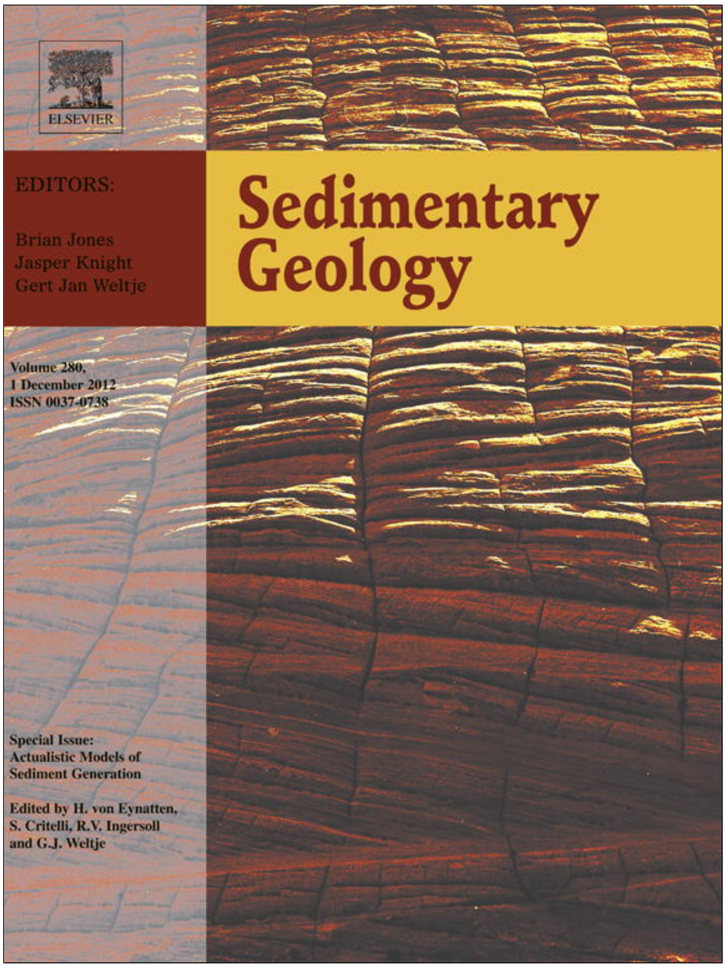
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Composition and provenance of Late Pleistocene–Holocene alluvial sediments of the eastern Andean piedmont between 33 and 34° S (Mendoza Province, Argentina)

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ABSTRACT

The Andean cordillera, and its piedmont in the central western Argentina, has been long considered as one of the main source areas of detritus for the Chaco–Pampean plain sand dune fields and loess/loess-like deposits of central Argentina. The main goal of this study is to evaluate the composition of the late Pleistocene-Holocene alluvial deposits of the Andes cordillera piedmont, from 33° to 34° S. The results are interpreted in the context of the regional geology, tectonic setting of the study area and its implications in the continent-wide perspective of modern alluvial sands proposed by Potter (1994). Sampling was conducted at the alluvial stratigraphic sequences of four study sites along three Andean piedmont arroyos; modal mineralogy in the very fine sand fraction (3 phi to 4 phi) was determined using standard petrographic microscope methods.

Q:F:LF average compositions indicate that the Late Pleistocene-Holocene very fine-grained alluvial sands of the Cordillera Frontal piedmont reflects the modern lithic arenites of the Argentine Association reported by Potter (1994). The results show two geologically distinct sources in the catchment areas, volcaniclastic and metamorphic rocks. High concentrations of mica and volcanic glass are likely related to particle morphologies and to the deposition sedimentary environment recorded in the alluvial sequences—floodplains. The overabundance of micas over the volcanic glass in the mid-late Holocene alluvial sequence indicates the drainage of a metamorphic area at the expense of other lithological sources. Source areas are located mainly in the Frontal cordillera, and to a lesser extent, in the piedmont Tertiary deposits, another likely source for the analyzed Quaternary alluvial sediments. The mineralogical signature of the late Pleistocene and Holocene alluvial sequences is in agreement with the composition of the southern Pampean sand mantles, loess and loess-like deposits mainly formed by a volcanic mineral assemblage with source areas placed at the headwaters of the main Andean rivers.

1. Introduction

The knowledge of detrital modes of Holocene sands of recognizable parentage should be a key thing to interpret ancient deposits (Basu, 1976). Potter (1978, 1994) and Franzinelli and Potter (1983) studied the modern sands of South American rivers to provide a worldwide model for sand production when studying ancient sandstones. In a continent-wide perspective, an Andean family of lithic arenites, together with the Transitional and the Brazilian families, has been described (Potter, 1994). The Andean family comprises an Argentine Association of modern river sands mainly dominated by volcanic grains, though an appreciable content of metamorphic grains is recorded (Fig. 1a and b). In such a context, and to contribute to the understanding of sand modern transport, some contributions focused on the analysis of textural characteristics of Quaternary detrital alluvial sands in Argentinean rivers. Among others, Mazzoni and Spalletti (1972) studied the *Río Grande de Jujuy* basin, Cordini (1949), Orfeo (1996) and Manassero et al. (2008) analyzed the Paraná River basin, and Blasi (1986) and Blasi and Manassero (1990) recorded the mineralogical features of the *Colorado* River and its tributaries, one of the main fluvial basins of central Argentina (~36°–39° S) draining the waters collected in its Andean headwaters to the South Atlantic Ocean. The Colorado River data show a volcanic association with a QM-F-L proximal average detrital mode of 8–39–53, an average of 13–50–57 for intermediate sands and of 18–22–60 for distal sands placed in the South Atlantic edge; indicating that alluvial sand composition is controlled by the relief, drainage systems, climate and tectonic environment of the source area, not necessarily the same tectonic environment along the river course (Blasi and Manassero, 1990).

Despite the existence of these works, no studies report the composition of the alluvial sediments transported by the main fluvial systems of the Andean Piedmont of Argentina in its central western portion—e.g. the drainage network of the *Desagüadero–Salado–Curacó* fluvial system, flowing from 28° S to 38° S along the Andean

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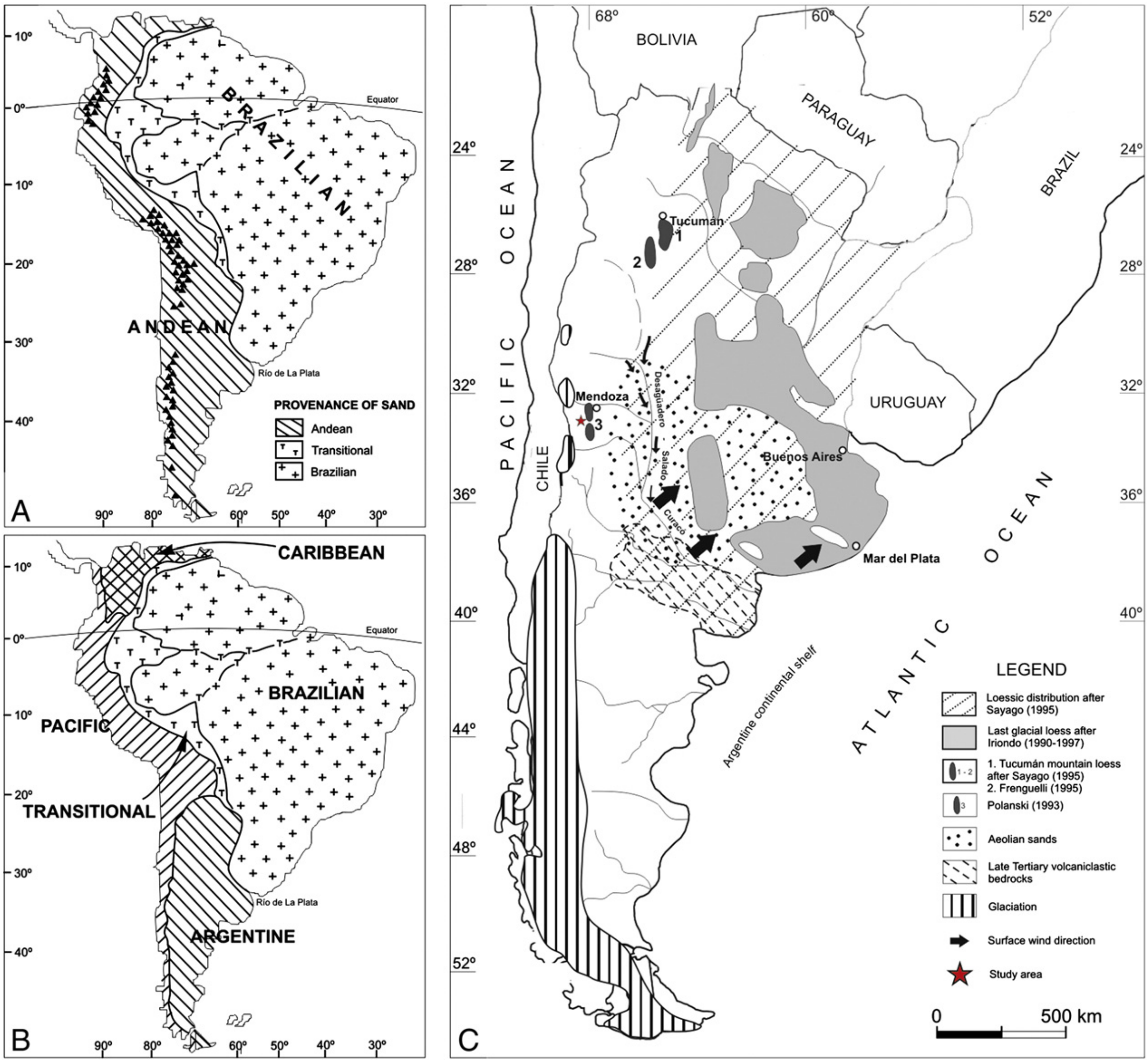

Fig. 1. A) Distribution of the three great families of modern sands across South America (from Potter, 1994). B) Continent-wide mineral associations (from Potter, 1994). C) Distribution of the loess, loessoid and aeolian sands in Argentina (adapted from Zárate, 2007).

piedmont with its several major tributaries that drained the glaciated Andes (Iriondo, 1990; Clapperton, 1993) (Fig. 1c). The Central Volcanic Zone and the Southern Volcanic Zone (SVZ) of the Andean cordillera, and its piedmont areas, have been long considered the main source area of the Chaco–Pampean plain sand dune fields and loess/loess-like deposits of central Argentina (Zárate, 2007). Likely the beginning of the loessoid sedimentation cycle in central Argentina is the consequence of a phase of Late Miocene orogeny in the Andes; with a Plio-Pleistocene record mostly composed of loessoid sediments modified by pedogenesis, and a Late Pleistocene/Holocene loess record exhibiting a heterogeneous composition across the region (Zárate, 2003). An Andean-derived volcanic composition prevails in the southern Pampas receiving a more significant input of loess material from the SVZ, while the northern Pampas and the eastern Chaco also show inputs from the Brazilian shield and the Pampean ranges in the eastern Pampas (González Bonorino, 1966; Zarate and Blasi, 1991, 1993; Zárate, 2003; Etchichury and Tófalo, 2004) (Fig. 1c). The light mineral suite of the southern Pampean sandy loess is dominated by the abundance of volcanic glass and other lesser components such as plagioclase, feldspar, quartz and volcanic rock fragments (Zarate and Blasi, 1991). The loess sediments were derived mainly from reworked pyroclastic deposits, primary tephra units and volcaniclastic sediments (Zárate, 2003, 2007). Different processes have been proposed to explain the nature of the particles forming the Pampean loess. Zárate and Blasi (1993) considered that the explosive volcanism was the most remarkable process leading to the formation of particles composing the southern Pampean loess. South of 28° S, the Andes cordillera was covered by large ice fields during the Late Glacial Maximum (Iriondo, 1997 and references there in); consequently, this region was a very productive source of silt, very fine sand, and illite as a clay mineral through physical weathering processes, with significative glacial and nival processes in the headwater tributaries of the *Bermejo–Desagüadero–Salado* fluvial system (Fig. 1).

The main goal of this study is to evaluate the rock fragment and mineral clast composition of the Late Pleistocene-Holocene very fine-grained alluvial sands of the eastern Andean piedmont between 33° and 34° S (Fig. 2) as a case of study of the wide-continent model proposed by Potter (1978, 1994). The nature of the sediments analyzed in the eastern Andean piedmont is interpreted in the context of the regional geology and tectonic framework of the study area (Figs. 1 and 2); also its implications as an Andean source area of aeolian deposit of central Argentina are considered.

2. Background

2.1. Environmental setting

The study area is located in the eastern piedmont of the Andes cordillera in the Mendoza Province, between 33 and 34° S and 69°–69°30′W (Fig. 2a), a region with a dry climate (Garreaud et al., 2009). At tropical and subtropical latitudes, dry and relatively cold conditions prevail along a narrow strip of land – 200 km – placed to the east of the Andes and known as American Arid Diagonal (Bruniard, 1982; Garreaud et al., 2009). Warm and humid conditions reign in the foreland from the Andes foothills to the Atlantic coast (Garreaud et al., 2009). The Mendoza Province lies on a temperature gradient with mean annual values decreasing from near 15 °C in the eastern plains to values lower than 5 °C in the western mountain region (Hudson et al., 1990). The study area has an arid climate with great thermal fluctuations during the day and among seasons (Compagnucci et al., 2002). The mean annual seasonal precipitation

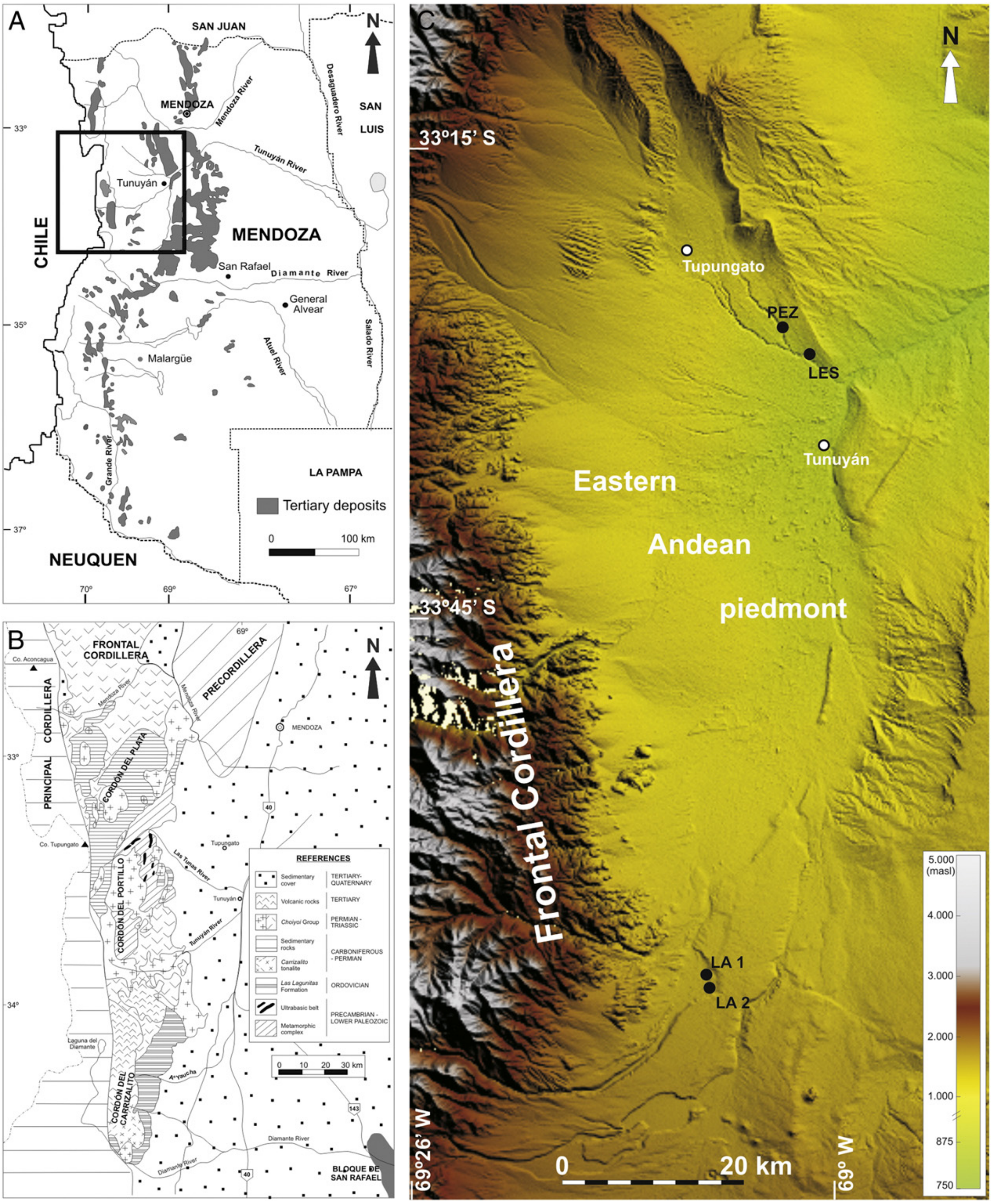

Fig. 2. A) Location map and Tertiary rock outcrops in Mendoza Province. B) Generalized bedrock geology map of the Frontal cordillera and its piedmont in Mendoza Province between 33° S and 34° S (adapted from Tickyj et al., 2009). C). Relief map and fluvial drainage network of the study area; PEZ (Puente El Zampal), LES (La Escala), LA1 (Los Alamitos 1) and LA2 (Los Alamitos 2) study sites.

averages 200 mm, occurring in short but relatively heavy rains during the austral spring and summer seasons (Barros and Silvestri, 2002). As a result a semidesert xeric vegetation has developed (Roig and Martínez Carretero, 1998). The region is under the influence of the semi-permanent subtropical Pacific anticyclone and the semi-permanent subtropical Atlantic anticyclone with prevailing winds coming from the southeast, with a higher frequency and intensity in the spring and summer.

Also, characteristically warm and dry winds descending down-slope from Andes mountains – known in the region as *Zonda* wind – occasionally affect the area in the autumn and winter (Prohaska, 1976; Hudson et al., 1990).

2.2. Geological setting

The studied alluvial sequences are located in a distal position in relation to the catchment basins of the arroyos draining the piedmont. The headwaters develop almost entirely in the Frontal cordillera, unit that together with the Cordillera Principal forms the main Andean ranges at this latitude. The Frontal cordillera contains 1) Proterozoic metamorphic rock complexes, 2) Ordovician metasedimentary rocks, 3) Carboniferous-Permian sedimentary rocks, 4) eruptive and intrusive igneous rocks of Permian-Triassic age and 5) Quaternary volcanic rocks (Fig. 1c).

In the area of *Cordón del Plata* (Fig. 2b) a metamorphic basement is exposed. It contains mostly low grade metasedimentary rocks – gray phyllites and calcareous schists – and meta diabase veins (Vujovich and Gregori, 2002). Also marine Upper Carboniferous to Lower Permian sedimentary sequences are exposed (Azcuy, 1993; Llambías et al., 1993) (Fig. 2b). Southwards, the area is composed of heterogeneous low to medium metamorphic sedimentary rocks with mafic and ultramafic rocks (Vujovich and Gregori, 2002 and references therein). The *Cordón del Portillo* area (Fig. 2b) exhibits a higher metamorphic sedimentary sequence composed mainly of schists and amphibolites (Caminos, 1993) and an associated regional contact metamorphism produced by the injection of Carboniferous age batholiths (Caminos, 1993). Finally, the southern extreme of Frontal cordillera known as *Cordón del Carrizalito* (Fig. 2b) is composed of an Ordovician metasedimentary sequence of variable metamorphic grade (Tickyj et al., 2009).

An extensive Permian-Triassic igneous record, the *Choiyoi* Group, occurs across Frontal cordillera. Pyroclastic processes dominate the Lower to Upper Triassic units with fewer intrusive rocks (Llambías et al., 1993). Also, Tertiary and Pleistocene rocks related to volcanic events are present (Polanski, 1963; Ramos and Nullo, 1993 and references therein; Sruoga et al., 2005).

At the study area, the piedmont of Frontal cordillera is composed of several alluvial lithostratigraphic units spanning the Pleistocene and the Holocene (Polanski, 1963) (Fig. 2b). The proximal piedmont is composed of Early to Late Pleistocene alluvial conglomerates while the distal piedmont is covered by a psammitic–pelitic alluvial sequence of Late Pleistocene-Holocene age, with the oldest exposures of ca. 50 ka BP located along cut banks of arroyos (Toms et al., 2004; Zárate and Mehl, 2008). A tectonic depression, the Tunuyán Depression, is filled with Middle to Late Quaternary deposits (Polanski, 1963) and is situated in the northern part of the study area. To the south, the area known as 'Valle Extenso del Campo Bajo', is mostly covered by Mid-Pleistocene pyroclastic deposits (*Asociación Piroclástica Pumícea*, Polanski, 1963) and exhibits Quaternary NW–SE faults concurrent with a transtensive structural regime (Perucca et al., 2011).

3. Methods

Sampling, focused on the rock fragment and mineral clast composition of alluvial sediments, was conducted at four exposures along the cut banks of Arroyo Anchayuyo, Arroyo La Estacada and Arroyo Yaucha (Fig. 2c). There Late Pleistocene and Holocene alluvial sequence outcrops show a predominance of psammitic and pelitic sediments, including some minor psephitic deposits (Mehl and Zárate, 2012 referred). The alluvial sequences of Arroyo La Estacada and its tributary the Arroyo Anchayuyo (Fig. 2c), are located at the northern tip of the Tunuyán depression. They compose three geomorphological units, an aggradational plain, a fill terrace and the present floodplain (Zárate and Mehl, 2008; Mehl and Zárate, 2012). The first two units are analyzed in this contribution. The El Zampal study site (33°26′52″S and 69°03′09″W), placed at the banks of Arroyo Anchayuyo and in the aggradational plain unit, records Late Pleistocene-Early Holocene sediments (Fig. 2c; Zárate and Mehl, 2008; Mehl and Zárate, 2012); while the Mid -to Late Holocene sediment record occurs at the La Escala study site (33°28′47.4″S and 69°01′15.8″W), situated at the banks of Arroyo La Estacada and in the fill terrace unit (Fig. 2c; Zárate and Mehl, 2008; Mehl and Zárate, 2012).

To the south, in the Valle Extenso del Campo Bajo area, the Lateglacial and Holocene alluvial deposits of the arroyo Yaucha compose two different fill terraces. These sediments were sampled at Los Alamitos 1 and Los Alamitos 2 study sites (34°03′54.36″S y 69°08′03.97″W; Fig. 2c) (Mehl and Zárate, 2012).

Grain size analysis was carried out with a particle size analyzer with a measuring range from 0.01 μm to 2000 μm—*Malvern Mastersizer Hydro 2000 μc* sampler. The samples were texturally classified according to Folk (1954, 1980). Organic matter and calcium carbonate contents were initially removed using hydrogen peroxide and a solution of hydrochloric acid both at a concentration of 10%.

Twenty four sediment samples with higher relative percentages of sand than the rest of the samples were chosen for the compositional analysis, according to the methodology used by Teruggi (1964), Teruggi et al. (1959) and Etchichury and Remiro (1967) to study littoral sediments of the Argentinian Atlantic coast. The analyzed very fine sand fraction (3 phi to 4 phi) is the most abundant size class of sand in the study area, and in some cases the only. This sand size was separated by sieving and then mounted in fixed with an ultraviolet adhesive of a known refractive index. These grain mounts were analyzed using a Nikon Eclipse E400 Pol. For grain mounts the very fine sand class is the most suitable for petrography studies (Milner, 1962; Pérez Mateos, 1965; Blasi, 1986). In bigger fractions most of the translucent minerals look as opaque minerals, while smaller fractions could obstruct the study and lead to imprecise determinations (Blasi, 1986); Dell (1959a,b) states that medium sand grains are too large to be mounted in a fixed thin-section while the fine sand size fraction could be easily mounted in balsam being large enough for easy identification with petrographic microscope. Likewise, Pollack (1961) considered that textural properties such as clast roundness could be easily identified in this size fraction.

Two hundred grains per grain mounts were counted on average and recalculated into mineral percentages. Detrital grain morphology (e.g. roundness and sphericity according to Powers, 1953; habit; crystalline structure,) along with alterations and their types (e.g. produced by weathering or hydrothermal solutions) were also described. Q:F:LF relations (association of total greatest stable components – e.g. quartz – , most abundant unstable single-crystal grains – e.g. feldspar – and unstable polycrystalline grains—e.g. lithic fragments and mixed pyroclastic) were established for each of the study sites considered.

4. Results

4.1. Grain size of the detrital alluvial sediment

At arroyo La Estacada basin, both the aggradational plain and the fill terrace sedimentary deposits are well sorted with a mean grain from silts to medium sands varying from ~6.64 phi to ~4.18 phi at Puente El Zampal study site and from ~7.16 phi to ~1.80 phi at La Escala study site. A few medium to coarse sand beds are interbedded within the alluvial sequences. Sedimentary sequences at arroyo Yaucha are characterized by sand, sandy silt and silt textures with mean grain sizes ranging from ~5.21 phi to ~0.65 phi in the Late Pleistocene-Early to Middle Holocene upper terrace (Los Alamitos 1 study site) and from ~5.80 phi to ~2.38 phi in the Mid -to Late Holocene lower terrace (Los Alamitos 2 study site). Values derived from the granulometric analysis suggest a uniform grain size trend along the analyzed alluvial sequences in accordance with the distal fan and the fluvial sinuous depositional environments inferred by Zárate and Mehl (2008) and Mehl and Zárate (2012 referred).

4.2. Very fine sand grain types

Variable proportions of volcanic glass, mica and alterites dominate the piedmont alluvial sedimentary sequences of Late Pleistocene-Holocene age (Fig. 3). The abundance of volcanic glass grains is inversely proportional to the amount of mica. Rock fragments and quartz grains are also abundant, but the amounts are lower than that of volcanic glass and mica. Accessory minerals include a light mineral fraction containing K-feldspars, plagioclases, mixed pyroclasts and a heavy mineral assemblage containing pyroxenes (hypersthene, augite, enstatite, diopside), amphiboles (hornblende, basaltic hornblende), epidote and olivine (Fig. 3). Grain surfaces are usually clean and fresh, with exception of alterite grains. Very fine sand grains range from angular to subrounded.

4.2.1. Major components

4.2.1.1. Volcanic glass. It is one of the major components of very fine alluvial sands ranging from 4% up to 71%. The volcanic glass shards are angular to subangular, and most of them have fluidal structure. They show a frothy appearance because of the presence of microvacuoles, and also a dirty aspect due to clay fillings in vacuoles and channels. Massive, clear glass shards are also present. Colorless volcanic glass shards are dominant, with a lesser proportion of light brown clasts (Fig. 3a and b).

4.2.1.2. Mica. Mica grains range from 1% to 88%, and they are mainly composed of muscovites with lesser biotite and chlorite. Most muscovites are colorless to yellowish. Mica alterations are mainly sericite, but there is also a green color alteration that might correspond to chlorite or epidote. Most grains have a straight extinction but some have undulose extinction (Fig. 3j–l).

4.2.1.3. Alterites. This group includes grains so altered by chemical weathering or hydrothermal solutions that identification of the precursor grain is not possible. Alterite abundance varies from less than 1% to 33%. Grains are rounded to sub-rounded with a dark brown to reddish-yellow color. Most of them show a coating likely of iron sesquioxides or clay minerals. Due to a thorough alteration some grains look like opaque minerals.

4.2.1.4. Rock fragments. These clasts were mainly derived from volcanic rocks, e.g. aphanitic or felsitic texture grains with abundant tabular phenocrystals of feldspar or maybe quartz, some of them surrounded by a glassy mass. Trachytic, trachytoid or poikilitic textures are the most common. Also, some lithic clasts were recognized to be composed of two or more mineral crystals e.g. quartz and plagioclase, mica and quartz, heavy minerals and plagioclases. Rounded to sub-rounded grain morphologies are associated with felsic or glassy clasts, while sub-angular to sub-rounded rock fragments are linked to grains formed by two or more mineral crystals (Fig. 3e and f).

4.2.1.5. Quartz. Quartz is less abundant than volcanic glass, mica and alterites, but similar to lithic clasts abundance. The concentration varies from less than 10% in half of the analyzed samples to 28% in the rest of the samples. Monocrystalline and fine-grained polycrystalline quartz prevail. Quartz grains with undulose extinction are present representing approximately 20% of the analyzed quartz grains. A few quartz grains contain solid inclusions such as rutile and zircon crystals. Sub-rounded to rounded grains are dominant, but angular forms with good development of conchoidal fractures are also observed. On the whole they exhibit fresh and clean surfaces, but there is a minor proportion of quartz grains showing weathering features such as embayments, iron sesquioxides and manganese oxides (Fig. 3g).

4.2.2. Minor components

4.2.2.1. K-feldspar and plagioclase. Plagioclase grains are slightly more abundant than those of K-feldspar. Tabular forms with rounded to sub-rounded edges are dominant, whereas, angular grains are scarce. Some grains show polysynthetic twinning and zoning. Plagioclase preservation is variable, ranging from unaltered to strongly altered surfaces. Some grains exhibit a core-sieved texture with clean rims. Most K-feldspar grains are sanidine, but some microcline specimens are also present. The feldspars are tabular and sub-angular to rounded. Some grains have fresh and clean surfaces, and others have sericite or kaolinite alterations (Fig. 3h and i).

4.2.2.2. Mixed pyroclasts. These grains are crystals surrounded by volcanic glass rims. They likely formed from violent volcanic eruptions producing huge volumes of pyroclastic materials (Meyer, 1971; Teruggi et al., 1978). Mixed pyroclasts are not abundant in the analyzed samples, but their presence, together with volcanic glass, indicates the volcanic nature of the detrital sand. Most of the crystals are euhedral, but some are broken and incomplete. Quartz, K-feldspar, plagioclases, hypersthene, hornblende and olivine are the main mineral specimens involved (Fig. 3c and d).

4.2.2.3. Heavy minerals types. The studied samples contain similar kinds and amounts of unstable heavy-minerals. Pyroxenes and amphiboles are the most common heavy minerals. Hypersthene is the most abundant of the pyroxenes, but minor amounts of augite, enstatite and diopside are also present. Amphiboles are mostly hornblende. Although green types of hornblende are the most abundant, the brown rich ferric iron hornblende variety – basaltic hornblende – is also observed. Epidote and olivine rarely occur. Some grains of these minerals preserve their euhedral form while others show broken vertices. Grain edges are sub-angular to sub-rounded.

4.2.2.4. Opaque grains. Opaque minerals (magnetite, hematite, etc.) are not abundant. They range from angular to rounded edges.

4.3. Rock fragment and mineral clast composition and classification of the alluvial sequences

The psammitic–pelitic sediments of Late Quaternary age from the Andean piedmont were likely reworked volcaniclastic sands (Pettijohn et al., 1984), since most of the detrital constituents were derived from pyroclastic–volcaniclastic rocks. Also, there is a portion of epiclastic sediments likely coming from metamorphic rock sources. Accordingly, these alluvial sediments can be classified as tuffites.

At the Puente El Zampal study site, the Late Pleistocene and Early Holocene alluvial sequence of the aggradational plain unit contains mostly volcanic glass and mica compared to other minerals (Fig. 4). Throughout the succession these two components have an inverse abundance, i.e., when volcanic glass is more abundant (lower and upper sections of the sequence) mica grains have lower concentrations. Volcanic glass varies from 61.5% to 3.3% and mica grains range from 1% to 88.8%. Lithic clasts show a similar pattern to that of volcanic glass, but they vary between 10% and 33%. Alterites display a

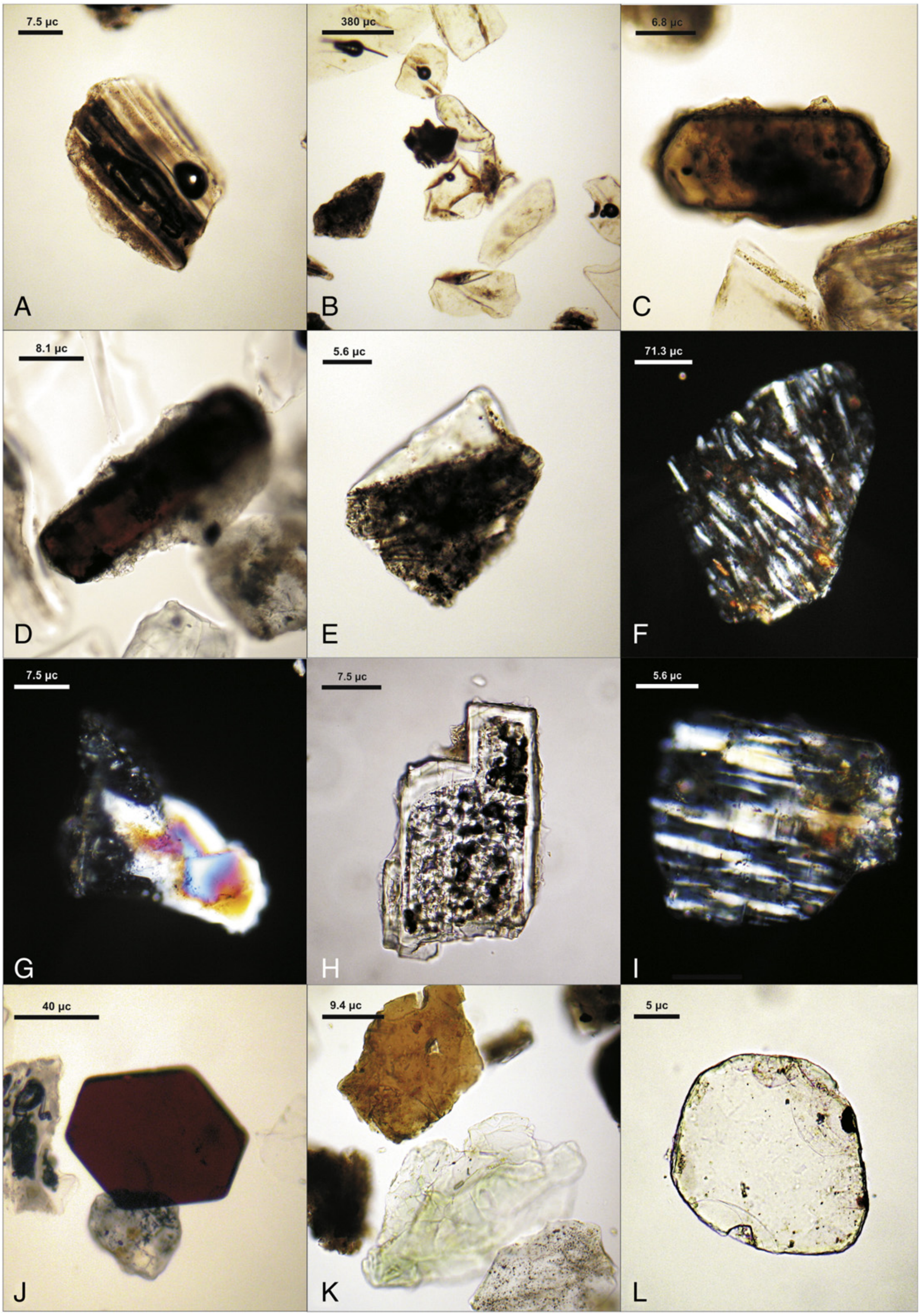

Fig. 3. Mineralogy of detrital grains. A–B) Volcanic glass under plane-polarized light (PPL) from Puente El Zampal study site. C–D) Mixed pyroclast, view under PPL, from Los Alamitos 2 study site. E) Lithic clast, under PPL, from Los Alamitos 2 study site. F) Lithic fragment (poikilitik texture), under crossed nicols, from Los Alamitos 1 study site. G) Policrystalline quartz, under crossed nicols, from Los Alamitos 2 study site. H) Mixed pyroclast form by a volcanic glass rim and a core-sieved plagioclase with clean rim, view under PPL, from Los Alamitos 2 study site. I) Microcline with replacement texture in the right side grain, under PPL, from Puente El Zampal study site. J) Biotite, under PPL, from Los Alamitos 1 study site. K–L) Muscovites, view under PPL, from Puente El Zampal study site.

maximum percentage of 33% and quartz fluctuates between 1 and 10%. Among the minor components, K-feldspars reach up to 7.4%, while plagioclases, mixed pyroclasts, pyroxenes and amphiboles percentages are lower than 5%.

At the La Escala study site, the Mid -to Late Holocene fill terrace alluvial sequence contains mica grains fluctuating between 7.8 and 55.7% (Fig. 5). In this sequence, volcanic glass and quartz also have an inverse relation, with the concentration varying between 3 and

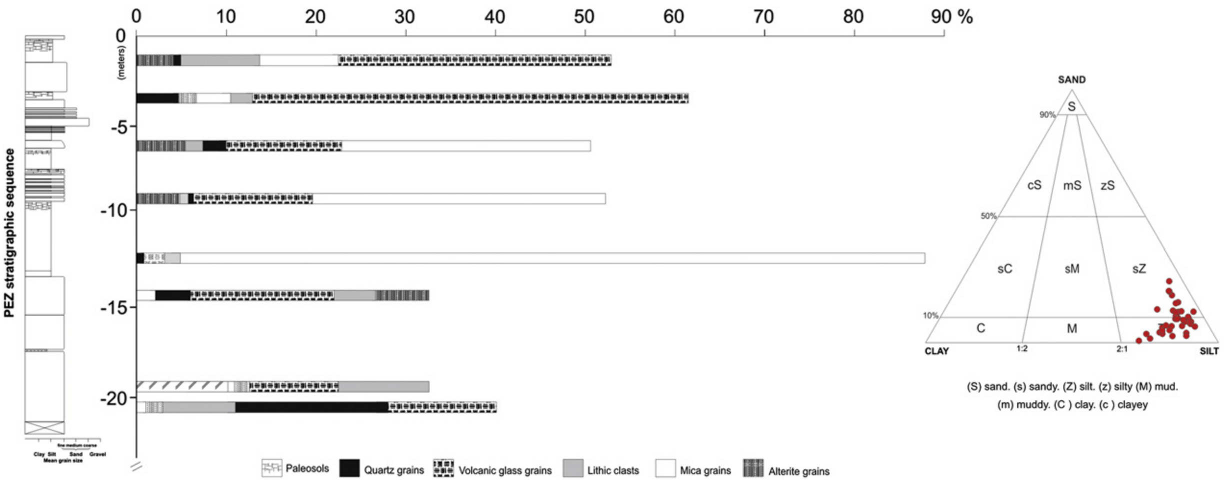

Fig. 4. Puente El Zampal study site. Most abundant mineral types frequencies in the stratigraphic sequence. Grain size analyses and textural groups (according to Folk, 1954).

24%. Rock fragments and alterites concentrations are variable, reaching a maximum abundance of 22% and 18.5% and a minimum of 1% and 4.2% respectively. Among the most abundant minor components of the sediments plagioclases and K-feldspars have concentrations up to 5.5% and mixed pyroclasts reach up to 3.7%. Amphibole and pyroxene values are lower than 1%.

At the Arroyo Yaucha, the Late Pleistocene-Early to Mid Holocene upper alluvial terrace (Los Alamitos 1) is dominated by volcanic glass grains (Fig. 6) with relative abundances that vary between 25.3% and 68.6%. Micas are the second most abundant component with their concentrations fluctuating between 10% and 24%. In general, these two components show an inverse relation along the sequence. Quartz, rock fragments and alterites reach maximum concentrations of 10.7%, 16.4% and 7.2% respectively. Minor components are mostly represented by plagioclases and K-feldspars, with values ranging between 0.3–7.4% and 0.3–5.2% respectively. Also, at the Arroyo Yaucha, the Mid -to Late Holocene lower alluvial terrace (Los Alamitos 2) is formed mainly by volcanic glass, mica and alterite grains (Fig. 7). The two first show an inverse relation, reaching up a 64.2% of volcanic glass and a 26.7% of mica concentration. The frequency of alterite grains increases from almost zero at the bottom of the alluvial sequence to near 20% in its upper part. Also, rock fragments and quartz are observed, with values up to 10%, while plagioclases and K-feldspars reach up to about 8.5%.

5. Discussion

The results show that the Q:F:LF composition of the very fine-grained alluvial sands of the Cordillera Frontal piedmont, from 33° to 34° S (PEZ ≈ 30.01:15.13:54.86, LES ≈ 49.86:13.42:36.71, LA1 ≈ 26.91:26.55:46.54 and LA2 ≈ 34.91:25.91:39.17; Table 1), corresponds with the composition of the modern lithic arenites of the Argentine Association dominated by volcanic rock fragments (average Q:F: Rf ratio 26:18:56, being Rf rock fragments) reported by Potter (1994). Potter (1994) also indicates the presence of the Andean sand family on the Argentine Atlantic passive margin in association with a predominant semiarid climate across much of the country, the narrowing of the continent in its southern part, and a Pleistocene inherited composition, probably a deglaciation relict. In agreement with the last proposed cause, the obtained results suggest that the alluvial sequences at the Cordillera Frontal piedmont reflect this average Q:F:LF composition at least during the last ca. 50 ka BP; where lithological characteristics, climate and topography should have been the main controlling factors of weathering and erosion in the catchment areas of fluvial basins (Weltje and von Eynatten, 2004).

The very fine-grained sand composition of the alluvial sediments reflects two geologically distinct sources in the catchment areas. The alluvial deposits are composed of material from volcaniclastic and metamorphic rocks coming from the erosion of both types of source

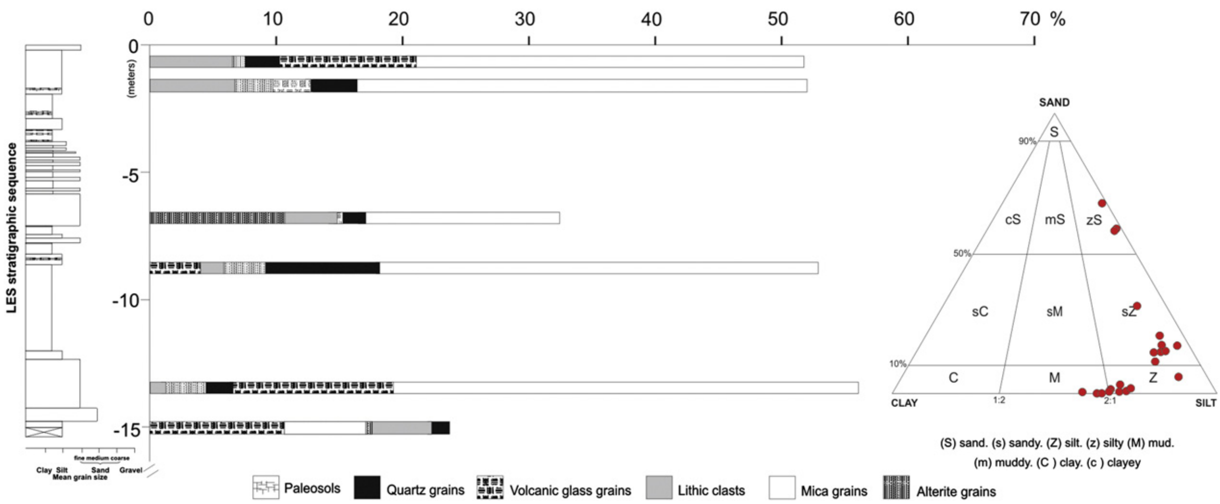

Fig. 5. La Escala study site. Most abundant mineral types frequencies in the stratigraphic sequence. Grain size analyses and textural groups (according to Folk, 1954).

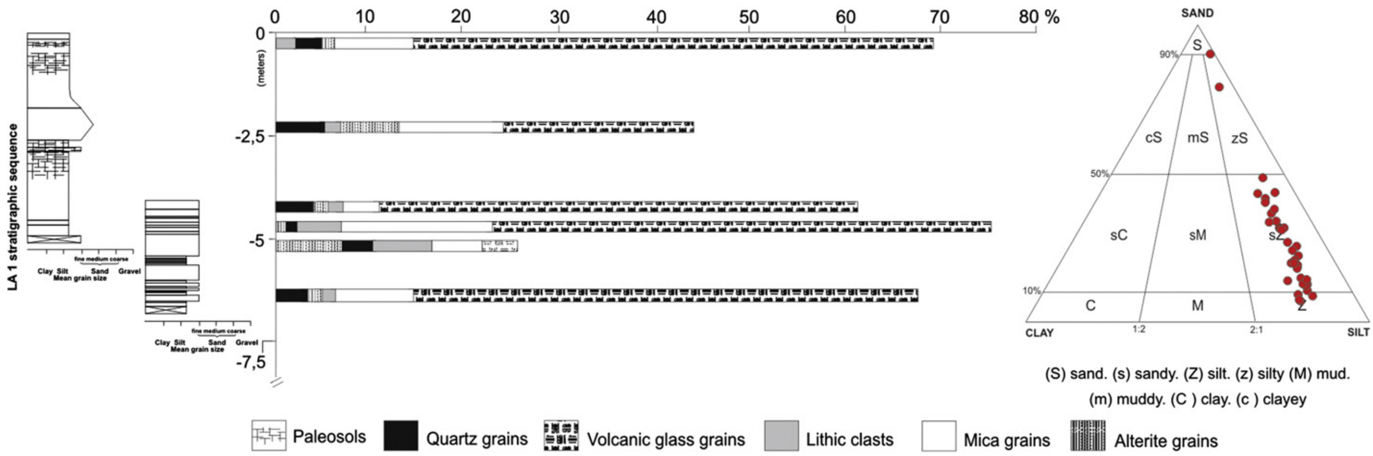

Fig. 6. Los Alamitos 1 study site. Most abundant mineral types frequencies in the stratigraphic sequence. Grain size analyses and textural groups (according to Folk, 1954).

rocks at the headwaters of the analyzed arroyos with subsequent fluvial–aeolian transport. However, some sediments could have been derived from the transport of primary and/or secondary volcanic ash. A volcaniclastic source can be inferred from the presence of abundant volcanic glass, mixed pyroclasts, rock fragments and quartz, all of them in association with heavy minerals like amphiboles (green type hornblendes and basaltic hornblendes), pyroxenes and olivines. Euhedral biotites, though scarce, also support this inference.

Although volcanic glass always occurs in the very fine sands, mica grains, quartz grains showing a undulose extinction (tectonic fabric), hornblende and epidote grains may indicate a metamorphic source likely corresponding to the wide Proterozoic metamorphic outcrops located in the arroyos' headwaters (Fig. 2b and c). As indicated by Potter (1994) metamorphic rock fragments are a secondary but not insignificant component of the Andean family sands of South America. Although, the prevalent production of volcaniclastic sands could be expected in the three volcanic zones of the Andes (Fig. 1a), metamorphic outcrops are also a productive source of sediments. Accordingly, the existence of a dominant metamorphic record in the middle Holocene very fine-grained alluvial sands of the Frontal Cordillera Andean piedmont indicates the drainage of an area dominated by metamorphic rocks at the expense of other lithological sources.

Sediments sampled at the arroyos of the Frontal cordillera piedmont are fair indicators of the arroyos' headwaters lithology, comprising a wide range of rocks that indicates the occurrence of a complex tectonic setting. The existence in the Frontal cordillera of a Permian-Triassic Choiyoi magmatic belt and Quaternary eruptive centers could be associated with a magmatic arc whereas the occurrence of a Proterozoic metamorphic basement and of Ordovician-Carboniferous metamorphic sedimentary sequences is likely related to a recycled orogen tectonic setting.

In the headwaters of the Arroyo La Estacada outcrops of Proterozoic metamorphic rocks, Carboniferous-Permian sedimentary rocks, Permian-Triassic igneous rocks and the Quaternary eruptive centers occur (Fig. 2b). The predominance of mica and volcanic glass at the Puente El Zampal study site indicates inputs from either metamorphic and volcaniclastic rocks during the late Pleistocene-early Holocene. At La Escala study site mica grains are the most abundant component reflecting a major contribution of metamorphic detritus since a greater metamorphic area was drained at the headwaters during the middle to late Holocene. In the Valle Extenso del Campo Bajo area, the Late Pleistocene-Holocene alluvial records of Arroyo Yaucha (Los Alamitos 1 and 2 study sites) exhibit a dominance of volcanic glass, nonetheless mica grains are also present. The abundant mica grains observed at Arroyo Yaucha could come from the green schists of Ordovician age (Las Lagunitas Formation) located at the Frontal cordillera high mountains headwaters; also the intrusive igneous rocks of Permian-Carboniferous age and the Permian-Triassic intrusive-volcanic igneous rocks of the area are another could be a possible source of mica grains. Once in the piedmont, the Arroyo Yaucha water runs over the extensive volcanic ash deposits of the *Asociación Piroclástica Pumícea* (Polanski, 1963) related to the caldera event of

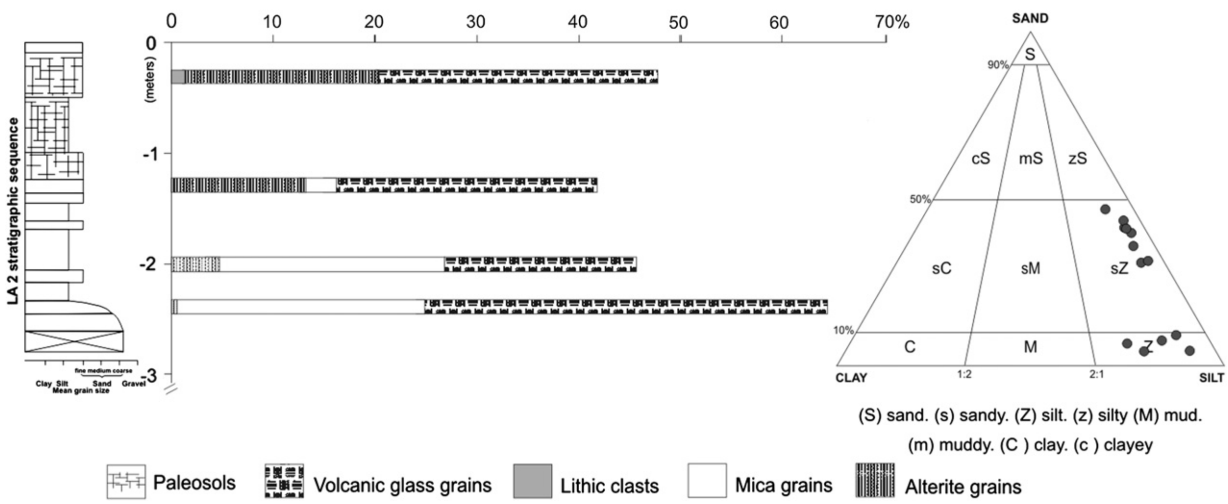

Fig. 7. Los Alamitos 2 study site. Most abundant mineral types frequencies in the stratigraphic sequence. Grain size analyses and textural groups (according to Folk, 1954).

Table 1
Total abundance of quartz (Q), feldspars (F) and rock fragments plus mixed pyroclasts (LF) and Q:F:LF relations in the very fine sand fraction of the study site analyzed alluvial sediments (PEZ: Puente El Zampal; LES: La Escala; LA: Los Alamitos).

Study site	Q	F	LF	Total	Q %	F %	LF %	Total %	~Q:F:LF
PEZ	71	36	130	237	30.01	15.13	54.86	100	30:15:55
LES	91	25	67	183	49.86	13.42	36.71	100	50:13:37
LA 1	30	30	52	112	26.91	26.55	46.54	100	27:27:46
LA 2	29	21	32	82	34.91	25.91	39.17	100	35:26:39

the Maipo volcano, with controversial dates ranging from ca. 2.3 Ma to ca. 150 ka (Sruoga et al., 2005; Lara et al., 2008) and likely the most important source of volcanic glass in this area of the Andean piedmont.

The abundance of either volcanic glass or mica shown by lithostratigraphic levels could be determined by their availability in large quantities in the source areas and also the proximity to them (Fig. 2c). In addition, their abundance can also be related to particle morphologies —a factor that could initially depend on the source rock, in situ weathering processes such as abrasion, corrosion and breakage (Garde and Ranga Raju, 2006) – and changes in the flow conditions causing mineralogical variations in the alluvial deposits (Rittenhouse, 1943). Accordingly, the apparent overabundance of volcanic glass and mica in relation to other minerals and rock fragments could be related to a lower flow regime of the studied arroyos' floodplains, main environments developed during the Late Pleistocene and Holocene in the fluvial basins of the Frontal cordillera piedmont between 33° and 34° S (Mehl and Zárate, 2012).

Floodplains were dominated by aggradation of sand and silt thin sheets commonly horizontal laminated and grading upward from sand to mud; they also show the sporadic occurrence of current ripple lamination, occasionally rapid deposition could be inferred from the presence of climbing ripple crosslamination (Mehl and Zárate, 2012).

The platy shape of mica grains and the low density of volcanic glass could have favored their transport as a suspended load over relative long distances and their subsequent deposition when floodwaters dry out and soak away after the flood subside (Blasi, 1986).

The extensive Tertiary sedimentary deposits placed in the eastern Andean piedmont (Fig. 2a and b), and acting in the study area as the likely substrate of fluvial systems, could be considered as another plausible source of the Late Pleistocene and Holocene piedmont alluvial sediments, being wind and fluvial water the possible agents favoring the erosion and transport of the fine sediments (fine sand and silty sand) from the Tertiary deposits. The lithic and mineral clast signature determined in this study is in agreement with an Andean source of detritus for the wide foreland Tertiary and Quaternary deposits of central Argentina (Zarate and Blasi, 1991, 1993; Etchichury and Tófalo, 2004; Iriondo and Krohling, 2007; Visconti, 2007).

6. Concluding remarks

The present study, contributes to an understanding of the compositional signature (rock fragments and mineral clasts) of the Late Pleistocene and Holocene alluvial sequences of the Andean piedmont at the latitude of 33°–34° S, an area comprised in a region that has been long considered as one of the main source area of the extensive Pampean loess and sand dune fields of central Argentina. The composition of the very fine-grained sands shows a positive correlation with the tectonic regime of the region and also with the Q:F:LF composition of the Argentine Association of modern sands included in the Andean family of sands described by Potter (1994). Although the source areas are mainly located in the arroyos' headwaters placed in the Frontal cordillera, the extensive Tertiary sedimentary deposits surrounding the study area – and corresponding to a previous sedimentary cycle – can be considered as another plausible source for the analyzed sediments. The main mineral and rock fragments of the Late Pleistocene and Holocene alluvial sequences are volcanic glass, mica, quartz, mixed pyroclast and alterites, all of them indicating a volcanic source for the analyzed detritus. This compositional signature supports the regional models for the southern Pampean sandy loess formed mainly from a volcanic mineral assemblage which source regions correspond to the headwaters of the main rivers of Central Andes cordillera. Notwithstanding metamorphic detritus – secondary metamorphic mineral association– are also abundant in the Late Pleistocene-Holocene very fine-grained alluvial record, particularly during the Mid -to Late Holocene.

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