ON THE FORMATIONS OF THE PAMPAS IN THE FOOTSTEPS OF DARWIN: SOUTH OF THE SALADO

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ABSTRACT

In 1833 during his journey across the Buenos Aires Pampas, Charles Darwin made observations that reflected his thoughts on two major landscape units, Pampa interserrana and *Pampa deprimida*, later identified by other authors. Darwin grouped the Pampean sediments into a single unit, the *Pampean Formation*, based upon the lithological homogeneity and the large extension of the deposits; the unit was thought to be of estuarine-marine origin and attributed to the Recent Epoch considering the paleontological content (vertebrates and mollusks). At present, the Pampean sedimentary succession, which accumulated approximately during the last 11-12 Ma, is interpreted as a pedosedimentary sequence due to the ubiquity of pedogenetic features throughout the deposits. Four main subcycles of sedimentation are identified related to reactivations of the Pampean landscape. At a regional scale, the outcrop distribution of Pampean sediments of different ages suggests the dominance of more stable conditions since the late Miocene-Pliocene in a vast area of *Pampa interserrana*, documented by the formation of calcretes. However, sedimentation during the late Pliocene-Pleistocene was active within the domain of the Salado tectonic basin and Sierras de Tandil. The regional disparity shown by the Pampean stratigraphic record reveals the major morphostructural differences of its basement.

Keywords: *Charles Darwin, Pampean sediments, Calcrete, Geomorphology, Buenos Aires.*

RESUMEN: *Sobre las formaciones de las Pampas en los pasos de Darwin: al sur del Salado.* Durante su viaje por la Pampa bonaerense en 1833 Charles Darwin efectuó observaciones que reflejaban las dos grandes unidades de paisaje posteriormente reconocidas en la región, la Pampa interserrana y la Pampa deprimida. La homogeneidad litológica y la vasta extensión de los depósitos fueron los criterios básicos empleados para agruparlos en una única unidad, la Formación Pampeano; basado en criterios paleontológicos le atribuyó origen estuárico-marino y la asignó a la época Reciente. Si bien han existido otras propuestas estratigráficas, Formación Pampeano o simplemente Pampeano, son denominaciones empleadas informalmente y con un significado algo vago. Actualmente, sobre la base de la ubicuidad de los rasgos pedológicos de la sucesión sedimentaria se la interpreta como una secuencia pedosedimentaria acumulada durante los últimos 11-12 millones de años, se han reconocido 4 ciclos de sedimentación principales relacionados con reactivaciones del paisaje pampeano. Regionalmente, la distribución areal de niveles aflorantes de distintas edades sugiere una mayor estabilidad relativa en el sur, marcada por la formación de calcretos en la Pampa interserrana a partir del Mioceno tardío-Plioceno y mayor continuidad del proceso sedimentario en el ámbito de la cuenca tectónica del Salado y de las sierras de Tandil. Las variaciones regionales exhibidas por el registro estratigráfico del Cenozoico tardío constituyen una manifestación del comportamiento diferencial de las unidades morfoestructurales que integran el basamento de la sucesión sedimentaria.

Palabras clave: *Charles Darwin, Sedimentos pampeanos, Tosca, Geomorfología, Buenos Aires.*

INTRODUCTION

In the course of the winter of 1833, Charles Darwin travelled across the Buenos Aires Pampas. His observations, as well as those by Alcide d´Orbigny (1842), the French naturalist who explored the region some years before Darwin, were part of the initial expansion stage of geology as a science. The explorations of both naturalists are framed within the creation of a universal scheme of the Earth history in which all the regions of the world would be incorporated (Podgorny *et al.* 2008).

In early August of 1833, Darwin disembarked from the Beagle at Patagones, a town by the Rio Negro, in northern Patagonia and began his journey heading north towards Bahía Blanca. From there he travelled across the southern Pampas to the Rio Salado area and Buenos Aires, continuing later to Santa Fe. Logistics for the trip was provided by Juan Manuel de Rosas - the Argentine administrator at the time - in the form of a passport to travel, horses, and a group of soldiers and gauchos to escort him. In his diary, Darwin took notes on the Pampean scenery, referring to the dominant vegetation, the available water sources, the topographic features and the sediments and rocks he found along the journey. He also provided a historical picture of Argentina with descriptions and his own viewpoints on the people and the ongoing war with the aboriginal groups to expand the frontier of the southern territories westward. The information gathered during the field trip was the raw material to write *On the Formations of the Pampas*, the fourth chapter of his *Geological Observations on South America* (1846).

The vast extent, the disputed origin and the abundance of fossil mammal remains were the three main aspects underlined by Charles Darwin when he summarized the characteristics of the Pampean sediments. What was the meaning of the *Pampean Formation* as used by Darwin?; what is the meaning of this term at present?; what is our present understanding of the late Cenozoic Pampean geology?. This paper is particularly focused on the Buenos Aires Pampas, south of the Rio Salado, the region that Darwin explored during the winter of 1833; it includes comments on specific observations he made elsewhere to understand better his interpretations and inferences. Consequently, the main goal is to analyze and discuss his observations on the landscape and the sediments within the framework of our present understanding of the late Cenozoic geology of the southern Pampean plain. With this purpose in mind, the present contribution brings in Darwin´s comments and interpretations on the landscape along with the nature, composition and areal distribution of the Pampean sediments (terms, descriptions, and special comments are quoted in italics and referred to his diary and the chapter on the Formations of the Pampas). These particular issues are then analyzed from our present geological perspective, providing an updated geological review.

DARWIN´S ITINERARY AND HIS PERCEPTION OF THE PAMPEAN LANDSCAPE

Charles Darwin travelled around 650 km (*400 geographical miles*) from Rio Colorado to Buenos Aires following the road that connected the military outposts (*Postas*) set up along the western frontier in 1833 during the ongoing war with the aboriginal groups (Fig. 1).

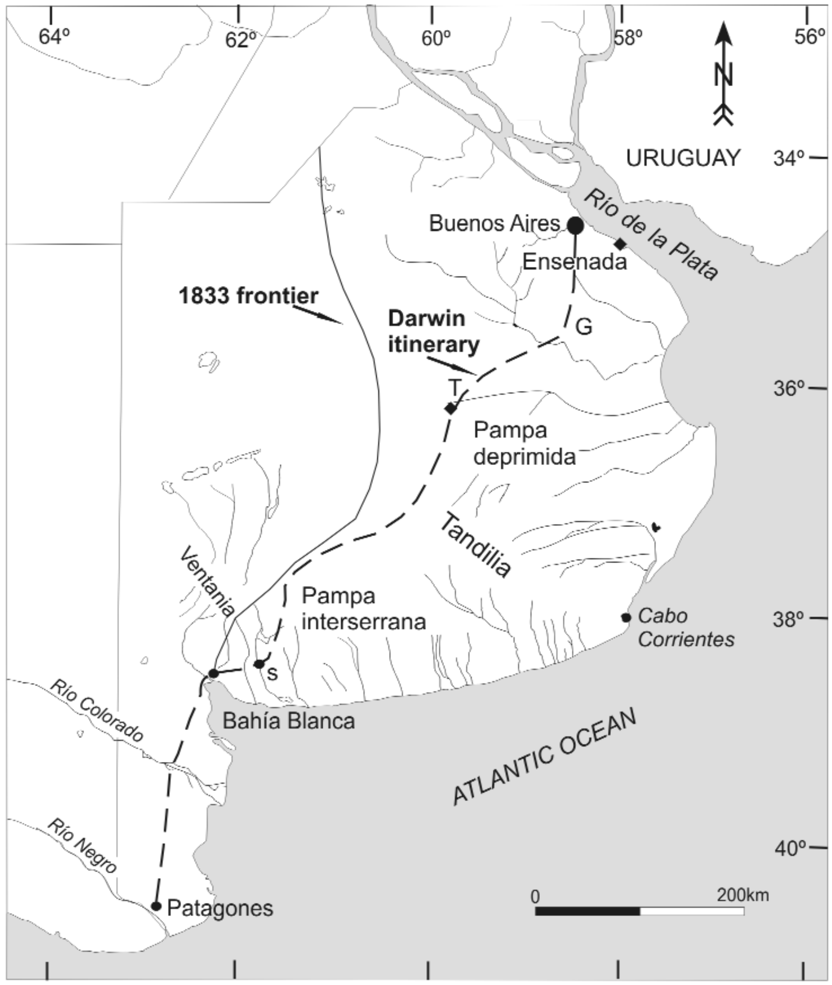

Figure 1: Darwin´s itinerary across the Pampean plain of Buenos Aires province. S: Sauce Posta, T: Tapalqué, G: Guardia del Monte; 1833 frontier adapted from Rolleri *et al.* (2005)

On the way to Bahía Blanca, once he crossed the Río Colorado, Darwin noticed a major change between the Patagonian and the Pampean environments "*...The country had a different appearance from that South of the Colorado: there were many different plants and grasses and not nearly so many spiny bushes and these gradually became less frequent; until a little to the North there is not a bush...*"(Darwin's Beagle Diary 1831-1836). In southern Buenos Aires province he examined the neighboring areas of Bahia Blanca and Punta Alta where he spent around a week. On August 27th Darwin continued to the next military outpost, "*Sauce Posta*", situated by the Rio Sauce Grande, "*…the distance was about 6 leagues* from *Sierra de la Ventana…*" (Darwin's Beagle Diary 1831-1836). It is likely that this Posta was situated in the vicinity of the present village of Saldungaray.

From the Sauce Posta, Darwin headed to Sierra de la Ventana (Ventania range). There he stayed for around 3 days exploring the ranges which were described as "*…a desert mountain of pure quartz rock.Its height is between 3 and 4000 feet …*" (Darwin's Beagle Diary (1831-1836). From the notes reported in his diary he probably examined the rock outcrops and the landscape of the upper basin of Rio Sauce Grande and its surroundings, reaching the area of the highest peaks

(Cerro Tres Picos). His observations include remarks on the vast extent of the plain surrounding Sierra de la Ventana "*…the plain was like the ocean…*", (Darwin's Beagle Diary 1831-1836); "*...the high plain round this range sinks quite insensibly to the eye on all sides...*"(Darwin 1846, p. 79). After surveying this sector of Sierra de la Ventana, he returned to the Sauce Posta. Several days later he continued northward to Sierras de Tandil (Tandilia range). Proceeding to the 3rd Posta, the landscape was perceived as "*…a dry grassy plain and on our left hand at a greater or less distance were low hills..*" (Darwin's Beagle Diary 1831-1836); this description seems to depict the plain sector northward of Ventania (Fig. 2). From there he travelled around 160 km between the two mountain systems. Heading to the 4th Posta the landscape is reported as "*…a low swampy country which extends for nearly 80 miles to the Sierra Tapalken…*" (Darwin's Beagle Diary 1831 -1836). After crossing this large swampy area Darwin arrived to the 7th Posta in the proximity of Sierra *Tapalken* (spelled Tapalqué nowadays) depicted as "*…a low broken ridge of quartz rock, 2 or 300 feet high extending to the east to Cape Corrientes…*" (Darwin's Beagle Diary 1831-1836). From this range Darwin headed to Buenos Aires along the basin of Rio Tapalken (at present arroyo Tapalqué); the 8th and 9th Postas were situated along this stream. On the way to the Rio Salado he described the plain as "*…partly swamp and partly good to the east of rio Tapalguen…*" (Darwin's Beagle Diary, 1831-1836). He arrived at Guardia del Monte (the present town of San Miguel del Monte) on September 19th, 34 days after disembarking in Patagones, Rio Negro.

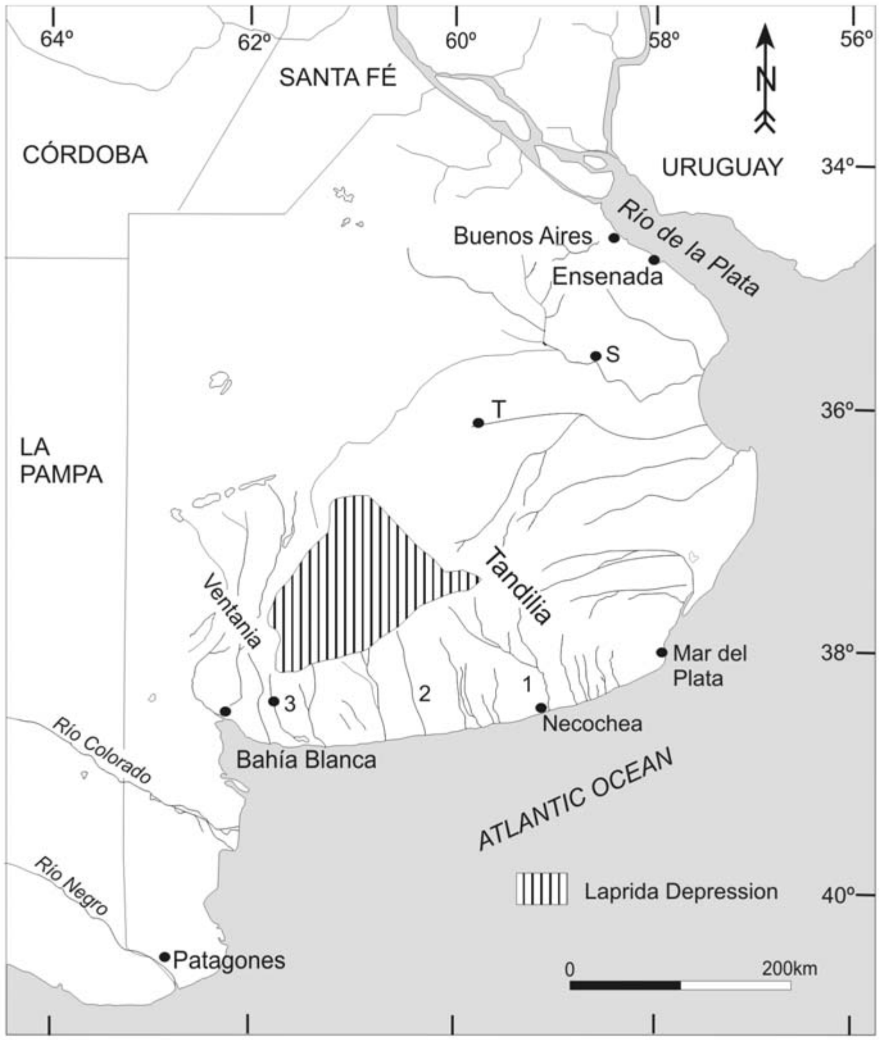

Figure 2: Geographical location of the Laprida depression, fluvial streams and localities mentioned in the text. 1: Río Quequén Grande, 2: Río Quequén Salado, 3: Río Sauce Grande, T: Tapalqué, S: San Miguel del Monte.

THE SOUTHERN PAMPEAN LANDSCAPE

Swampy or dry areas, scarcity or more frequency of *tosca* outcrops and rounded or flat topped hills were some of the fundamental geographical attributes used by Darwin to describe the landscape of the Buenos Aires Pampas. Southward of Tandilia, he perceived the region as a dominantly dry environment; northward, in the Rio Salado basin, Darwin referred to more *fertile lands*, the dominance of swampy environments and a general paucity of tosca exposures. The attributes of the landscape and the environmental features reported by Darwin essentially reflect the major geomorphological differences between the so-called *Pampa deprimida* (depressed Pampa) and *Pampa interserrana* (intermontane Pampa) (Frenguelli 1950), a still current subdivision of the Buenos Aires Pampean plain (Fig.1). The Tandilia and Ventania mountain systems together with the *Pampa interserrana,* situated in between the two ranges, constitute the geomorphological expression of a geologically complex structural block named *Positivo Bonaerense* by Yrigoyen (1975). This positive structural unit separates the Salado and the Colorado tectonic basins (Fig. 3).

The Pampa interserrana, characterized by Darwin as a *dry plain of tosca higher than the country rock* (Darwin 1846, p. 79) is a large-scale plain extending across most of southern Buenos Aires province and continuing southwestward into La Pampa Province, where it has been interpreted as a structural plain (Calmels 1996). The plain is dissected by fluvial systems that drain the central part of *Pampa interserrana* and the neighboring ranges of

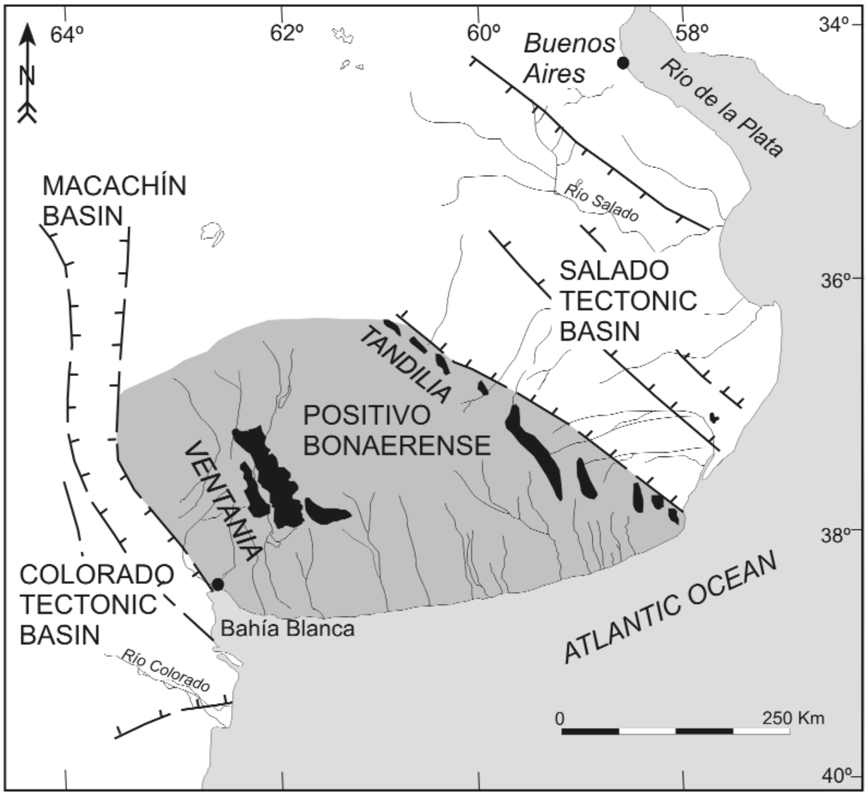

Figure 3: Morphostructural units of Buenos Aires province, modified after Yrigoyen (1975).

Tandilia and Ventania. Fluvial terraces are present along the main river valleys generating a stepped topography. In the upper basins of some of the main rivers (Quequén Grande, Quequén Salado, Sauce Grande), as well as other streams draining the Ventania range, the erosional retreat of the plain surface during the excavation of river valleys gave rise to a hilly and moderately undulating landscape composed of flat-topped and smooth-shaped isolated hills (Fig.4a).

The plain is capped by a calcareous duricrust (Fig. 4b) or calcrete (Darwin´s *tosca rock*, see below), in turn covered by a large apron of eolian sandy silts and silty sands, around 1.5- 2 meters thick, making up the parent material of the presently cultivated Pampean soils. North-northwestward the landscape grades into a low -gradient area characterized by very poor drainage conditions with numerous shallow lakes and flooded environments, known as Laprida depression (Fig. 2), an endorheic sector (Dangavs 2005) still poorly known. The environmental features of this area fit Darwin´s description of a large swampy environment before he reached *Sierras de Guitru Gueyú* (the present group of low ranges at the northwestern part of Tandilia).

Since Darwin´s observations on some general morphological characteristics of the southern ranges of Buenos Aires, the geomorphology of Tandilia and Ventania has been the focus of only a few studies, although these have documented significant stages of landscape development, some not yet fully understood. In Sierra de la Ventana, Keidel (1916) pointed out the presence of old erosion surfaces at different altitudes in the area of the upper basin of Rio Sauce Grande. In turn, Teruggi and Kilmurray (1980) mentioned the presence of monadnocks and old peneplain surfaces in the Sierras de Tandil. Recently, a stepped topography composed of erosion surfaces at different elevations was recognized and geomorphologically correlated at both mountain ranges (Demoulin *et al.* 2005). A model of landscape evolution has been proposed hypothesizing that the highest erosion surfaces of both ranges formed prior to the break-up of Gondwana and the rifting process which led to the opening of the South Atlantic Ocean. This long-lasting history of denudation included intervals of landscape stability and reactivation which are thought to be related to the evolution of the Colorado and Salado tectonic basins (Demoulin *et al.* 2005). In this context, one of Darwin´s observations in Sierra de la Ventana, becomes particularly revealing. He reported a rock outcrop, "*…a few small patches of conglomerate and breccia firmly cemented by ferruginous matter at a height of 300 to 400 m…*" (Darwin 1846, p. 79). This description is in agreement with the geomorphic setting and the general lithological characteristics of *Brecha Cerro Colorado* (Andreis *et al.* 1971) or *Conglomerado Rojo* (Harrington 1936), a deposit associated with one of the regional erosion surfaces identified in Sierra de la Ventana (Keidel, 1916, Demoulin *et al.* 2005).

Northward of Tandilia range, in the domain of the Salado tectonic basin, the landscape can be subdivided into two main geomorphic settings. Along the Sierras de Tandil, Tricart (1973) pointed out the occurrence of extensive areas of fluvial discharge interpreted as alluvial fans that reached the Río Salado. Later, Fidalgo (1983) described a 20-km wide piedmont region and also identified alluvial fan-like landforms exhibiting a distributary drainage pattern. The area of arroyo Tapalqué visited by Darwin is located in this piedmont setting, characterized by a progressive altitudinal decrease northward, reflecting a gradual change to imperfect drainage conditions. A very flat topography with gradients ranging from 0.1% to 0.01% typifies the central part of the Salado tectonic basin; numerous shallow lakes (*lagunas*) and swampy environments are present. The Río Salado floodplain, several kilometers wide in some areas, and including shallow lakes interconnected during flooding

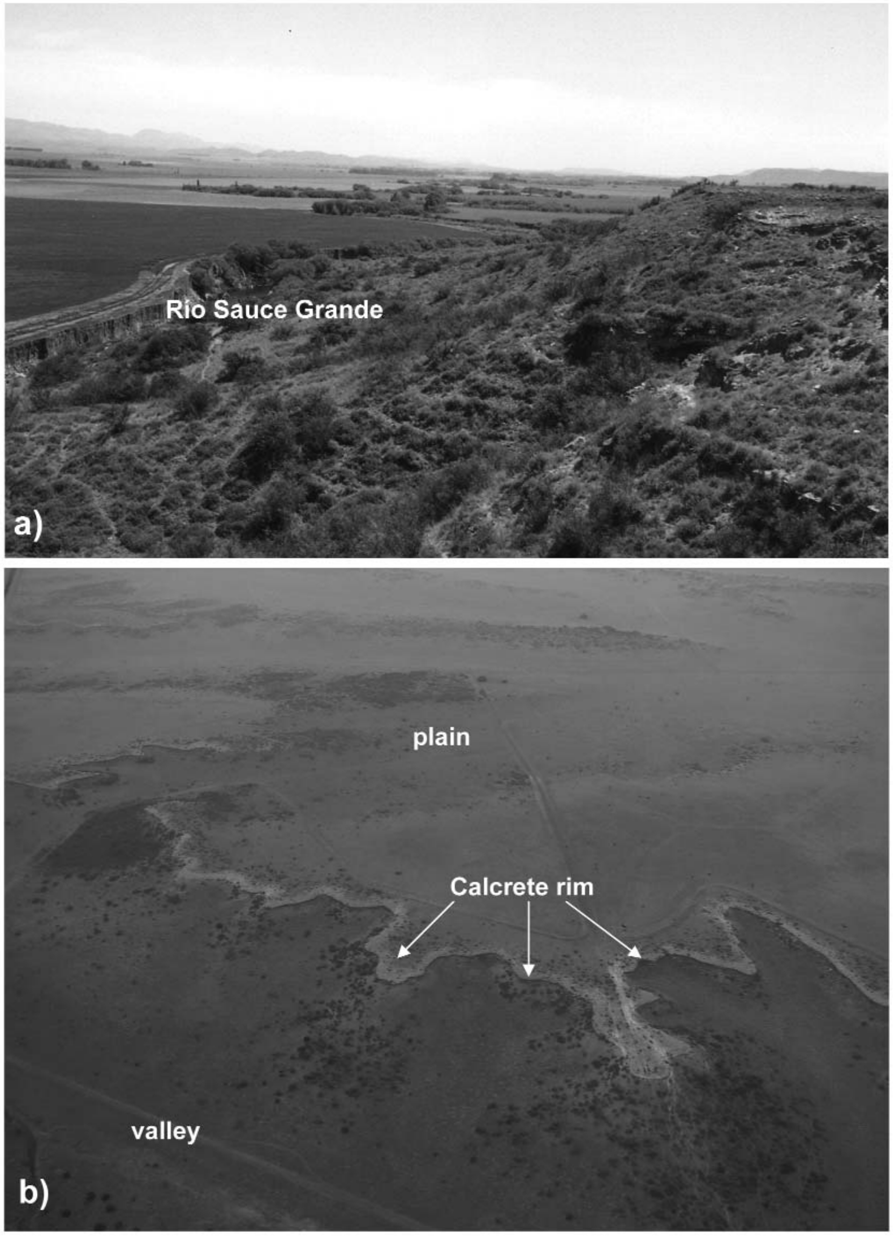

Figure 4: Plain capped by the *tosca* rock (calcrete). a) Isolated hill formed by fluvial erosion of the Río Sauce Grande, south of Saldungaray; Sierra de la Ventana at the background; b) Calcrete crust and resulting tableland aspect of the plain by the Río Sauce Chico valley, west of Bahia Blanca.

events, was crossed by Darwin who pointed out: "…*12th to 13th to 14th posta: we had to ride for a long distance in water above the horse knees*..." (Darwin's Beagle Diary, 1831-1836). After passing the Río Salado and before arriving to Guardia del Monte, he stayed at a large estancia owned by Juan Manuel de Rosas. Several isolated hills (Los Cerrillos), occur in this sector. These features are around 10 meters above the surrounding plain and are located on the eastern side of shallow lakes (Fig. 6). The hills represent lunettes generated by eolian deflation of the topographic depressions, presently occupied by shallow water bodies, under drier conditions (Tricart 1973, Dangavs 2005).

Stratigraphy and lithology of Pampean sediments: the meaning of the Pampean Formation

Darwin typified the sediments of the Pampean Formation as "...*a dull reddish, slightly indurated argillaceous earth or mud, often but not always, including in horizontal lines concretions of marl, and frequently passing into a compact marly rock*..." (Darwin 1846, p. 89). The reddish argillaceous earth was named "*Pampean mud*". Darwin emphasized the great extent of the Pampean Formation as one of its most striking features. According to his own observations and the reports from d´Orbigny and other travelers he considered that the unit extended from the vicinity of Rio Colorado in the south to beyond Santa Fe in the north "…*M. d´Orbigny traced it for 250 miles further north*…"(Darwin 1846, p. 97); and from Banda Oriental (Uruguay) in the east to Cordoba to perhaps Mendoza in the west. Finally he stated "… *the area of the Pampean Formation, as remarked by d´Orbigny is at least equal to that of France and perhaps twice or three as great*…" (Darwin 1846, p. 97). Thus Darwin correctly perceived what we now know to be the great geographic extent of the Pampean Formation.

Darwin also stressed the lithological homogeneity of the sediments that he grouped into a single unit, the Pampean Formation. The concept of Formation (*gebirgsformation*), as a geological unit, was coined by Abraham Gottlob Werner (1749-1817), a German geologist from the School of Mines at Freiberg, with the purpose of defining a historical entity that included rock bodies formed during the same time interval; at a higher hierarchical rank, the term terrain grouped several formations. Both terms, formation and terrain, although representing units of different stratigraphic hierarchy, were later used as synonyms by other authors. Nevertheless, during the decade of the 1840s, the term *formation* took root in the Anglo-Saxon community, while terrain, as a synonym of formation, was adopted in the French geology literature (Podgorny *et al.* 2008).

Since Darwin´s visit, several other researchers have stressed the apparent lithological homogeneity of the Pampean sediments. At a regional scale of analysis the deposits look rather alike, dominantly composed of sandy silt and silts of light brown to reddish brown colors, common presence of calcareous accumulations of various morphologies and a general massive appearance. This perception of lithological homogeneity was accentuated by the nature of the exposures, scattered and discontinuous outcrops of relatively reduced thickness and mostly situated along river banks, which constrain the detailed analysis of the spatial and temporal relationships of the sediments. Exceptions were the exposures along the Río Paraná and the Monte Hermoso sea-cliff, where Darwin was able to examine the deposits and their paleontological content in better exposures. To examine the Pampean subsurface he described the lithology of some wells in the vicinity of Buenos Aires and south of Bahia Blanca:"… *in a well at the depth of seventy feet, according to Ignatio Nunez, much tosca-rock was met with, and at several points, at 100 feet deep, beds of sand have been found...*" (Darwin 1846, p. 77). Also, 50 km SE Buenos Aires, along the coast of Rio de la Plata at Ensenada (Fig. 2), Darwin examined the exposures of a quarry "…*specimens from near Ensenada, given me by Sir W. Parish, where the rock is quarried just beneath the surface of the plain...*" (Darwin 1846, p. 78).

Since the mid-XIX century, many contributions have been focused on the stratigraphy and several different classifications were proposed. The purpose herein is not to make a review of the different stratigraphic classifications, but to stress the concepts and ideas on which the subdivision of the Pampean sediments is based. Up to the present, however, Pampean stratigraphy has remained a controversial and debatable issue; various different schemes are still used simultaneously (Table 1).

The homogeneity of the deposits together with the discontinuity of the exposures forced the search of a criteria other than the lithology to separate the Pampean sediments. Eventually this led to the utilization of the fossil vertebrate content to separate the deposits into different stratigraphic units. Therefore, those

TABLE 1: Some of the best known stratigraphic schemes of the Pampean sediments. Those by Fidalgo *et al.* (1973) and Riggi *et al.* (1986) are currently used.

Ameghino (1908)		Kraglievich (1952)	Frenguelli (1957)	Fidalgo *et al.* (1973)	Riggi *et al.* (1986)
Post pampeano	Platense Lujanense	Fm de Lobería	Serie postpampeano	Fm La Postrera /Fm Luján	Fm Buenos Aires
	Boanerense	Fm de Arroyo Seco	Bonaerense		
	Ensenadense	Fm de Miramar Fm de San Andrés	Ensenadense		
Fm Pampeano		Fm de Vorohué Fm de Barranca de los Lobos		Fm Pampiano	Fm Ensenada
Fm Araucano	Chapalmalense Monte-hermosense	Fm de Chapadmalal	Chapadmalense		

localities with exposures laterally continuous for several km as the Mar del Plata sea-cliffs, the Río Paraná bank exposures and the sea-cliff at Monte Hermoso were subdivided on the basis of their paleontological content (among others Ameghino 1908, Frenguelli 1957, Kraglievich 1952). At the end of the 19th century, the stratigraphic analysis of the Pampean deposits was benefited significantly by deep excavations during the construction of the harbours at Buenos Aires and La Plata. These temporary exposures provided sections several meters thick that became type localities, not later available, to characterize the uppermost interval of the Pampean deposits (Ameghino 1908). The resulting schemes became the groundwork that guided subsequent stratigraphic studies.

Much later, the identification of units on the basis of the vertebrate fossil content evolved into the concept of land-mammal ages (Pascual *et al.* 1965), a fundamental stratigraphic tool still widely accepted and used. In recent years, these biostratigraphic units have been redefined and updated (Cione *et al.* 2007 and references therein). The relative degree of evolution inferred from the fossil assemblages was used in the stratigraphic arrangement of the Pampean deposits. Accordingly, and considering their paleontological content, several units were identified, and classified as lithostratigraphic units (formations) receiving their names after the locality where they were described (among others, Epecuén Formation, Saldungaray Formation, Irene Formation, Arroyo Chasicó Formation; Fidalgo *et al.* 1975 and references therein).

As time passed, in spite of the numerous schemes proposed, *Pampean Formation* or simply *Pampeano* developed into terms that became deeply rooted in the Argentine geological literature; both became synonyms to refer to the Pampean deposits. At present, the term *Pampeano* is still used informally with a rather loose significance. However, general agreement exists to separate the surficial Late Pleistocene-Holocene sedimentary cover from the underlying Pampean deposits. Following this line of reasoning, the prelate Pleistocene deposits exposed in the *Pampa interserrana* and the Salado Basin were grouped again into a single unit, the *Formación Pampeano* (*Pampean Formation*) identified exclusively on the basis of lithological attributes (Fidalgo *et al.* 1973). This proposal is somewhat close to the original meaning given by Darwin to the term *Pampean Formation*. Regardless of its vertebrate fossil content, the unit defined is nevertheless useful for mapping purposes and well descriptions. More recent schemes tend to divide the upper part of the Pampean deposits into two units (Ensenada and Buenos Aires Formations) distinguished on the basis of their paleontological content (Table 1). In turn, the uppermost sedimentary mantle was subdivided into several lithostratigraphic units that represent lithofacies of different geomorphic processes and environmental settings such as eolian, fluvial and littoral deposits (among others Fidalgo *et al.* 1973 a,b).

The Pampean sediments today: current ideas and interpretations

At present the Pampean sediments are lithologically characterized as light brown to reddish brown sandy silts or silty sands, moderately indurated with a general massive appearance. Darwin´s interpretation was that the "...*deposits were accumulated in the former estuary of Rio de la Plata and in the sea adjoining it…*" (Darwin 1846, p. 99); the source area of the Pampean mud was thought to come from the weathering of igneous and metamorphic rocks of Brazil and Uruguay (Darwin 1846, p. 100).

The mineral composition of the Pampean sediments reflects their derivation from volcaniclastic material in turn mostly derived from Andean rocks, with minor contributions (Precambrian granitic and metamorphic rocks and Paleozoic quartzites) from the Tandilia and Ventania ranges in the southern part. Northward, the Pampean ranges of Córdoba and San Luis and the Brazilian shield were secondary source areas (Teruggi 1957, González Bonorino 1965, Zárate 2003 and references therein). A detailed analysis of the deposits reveals grain size changes and variations in the density, color, and mineralogical composition according to the sediment age and the geographic setting considered within the Pampean plain.

The massive appearance and the rather uniform lithology, among other attributes, were usually taken as evidence of an eolian origin and the sediments have been interpreted as loess. Nervertheless, Teruggi (1957) pointed out that the distribution of primary loess was quite limited, a statement reconfirmed by more recent studies (Zárate 2003 and references therein). Across the Pampean environment, primary loess facies have a low preservation potential. The deposits are locally reworked either by aqueous transport agents (loess-like or loessoid deposits) or modified by pedogenesis (weathered loess). Loess-like deposits exhibit a weak and poorly expressed sedimentary structure consisting either of horizontal bedding or cross bedding. Along the piedmont areas, channelized lithofacies representing fluvial paleoenvironments include rock fragments from bedrock of the Tandilia and Ventania ranges. At distal settings from the ranges, the coarse fluvial facies are made up of bones and *tosca* fragments embedded in a sandy matrix.

Paleosols are a very common feature with pedogenic traits (pedogenic structure, textural changes resulting from eluviation, carbonate leaching, evidences of bioturbation features from soil microfauna and vegetation) distributed throughout the Pampean sediments. Welded paleosols resulting from the superposition of pedogenetic process have been reported in both Pliocene and Pleistocene stratigraphic sections of the Pampean succession. Micromorphological studies also point to the occurrence of intervals when sediments accumulated progressively on the surface while soil formation was active, resulting in accretionary soil surfaces. From a sedimentological perspective, the occurrence of numerous paleosol levels throughout the deposits documents an episodic sedimentation process. Due to the ubiquity of pedogenic features, the Pampean succession is interpreted as a pedosedimentary sequence (i.e. Kemp and Zárate 2000, Zárate *et al.* 2002). The presence of welded paleosols and intervals of accretionary pedogenesis suggest a variable balance of pedogenesis and sedimentation through time. At some sections, the occurrence of discrete paleosol levels, stratigraphically superposed, allow inferring some sort of cyclicity in soil formation that has been related to climatic changes (among others Nabel *et al.* 2000, Kemp and Zárate 2000).

Yet not assessed, bioturbation structures are an outstanding feature of the Pampean sediments. Not only are there traces of invertebrates in the sediments, particularly those beds more intensely modified by pedogenesis, but also burrows, caves and galleries (krotovinas) excavated by small rodents and larger mammals, mainly xenarthrans (Vizcaino *et al.* 2001). The resulting structures are filled in by diamicton-like deposits, including fragments of *tosca*, paleosol aggregates and bones redeposited by water. Also, some burrows and caves are filled with eolian and/or fine grained laminated sediments.

In the Pampean sediments, minor erosive episodes are recorded by both the partial truncation of paleosol surfaces and the local incision of fluvial paleochannels (Ruocco 1989, Zárate and Fasano 1989). Three major episodes of landscape reactivation, inferred from stratigraphic analysis and gemorphological evidence, are documented by cycles of fluvial incision. These generated erosional unconformities in the sedimentary record as well as terrace formations and different aggradational surfaces in the Sierra de la Ventana piedmont (Zárate 2005).

Carbonate accumulations of the Pampean sediments: the *Tosca*-rock

Darwin gave special attention to the calcareous accumulations in his general characterization of the Pampean Formation. The duricrust (calcrete) that caps the sediments in the *Pampa interserrana* area, and constitutes massive accumulations in some other locations, was described as a *marly rock* and named *tosca-rock*, after the popular term given to the carbonate deposits by the local Pampean inhabitants (Darwin 1846). He reported the morphology (*nodular and stalactiform concretions, compact stratified tosca rock*), the relation with the Pampean mud, as well as the geographical distribution and relative occurrence (more frequent outcrops of *tosca* in the area of the ranges and the

Pampa interserrana, general scarcity of *tosca* exposures in the Rio Salado basin, almost no *tosca*-rock in northeastern Buenos Aires province:"… *At Arroyo del Medio the bright red Pampean mud contains scarcely any tosca-rock…*", "… *At Rosario there is but little tosca-rock...*" (Darwin 1846, p. 87). He also made comparisons of *tosca* samples collected throughout the Pampas, referring to their similar characteristics (*the absolute identity* in his own words) of specimens collected in the northern Pampas, Tandilia (Tapalqué) and south of Bahia Blanca. In addition, thin sections of *tosca* were petrologically analyzed by a colleague "...*Dr Carpenter has kindly examined under the microscope, sliced and polished specimens of these concretions and of the solid marl-rock collected in various places between the Colorado and Sta Fe Bajada….*" (Darwin 1846, p. 77).

Despite the economic importance of calcareous crusts as a source of road building material and in agricultural development across most of the southern Buenos Aires Pampean plain, no detailed and systematic studies of these materials have been carried out. In the *Positivo Bonaerense* area, the morphology and thickness of calcretes vary according to the relative age of the geomorphic surfaces that they cover. The oldest crust capping late Miocene-Pliocene deposits is up to 1.5-2 m thick. The general morphology of calcretes suggests a high degree of relative development close to morphological stages 5 and 6 as defined by Machette (1995). Thus, a typical calcrete section is usually composed of three main parts from top to bottom. The uppermost part is made up of platy calcrete consisting of 5-10 cm thick indurated layers, showing an irregular horizontal fracturing (Fig 5B). Lamination, brecciation, and dissolution are very common features suggesting a very complex history of multiple episodes of carbonate precipitation and weathering on the surface. The middle part consists of powdery and massive carbonate grading downward into the host Pampean sediments or showing a very sharp lower contact (erosional surface) on those deposits. Carbonate nodules, concretions and massive accumulation of *tosca* are also very frequently found. Studies on specific accumulations suggest different mechanisms of formation, such as precipitation from phreatic waters, capillary rise, and pedogenic carbonate leaching (Bk horizons) (Tricart 1973, Imbellone and Teruggi 1986).

Age and origin of the Pampean sediments

On the basis of its lithological homogeneity (similar composition) and "...*the apparent absolute specific identity of some of its mammiferous remains...*" (Darwin 1846, p. 100), Darwin inferred that all over its large area the Pampean Formation belonged to the same geological epoch. This age interpretation followed Charles Lyell´s ideas, where the percentages of living and extinct mollusks was a fundamental tool for assigning relative ages to the Tertiary strata. He collected some of the mollusk shells from late Pleistocene-Holocene marine deposits exposed along the Pampean coastal fringe. At Punta Alta Darwin considered that the proportion and specimens of shells found in the sediments was comparable to those species living today in the bay. Therefore, taking into account the paleontological content including living species of mollusks that he considered contemporaneous with the *mammiferous remains* found in the sediments, Darwin attributed the Pampean Formation to the Recent Period or what is now called the Holocene. From a stratigraphic viewpoint, Darwin recognized stages in the Pampean Formation on the basis of both the different altitudes shown by the outcrops of Monte Hermoso, Punta Alta and Sierra de la Ventana, and an observation now regarded as a taphonomic attribute of a fossil remnant: "...*From the rolled fragment of black bone and from the plain of Punta Alta being lower than that of Monte Hermoso, I conclude that the course sub-littoral deposits of Punta Alta are of subsequent origin to the Pampean mud of Monte Hermoso; and the beds at this latter place… are probably of subsequent origin to the high tosca-plain round the Sierra Ventana...*" (Darwin 1846, p. 87).

The Pampean succession is now interpreted as the late Cenozoic (approximately the last 12 Ma) continental record of central Argentina. Sediments of the Pampean succession accumulated after a Miocene regression of the Paranense sea (Folguera and Zárate, submitted). Major differences are evident with regard to the regional distribution of the deposits. Fidalgo *et al.* (1975) mapped the exposures bearing Late Miocene and Pliocene vertebrate fossil assemblages, showing a distribution restricted to the *Positivo Bonaerense* area. Darwin examined an outcrop on the bank of the Río Sauce Grande noting that "...*there is an imperfect section about 200 feet high displaying in the upper part tosca rock and in the lower part red pampean mud...*". This likely corresponds to late Miocene?-early Pliocene sandy siltstones. Several other outcrops are discontinuously exposed along other neighboring river systems as well as some railroad cuts. Northward, in the Río Salado valley, the relatively oldest exposures of Pampean sediments are much younger (Pleistocene s*ensu lato*, see below). These deposits consist of compacted clayish silts and sandy silts, showing evidence of hydromorphic conditions (mottles, greenish colors, manganese nodules, massive carbonate accumulations).

Considering the stratigraphic relations, numerical ages and relative ages inferred from the vertebrate fossil assemblages, the Pampean succession of sedimentation has been recently subdivided into four stratigraphic intervals, interpreted as subcycles of sedimentation (Zárate 2005) (Table 2).

The oldest sedimentary subcycle, is exposed in the *Positivo Bonaerense* and the northern part of the Colorado tectonic basin. It is composed of Late Miocene deposits (11-12 Ma to *circa* ?7-6 Ma) bearing Chasicoan and Huayquerian fossil remains. These deposits have an average thickness of 150-200 m, and overlie the Precambrian and Paleozoic bedrock of

Figure 5: Plain edge in the area of Bahía Blanca. a) Plain surface with a thin eolian cover and fragments of calcrete, Atlantic Ocean in the background; b) Calcrete section at a quarry showing typical platy structure in upper part, grading downward into Pliocene sediments. Note hammer for scale.

Pampa interserrana. The geographical distribution of this unit is broad, extending southwestward into La Pampa province (Folguera and Zárate, submitted). Geomorphologically, these late Miocene deposits, capped by the thickest calcrete crust form the very extensive plain within which the present river valleys were excavated.

The second sedimentary subcycle, represented by late Miocene?-early to late Pliocene deposits (?7-6-3.2 Ma) is discontinuously exposed along the river banks of the drainage system. The deposits include Huayquerian, Montehermosan and Chapadmalalan fossil remains. The outcrops are located in the *Positivo Bonaerense* and distributed throughout the Sierra de la Ventana piedmont, the valleys of Quequén Salado, Quequén Grande as well as of minor streams of the southern part of *Pampa interserrana*, and along the lower section of the Mar del Plata-Chapadmalal sea-cliffs. The Monte Hermoso stratigraphic section (Quattrocchio *et al.* 2009) is included in this cycle of sedimentation. Farther southward, deposits of comparable age crop out in the Colorado tectonic basin. Exposures up to 15 meter thick and 200-300 m long can be found at various quarries in the surroundings of Bahia Blanca. The sediments consist of fluvial facies, including rock fragments from Sierra de la Ventana, capped by a 1-1-5 meter thick calcrete (Folguera and Zárate, submitted). Darwin explored the very top part of the exposures (Fig. 5a) "…*At the settlement of Bahia Blanca, the uppermost plain is composed of very compact, stratified tosca rock containing rounded grains of quartz distinguishable by the naked eye*...". Further eastward, deposits of this cycle still poorly known, crop out along the lower reaches of the Quequén Salado and the Quequén Grande rivers; Huayquerian, Montehermosan and Chapadmalalan fossil remains have been exhumed (among others Verzi *et al.* 2008). Along the Mar del Plata-Chapadmalal sea cliffs, this stratigraphic interval is composed of early to late Pliocene (3.2 to 4.5-5 Ma), massive siltstones with well developed paleosols bearing Chapadmalalan fossil remains.

The third subcycle of sedimentation (late Pliocene-late Pleistocene *circa* 3.2 Ma-0.040/0.030 Ma) includes deposits bearing Marplatan, Ensenadan and Bonaerian fossil remains. They are distributed in the Salado tectonic basin, forming the bedrock in which fluvial valleys are excavated. The lower sections of deep quarries sometimes penetrate levels containing Ensenadan fossil mammal remains. Rabassa (1973) reported sediments bearing Ensenadan fossil remains in the central part of Tandilia range. These deposits are also discontinuously exposed along the SW piedmont of Tandilia, along the Atlantic coast between Mar del Plata and Miramar. The late Pliocene-late Pleistocene subcycle unconformably overlies Pliocene siltstones along the Mar del Plata sea cliff. Included in this subcycle are the Sauce Grande fluvial terrace sediments with Bonaerian fossil remains reported by Deschamps (2005).

TABLE 2: Age, geographic distribution and fossil mammal remains of the subcycles of sedimentation identified in the Pampean deposits (after Zárate 2005).

Age of sedimentation subcycles	Morphostructural unit	Areal distribution	Fossil remains stage/age Cione *et al.*(2007)
Late Pleistocene-Holocene 0.040-0.030 Ma-present	-Positivo Bonaerense -Salado and Colorado tectonic basins	-Eolian mantle covering the entire region -Fluvial sequence of present Pampean river systems	Platan Lujanian
late Pliocene-late Pleistocene circa 3.2 Ma-0.040-0.030 Ma	-Positivo Bonaerense -Salado tectonic basin	-Tandilia piedmont and intramountain valleys -Fluvial terrace Río Sauce Grande -Lower reaches of Pampa interserrana fluvial valleys? Bedrock of fluvial valleys	Bonaerian Ensenadan Marplatan
(Late Miocene?)-early to late Pliocene 7-6? to 3.2 Ma	-Positivo Bonaerense -Colorado tectonic basin	Pampa interserrana, Ventania piedmont. Tandilia piedmont. Chasicó depresión Colorado valley.	Chapadmalalan Montehermosan Huayquerian
Late Miocene-(early Pliocene?) 11-12 to 7-6? Ma	-Positivo Bonaerense basin, Macachín tectonic basin -Bloque de Chadileuvú -Colorado tectonic basin	Pampa interserrana, Piedmont of Ventania Structural plain of La Pampa province Chasicó depression	Huayquerian Chasicoan

Along the Atlantic coast, between Miramar and west of Necochea, the sea cliffs are composed of fine sandy facies including diamicton layers with a high content of calcareous nodules and capped by a platy calcrete. Inland, at a distance of several kilometers from the coastline, the uppermost 2 meters of these deposits are exposed in numerous quarries and roadcuts, suggesting that they form an extensive plain. The stratigraphic and geomorphologic relationship with older deposits is still unknown. The lithofacies are similar to the Pleistocene exposures of Mar del Plata and might be part of the late Pliocene-late Pleistocene subcycle of sedimentation which should be confirmed in future studies.

The most recent subcycle of sedimentation (40-30 ka-to the present) is composed of a large eolian apron along with fluvial deposits accumulated during the last glacial cycle. Recent numerical ages obtained in fluvial deposits of northern Buenos Aires point to an older age for the beginning of this cycle of sedimentation (Blasi *et al.* 2008). The eolian lithofacies constituting the parent material of the present cultivated soils are composed of sandy deposits towards the west, grading into sandy silts and silt east and northeastward. In the *Pampa interserrana* area the eolian mantle consists of loessial sands, sand mantles, and sandy loess (Zárate and Blasi 1993, Bidart 1996), representing proximal eolian facies derived by deflation from the Río Colorado flood-

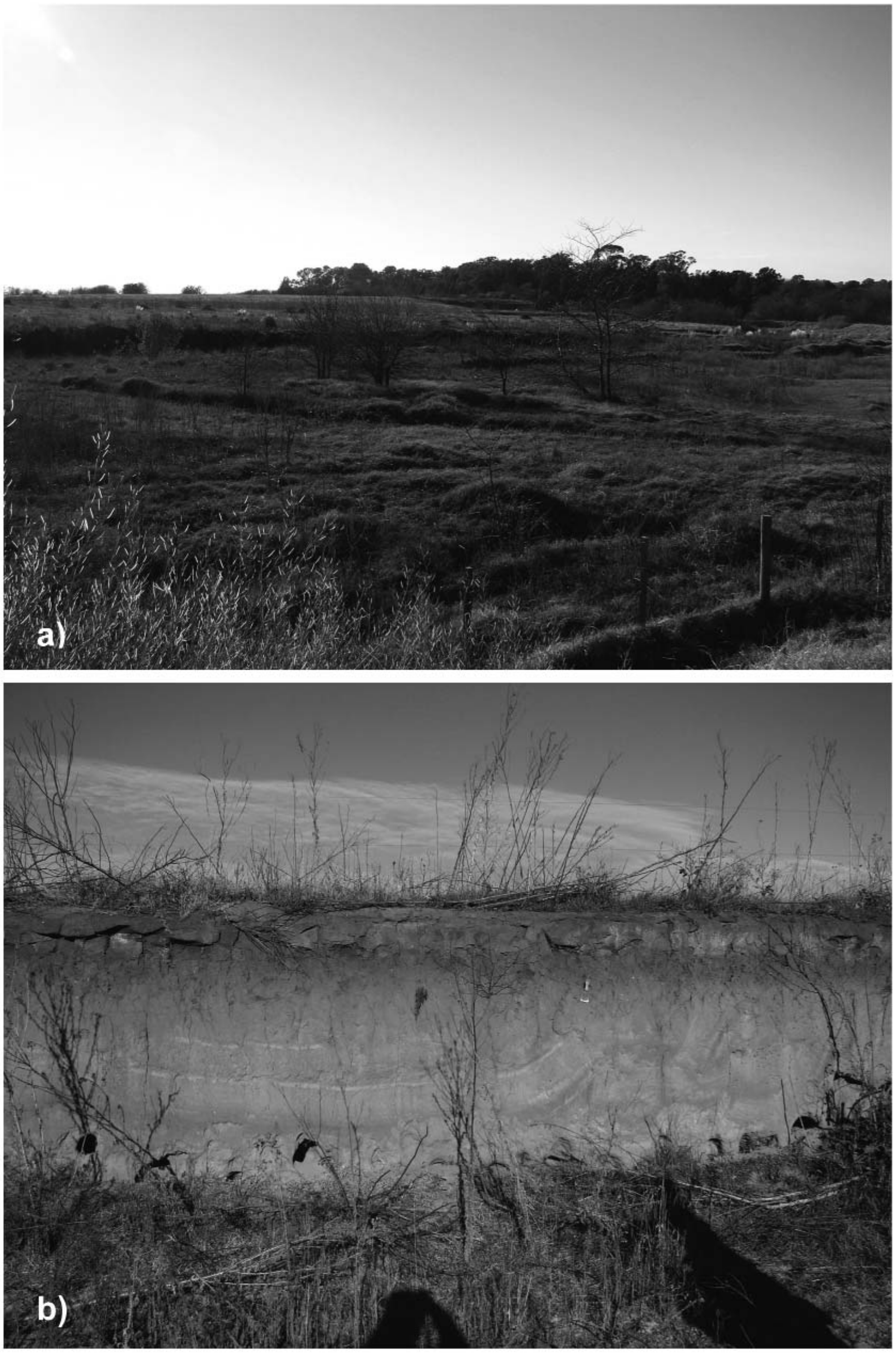

Figure 6: The Río Salado Valley, south of San Miguel del Monte (Guardia del Monte). a) Hill on the northeastern-eastern side of the Río Salado floodplain; b) Quarry excavated at the hill showing a 3 m thick loess section; present soil developed on top.

plain. In the area of the Río Salado valley, the eolian facies are made up of silty deposits (loess) named La Postrera Formation by Fidalgo *et al.* (1973) (Fig. 6b).

FINAL REMARKS

Darwin as well as many other researchers after him emphasized the relatively uniform lithological composition, the vast extent and the rich vertebrate fossil content of the Pampean sediments. His perception of the Pampean environment illustrated not only the major landscape differences but also some key lithological features of the deposits. To date, the geographical distribution of exposures of different ages suggests significant variations of the sedimentary dynamics throughout the region, and four main subcycles of sedimentation have been identified. The outcrops of the first two cycles recording the late Miocene and most of the Pliocene sedimentation are restricted to the *Positivo Bonaerense* (Sierra de la Ventana piedmont, part of *Pampa interserrana* and Sierras de Tandil). A remarkable geomorphological characteristic of this southern area is the occurrence of several intervals of landscape stability documented by the development of calcrete crusts (*tosca*-rock) on topographic surfaces of different ages. During the very late Pliocene-Pleistocene, sedimentation continued in the piedmont of Sierras de Tandil and the Salado tectonic basin. In the meantime, the *Positivo Bonaerense* was geomorphologically much more stable with episodes of fluvial incision along the main river systems. Yet, no information is available on the Laprida depression, the swampy environment crossed by Darwin, and the Atlantic fringe where possible Pleistocene deposits are exposed. In both the *Positivo Bonaerense* and the Salado tectonic basin, the last subcycle of sedimentation is related to incision of the present fluvial valleys sometime *circa* 40 ka and the accumulation of an eolian mantle during the last glacial cycle.

What was the primary control of sediment accumulation at a regional scale?. Why did sedimentation cease in the late Miocene over a vast area of *Positivo Bonaerense*?. Which factor triggered the subcycles of sedimentation now identified?. At present, research in progress is addressing these main questions. The studies under way are focused on the potential role that might have been played by both Andean tectonism and tectonic dynamics of the Colorado and Salado basins. With this purpose, future stages of current research will be mainly directed towards establishing improved chronological control of the deposits along with detailed mapping and sedimentological analysis of the areas, still poorly known (the northern area of *Pampa interserrana*, the Laprida depression and the Atlantic sea cliff west of Mar del Plata.

Last but not least, the *Geological Observations on South America* was read by one of us (MZ) in the early 1980s. From the present perspective, after almost three decades of exploring the geology of this vast environment, Darwin´s careful and detailed descriptions and his interpretations, capture the attention of those of us who have devoted time and patience to understanding the nature of the Pampas.

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