Fig. 1). It forms a large alluvial fan, 65,000 km² in area, 30% of

TABLE 1

Correlation table

Age	Salado	Bermejo	Pilcomayo	Parapetí	Río Grande	Climate
Present	fluvial belts 1000 BP	fluvial belts 1000 BP	fluvial belts 1000 BP	fluvial belts 1400 BP	fluvial belts 1400 BP	humid
Upper Holocene	loess deflation hollows 3500 BP	loess deflation hollows 3500 BP	deflation hollows 3500 BP	dunes 3400 BP	dunes 3400 BP	arid
Mid and lower Holocene	soil W alluvial fan	soil lower terrace	soil lower terrace	soil lower terrace	soil lower terrace	humid
Late Pleistocene	loess spillouts	loess spillouts	loess spillouts	loess dunes	loess dunes	arid
UpperPleistocene	fluvial belts	?	upper terrace	upper terrace	upper terrace	humid

which forms the northwestern corner of the Chaco; the rest belongs to the amazonic Llanos. The Chaco part of the system is described as follows:

Two river terraces are conspicuous on the flanks of the Sierras. The oldest one is 50 m above the present river level; its surface is modified by a tropical half-orange morphology (characterized by rounded hills) and covered by yellowish brown loess. The terrace is equivalent to similar geofoms of the Pilcomayo and Parapetí.

The lower terrace is 10 m high at the mountain front, diminishing to 3.30 m 700 meters downstream. The stratigraphic section is shown in profile in Fig. 8. Bed A is composed of channel sand. Bed B is a sequence of a silty abandoned channel infilling, with a brown soil at the top. Both beds correlate with the lower terrace of the Pilcomayo. Bed C, composed of a massive soft silt, is clearly younger, corresponding to overflow sediments deposited simultaneously with the Holocene sand mobilization.

The major bed of the river, which is active during floods, is 300 m wide at the foot of the mountain and 5 km wide at a distance of 100 km downstream. It is covered by ill-defined bars of very fine sand that contains more than 95% quartz. In some sectors, small accumulations of pebble-sized quartzites are frequent. Minor overflow channels, partially filled with silt and clay, are common. During the dry sea-

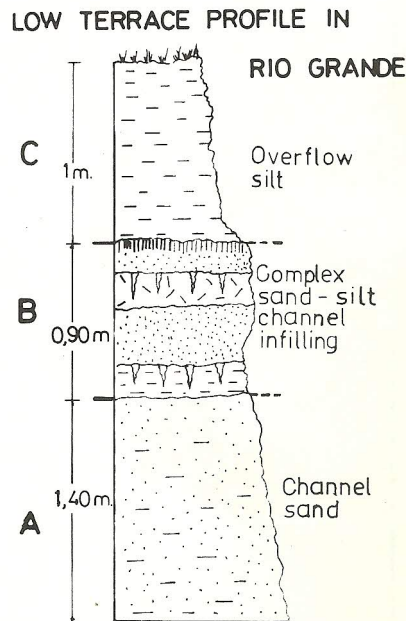


Fig. 8. Stratigraphic profile of Río Grande at Puerto Camacho. Bed A is composed of channel sand. Bed B is a silty channel infilling, with mud cracks and sand levels. Bed C is a soft gray silt originated in overflow sedimentation.

son, large dessication polygons up to one meter in diameter appear in the silt. Transverse and diagonal bars of quartzite pebbles and blocks are visible every 100–300 m in the dry channels. Excepting the pebble bars, the sedimentary characteristics of the major channel are similar to those of Bed B in the lower ter-

race. The minor channel is 80 m wide and has a meandering pattern.

The river at Pailón (Fig. 1), some 200 km downstream, is similar to the upstream section. The major bed is composed of very fine sand and large planar bars. Large amounts of tree trunks, branches and other vegetative debris are buried in the sand.

Overflows and paleochannels of the Río Grande cover the northwestern corner of the Chaco. Overflow deposits are composed of brown quartz silt with subordinate illite; they extend to the very foothill of the Precambrian Shield, at the northern boundary of the Chaco. Even as far as San José de Chiquitos (Fig. 1), Río Grande silts fill the valley, without any sedimentary contribution from the surrounding low mountains. The unit is equivalent to the Parapetí loess and the western Formosa general surface.

Several paleochannels of the Río Grande incise the surface and convey clean water during the rainy season. They are 40 to 80 m wide, 2 to 3 m deep, and join the San Pablo river to the north. Such channels are locally named "cañadas"; the most important of them are Los Aceites, Los Papagallos and Kolla Muerto; they have the same age as the paleochannels in the Bermejo and Pilcomayo alluvial fan systems.

The aeolian episodes

Like the rest of South America, the Chaco experienced climatic changes during the Quaternary. In tropical latitudes such changes were generally expressed as variations in precipitation, rather than in temperature changes. Geomorphological and sedimentological evidences of climates drier than the present one, with dominant wind activities, can be observed throughout the Chaco. According to the stratigraphic data obtained from the present research, two arid periods occurred during the last several thousand years. One of them coincided with the Last Glacial Maximum; the sec-

ond one, shorter and milder, is late Holocene in age.

During both dry events, two regional wind systems appeared, one in the south and central regions, the other in the northwest, parallel to the Sierras Subandinas. The main interest concerning the northwestern system is the fact that the dry air masses came from the Amazon lowlands.

Pleistocene arid period

Southern or Pampean circulation system

The ice cap located on the Patagonian Andes generated an anticyclonic center in northwestern Patagonia, sending cold, dry winds across the Pampa (Fig. 9; Iriondo, 1990a). As a consequence, widespread deposits of sand and loess accumulated in central and north Argentina. The southwestern half of the area was covered by a large sand sea; behind it, a 300 km wide belt of brown loess was deposited, reaching the southern Chaco in Santa Fe and

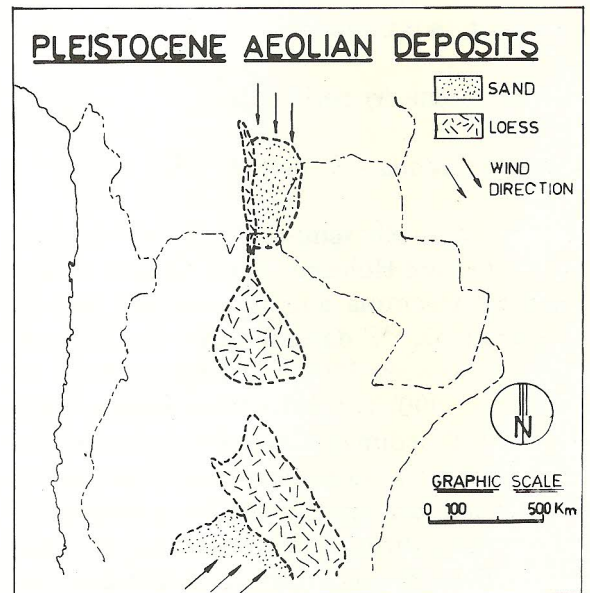


Fig. 9. Areas covered by aeolian deposits during the Last Glacial Maximum (late Pleistocene) in Chaco and surrounding regions.

Santiago del Estero. In the latter region, the typical loess is interbedded with loessic silt deposited in a swamp environment and is characterized by brownish to greenish-gray colour and manganese concretions (Iriondo, 1987a).

Northwestern system

Large surfaces of the Bolivian and northwestern Paraguayan Chaco are covered by aeolian sands, upon which a soil horizon subsequently formed. Associated with the sand, a 10 to 18 m thick mantle of loess (the Urundel Formation) partly covers the eastern valleys of the Sierras Subandinas, extending 900 km from Santa Cruz de la Sierra to Tucumán. At the front of the aeolian sedimentation system the loess mantle extends farther to the east in a broad belt in the Argentinian provinces of Chaco and Salta (Iriondo, 1991). The middle sector of the loessic sedimentation was dated at $16,900 \pm 290$ yr BP in wood by the radiocarbon method in the laboratory of Teledyne Isotopes (sample I-16,661). At present, the loess is partially eroded by the Holocene fans of the Bermejo and Salado rivers. The mineralogic composition is dominated by quartz and illite.

Late Holocene dry period

Pampean circulation system

A dry, basically semi-arid, climate occurred during the late Holocene in the Chaco–Pampa plain in Argentina and surrounding regions. The available ^{14}C dates indicate that the area was dry between 3500 and 1000/1400 yr BP (Iriondo, 1990b). Wind action caused erosion of surficial sediments and deposition of the eroded material in an extensive sand and silt mantle and local dune fields. Measurement of paleowind indicators and associated information indicate the occurrence of a stationary anticyclonic system centered over northeastern Córdoba (Fig. 10).

The Pampean circulation system affected the

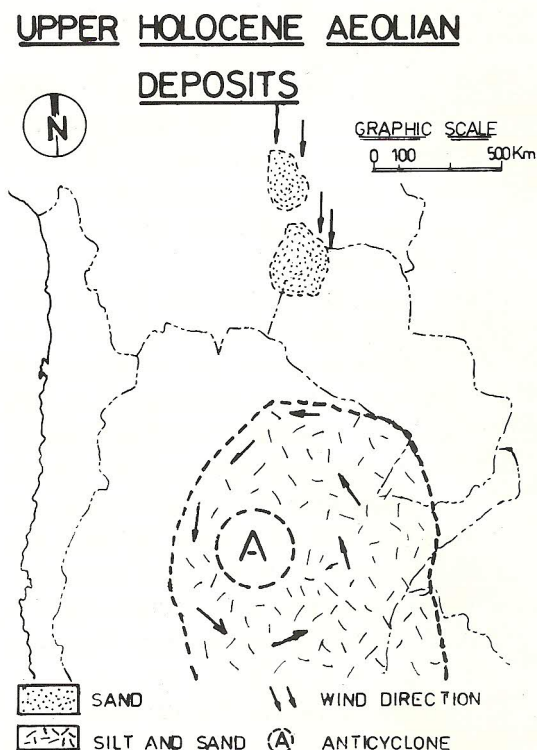


Fig. 10. Areas covered by aeolian deposits during the late Holocene semi-arid climate in Chaco and surrounding regions.

distal regions of the Salado and Bermejo alluvial fan systems, depositing a 20–40 cm thick aeolian silt and forming circular and elliptical deflation depressions, 200 to 2000 m in diameter.

Northwestern system

The Pleistocene sand was remobilized by the wind in several areas in the northwestern Chaco. The largest one is the Parapetí dune field, with an area of 25,000 km² in Bolivia and Paraguay. Smaller dune fields are located in Guanacos, Piraí, Biru-Biru, etc. The sand was transported by north–south winds, which built parabolic dunes up to 10 km in length. According to radiocarbon dates (Servant et al., 1981), the dry climate dominated the region from 3500 to 1400 yr BP.

Present dynamics

As described in previous sections, the present dynamics in the Chaco are characterized by pedogenesis and peat accumulation in the eastern sector, and by floods of allochthonous rivers and winter deflation in the semi-arid west. All processes are marked by the location of the Chaco in tropical regions.

Acknowledgements

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