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Geomorphological study of the Cafayate dune field (Northwest Argentina) during the last millennium

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ABSTRACT

The Cafayate depression is a dry valley located in the Pre-Andean region of northwest Argentina. The area shows the development of a large dune field. Its significance has been established from geomorphological and mineralogical evidence, grain shape characteristics and chronological data (OSL dating, archaeological remains, and historical data). The dating results were between 1000–1100 AD to1740–1830 AD showing that the aeolian dynamics remained active during the last millennium. It was not possible to identify stabilised phases marked by ruptures or paleosol development. Nevertheless, other regional and local proxies from Northwest Argentina (archaeological, documentary, etc.) were used to complete the interpretative framework to propose the paleoenvironmental evolution of the area. In addition, human activity and land use must be considered as a complementary factor affecting aeolian dynamics during the most recent stage.

1. Introduction

Aeolian deposits are morphosedimentary records that can be used to produce valuable palaeoenvironmental reconstructions (Hesse, 2009; Iriondo et al., 2009; May, 2013; Thomas, 2013; among others) because sand dune dynamics are strongly influenced by short-term climatic fluctuations during the Late Pleistocene and Holocene (Muhs, 1985; Gaylord, 1990; Forman et al., 1992; Lancaster, 1997; Munyiwka, 2005; Hanson et al., 2009). Moreover, human action can trigger or accelerate aeolian processes during historical times (Levin and Ben-Dor, 2004; Wolfe et al., 2007). For instance, when vegetation cover is reduced below a threshold of ca. 30%, caused by environmental change, overgrazing and/or fire, sands are exposed sufficiently to allow aeolian mobilisation (Pye and Tsoar, 2009).

Aeolian accumulations (dunes and loess) cover large areas in Argentina, especially in the central regions of the country (Andean pediment, Pampean plains and the North Patagonian plateau) (Iriondo and Kröhling, 1996; Iriondo, 1990, 1999; Carignano, 1999; Muhs and Zárate, 2001; Tripaldi, 2002; Tripaldi and Forman; 2007; Tripaldi et al., 2010; Zárate and Tripaldi, 2012; among others). Most of the dunes are Upper Pleistocene (33–20 kyr) in age (Iriondo and Kröhling, 1996; Kröhling, 1999; Zárate, 2003). Furthermore, some dunes of the Pampean Region were reactivated heavily during the Holocene (Tripaldi and Forman, 2007; Forman et al., 2014) and even during the 20th century (Tripaldi et al., 2013).

However, dune accumulations in the Andean intermontane basins have received less attention. The dune field at Cafayate, located in the northern area of the Santa María valley (northwest Argentina), represents a unique opportunity for study, as it shows high levels of current activity of the aeolian deposits linked to land use change for agricultural purposes. Previous studies on the Cafayate dune field are scarce and mainly dealt with sedimentology and mineralogy for industrial applications (Cortelezzi et al., 1984).

The main objective of this paper is the geomorphological study of the Cafayate dune field. We present geomorphological mapping, aeolian deposit data (grain size, mineralogy, and grain surface microtextural analysis) together with palaeoenvironmental interpretation. Although 6 OSL ages were determined, it was not possible to obtain enough chronological and stratigraphical information to define accurate stages in

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the dune dynamics over time. Nevertheless complementary regional data are provided to give support to the main interpretation.

2. Regional setting

The Cafayate depression is located in the northern area of the Santa María valley in the Valles Calchaquíes in the province of Salta (Fig. 1). This is an elongated north–south trending graben, surrounded by the Northern Sierra Pampeanas. The east is bordered by the Cumbres Calchaquíes (La Hollada, 4177 m) and the west by the Sierra de Quilmes (Cerro Chuscho, 5468 m). Its northern area is wider and bordered by the Cerro El Zorrito (3224 m), where the Santa María and Calchaquí rivers meet. This is the starting point of the narrow canyon of the Las Conchas River that forms part of the basin of the River Juramento. The Santa María and Calchaquí rivers flow across the Cafayate depression and drain a large fluvial basin (19,760 km^2). This fluvial system receives abundant water discharge because of summer rains and snowmelt in the headwaters, while the rivers remain almost dry during winter.

The region has a complex geology (Galván, 1981). In the Sierra de Quilmes and north-eastern sector of Cumbres Calchaquíes, a Precambrian–Lower Cambrian geological basement comprising granitic and low-medium grade metamorphic rock outcrops (Rapela, 1976; Toselli et al., 1978) (Fig. 1). During the Upper Cretaceous–Miocene (Salfity and Marquillas, 1999; Bossi et al., 2001) a rifting stage favoured the formation of a graben filled with a sedimentary sequence of continental detrital and carbonate rocks of the Salta Group. These are overlain by detrital deposits from the Santa María Group (Pliocene) (Galván and Ruiz Huidobro, 1965; Galván, 1981). A compressive Pliocene phase affected this sedimentary sequence and developed north–south trending folds, as well as activating the marginal fault system of the Santa María graben.

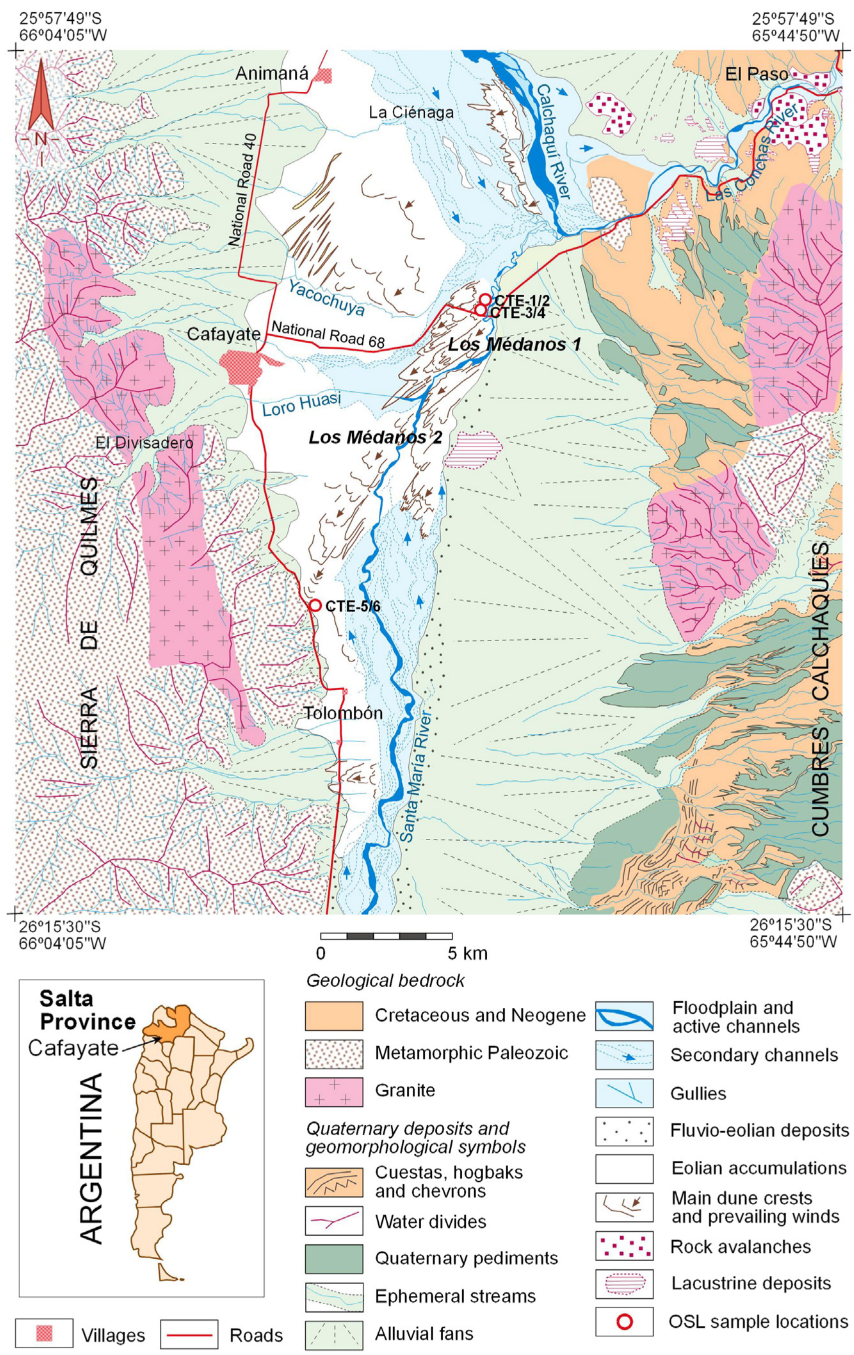

Fig. 1. Location and geomorphological maps of the Cafayate depression.

The base of the depression is covered by Quaternary alluvial, aeolian, and lacustrine sediments.

Cafayate is located in the north of the basin at 1683 masl (metres above sea level) at a subtropical latitude (26°40′S). Climatically it is characterised by strong aridity. Average annual temperature is 17.1 °C, oscillating between 21.5 °C (February) and 9.7 °C (July) (Fig. 2). Humid winds coming from Atlantic anticyclones are blocked by the Cumbres Calchaquíes, and as a consequence, average annual precipitation at the bottom of the basin is only 207 mm. Most rainfall is in summer and the winters are dry (Fig. 2). According to the Köppen classification the Cafayate climate is type Bwk′ (arid with average temperature less than 18 °C and cool winter due to altitude) (Minetti et al., 2005). Vegetation belongs to the ‘Ecoregión del Monte’ and is composed of carob trees (*Prosopis nigra*) and jarillas (*Larrea divaricata*). In the lower areas it changes to thorny and shrub steppe with cardons (*Trichocereus atacamensis*) (Mendoza, 2005).

The aeolian accumulations are found at the lowest elevations of the west side of the valley (between 1600 and 1700 masl) for a 30 km stretch between Animaná and Tolombón (Fig 1). Most active dunes are located around Cafayate city, where the dune field extends to 10 km in width.

3. Material and methods

Geomorphological mapping of the study area was carried out by photo-interpretation (aerial photographic regional flight 1:50,000 (1969), and Google Earth images 2003–2009) and field work. Special attention was given to the Quaternary morphosedimentary units (lacustrine deposits, alluvial fans, channels with related floodplains, and sand dunes) covering the bottom of the Cafayate basin. This cartography permits us to locate the dune field in spatial and chronological context in relation to other regional geomorphological features.

The geomorphological mapping was accompanied by a full coverage survey that permitted identification of active and ancient dunes. The location of deep cuts to sample the ancient dunes was difficult except in areas exceptionally affected by deflation corridors. Field work showed the presence of old sedimentary sequences, by its different degrees of consistence, compaction, and colour appeared to correspond to different aeolian activation stages. The sampling strategy was directed to cover all situations taking profit of the exposed profiles, testing the North dune field (Los Médanos 1) as well as the South dune field (Los Médanos 2). Samples CTE-1, CTE-2 (both at 26°02′58.22″S; 65°53′04.79″W; 1553 masl), CTE-3, and CTE-4 (both at 26°03′04.24″S; 65°53′11.64″W; 1555 masl) were taken in the Los Médanos 1 area, near National Road 68; samples CTE-5 and CTE-6 (both at 26°08′25.34″S; 65°57′30.62″W; 1625 masl) were taken in the Los Médanos 2 area, near the road between Cafayate and Tolombón (Fig. 1).

Grain size distributions were obtained by dry, mechanical sieving of an aliquot of 100 g obtained by using a sample splitter; samples were previously mechanically disaggregated. The distribution of particle size was determined by this method from 2680 to 37 μm. Mineralogical analysis was carried out by X-ray diffraction (XRD) (Philips PW 1729 diffractometer at the University of Zaragoza). Semi-quantitative mineralogical composition was determined with the powder method and using the RIR in the literature (Hillier, 2003; Muhs, 2004). One hundred grains of the <63 mm fraction were selected randomly for heavy mineral analysis. Separation was made with bromoform (S.G. = 2.9) and subsequent identification was carried out under a petrographic microscope. Finally, a study of grain morphology and the surface textures of grains with diameters of 297–351 μm from the light fraction was conducted. Microanalysis was performed by SEM/EDX using an Inspect (FEI) electron microscope, equipped with an energy dispersive X-ray analyser (W source, DX4i analyser and Si/Li detector) at the Universidad Autónoma de Madrid. Chemical analysis using energy dispersive X-ray analysis (EDX) was also carried out on selected grains.

Dune samples were dated by Optically Stimulated Luminescence (OSL) at the Luminescence Dating Laboratory at the Australian National University. Analyses were carried out using sand-sized (180–255 μm) quartz grains, measured using the SAR protocol (Murray and Wintle, 2000, 2003). Gamma and beta dose rate values were calculated using Neutron Activation Analysis. A uniform water content value of 5 ± 2.5% was used in age calculations, based on measured values. OSL measurement and analysis procedures are similar to those described by Teeuw and Rhodes (2004) and Rhodes et al. (2003). Only low volumes of suitable quartz grains were separated from these immature sands, and as a result only preliminary age assessment was possible owing to the low number of aliquots that could be measured for each sample. However, these age estimates form an apparently coherent dataset, and are supported by characteristic archaeological remains found at the Los Médanos 2 sampling site. Pottery remains were identified in situ by archaeologists from the Laboratory of Geoarchaeology at the Universidad Nacional de Tucumán. These remains were placed within in the cultural sequence of the Santa Maria valley. In addition, other proxies were used to support our data, such as historical documentation and dendrochronology of the same chronological frame time.

4. Results and discussion

4.1. Geomorphology of the Cafayate dune field

The landscape of the Cafayate basin is dominated by the floodplains of the Santa María and Calchaquí rivers. These rivers are located in the central axis of the valley, and represent the local base level. The riverbeds contain multiple channels and braided bars formed by clay and sands that remain dry almost all year. A wide network of gullies (*quebradas*)

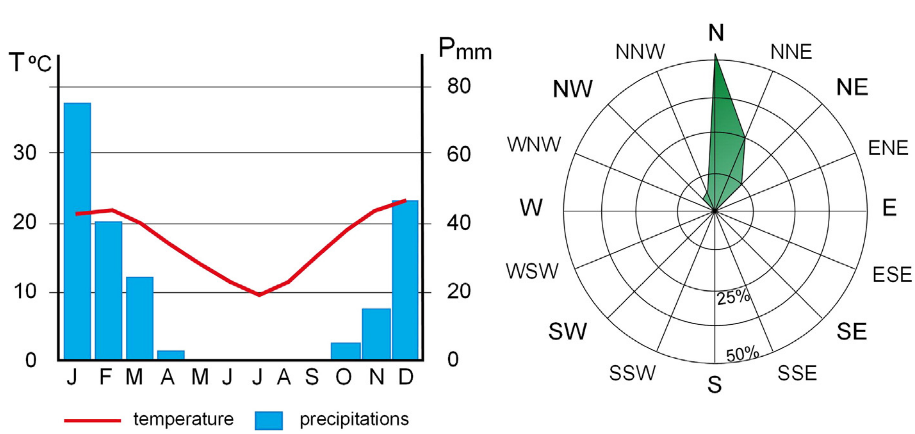

Fig. 2. Monthly temperatures and precipitations, and wind rose of Cafayate (Finca La Florida meteorological station, Bodega Etchart, 1982–2014 period).

organises the drainage from the mountains to the main rivers — with large segmented alluvial fans that are particularly well developed in the eastern piedmont coming from the Cumbres Calchaquíes (Fig. 1). Extensive aeolian landforms were identified in the valley floors at the confluence of the Calchaquí and Santa María Rivers until the Tolombón area, as well as scattered lacustrine deposits in the centre and northeast of the depression (Fig. 1).

The sides of the River Santa Maria valley are asymmetrical because the river flows close to a fault affecting the Sierra de Quilmes piedmont (Fig. 1) and because of differences between the dynamics and characteristics of both sides of the tributary basins on both sides. The tributaries coming from Sierra de Quilmes have small basins with steep courses and torrential regimes. For this reason, some sections close to the city and farm areas of Cafayate are artificially channelled (Yacochuya, Mishi, and Loro Huasi gullies). Water courses from Cumbres Calchaquíes have more extensive basins and large segmented alluvial fans that are currently very active.

The Santa María floodplain marks the base level of the latest stages of alluvial fan development during the Late Holocene, located below the culminant surface defined by lacustrine Pleistocene sediments. In the southern sector, near Tolombón, alluvial fan sediments are more than 5 m thickness and alternate with volcanic ash layers. Clayey sediments are dominant in the lower parts of the alluvial fans. These sediments are mobilised by wind to form an area of fluvio-aeolian transition (Fig. 1). Only the eastern side of the valley (Fig. 1) shows older cones and pediments (Pleistocene) and these are found at least 15–20 m above the Holocene alluvial fan surfaces.

The remnants of lacustrine sediments are related to the blockage of the River Las Conchas due to a large landslide in the El Paso area (Trauth and Strecker, 1999; Bookhagen et al., 2001; Trauth et al., 2003b; Hermanns and Strecker, 1999; Hermanns et al., 2000; Hermanns and Niedermann, 2011) (Fig. 1). Landslides were related to an increase in rainfall or seismic–tectonic causes (Trauth et al., 2003a; Hermanns et al., 2006, 2011). The resulting large landslide-dammed lake reached as far as Tolombón, and a sequence of laminated sediments 47 m thick were deposited. Radiocarbon age estimates of freshwater-snail shells place the beginning of the lake around 36–28 kyr BP (Trauth and Strecker, 1999). Other radiocarbon dating surveys indicate that the lake was still present during the early to mid Holocene (10.8–4.7 kyr BP) (Hermanns et al., 2006; Hermanns and Schellenberger, 2008). The lacustrine record indicates increasing sediment accumulation during wet phases. The opening of the dammed lake generated the emptying of the basin through the River Las Conchas during the Mid and Late Holocene. Accordingly, aeolian accumulations in the valley are chronologically located after the lake emptied (4.7 kyr).

The most important aeolian accumulations are in the west margin of the valley, from the lower areas of the alluvial fans of San Carlos-Animaná to the south of Tolombón. The dunes are partially vegetated and fixed, but there are still some active areas. The dunes can be divided into two main groups (Figs. 1 and 3a): Los Médanos 1 and Los Médanos 2. Other minor active dunes appear around La Ciénaga close to the River Calchaquí.

Predominant dune types are barchans and barchanoid ridges (Fig. 3b and c), as well as parabolic dunes with vegetation (Fig. 3d). Mixed forms are common, especially where the horns of the barchans adopt the shape and dynamics of a parabolic dune. There are also some isolated linear and hummock dunes in marginal areas with less sand and dispersed vegetation. Even through the dominant winds are from the N and NNE (Fig. 2), all kind of dunes tend to be aligned from NE–SW in the Cafayate section, following the shape of the alluvial floodplain (except in the Tolombón area where dunes are E–W).

The vegetation that stabilises dunes is composed of several species adapted to arid and warm climatic conditions, such as *Sporobolus rigens*, associated with *Atriplex sp.* and *Saueda sp.*, *Gomphrena martiana* and *Heliotropium mendocinum*, all of which have extensive root systems (Hueck, 1950). In older fixed dunes the carob tree (*P. nigra*) is dominant, and in several places it was used for wood, firewood, or support-poles for vineyards. Overgrazing, intentional fires, and (in recent years) the increasing working of the land for profitable vineyards has favoured the progressive elimination of vegetation cover and the reactivation of aeolian sands.

At present the Cafayate dune field is very active, even some sectors are stationary by vegetation development. The location of the basin and the degradation of the vegetation favour the development of convective winds during the afternoons that form dust devils (Minetti et al., 2005). Large storms are responsible for the mobilisation of vast amounts of sediment, generating persistent dust in suspension over extended periods of time. During these times, blowouts and deflation corridors develop in some areas and rapid dune advance occurs in other areas. A section of National Road 68 is frequently affected by this problem. Even the Santa María riverbed narrows in some sections because of the advancing dunes — as occurs at the confluence with Loro Huasi gully (Fig. 1).

The Los Médanos 1 sector begins at the confluence of the Santa María and Calchaquí rivers and extends to the protected area called 'Los Médanos' and the Yacochuya gully, after crossing Road 68. Near to the bridge on the road, it was possible during September 2003 to study outcrops corresponding to ancient dunes, fixed by carob trees and forming yardangs after aeolian deflation. The resulting dune cross-sections enabled the observation of aeolian structures and sampling for various analytical procedures. Sampling was made in two outcrops 200 m apart. Samples CTE-1 and CTE-2 correspond to the northernmost dune (Fig. 4a,b,c) and samples CTE-3 and CTE-4 were taken from a dune near the bridge on the National Road 68 (Fig. 5a,b,c). It is necessary to remark that it was an exceptional opportunity because in a later visit (2013) several meanders of River Santa María had been artificially cut and the dunes had been completely flattened and planted with tamarisks (*Tamarix gallica* L.).

The Los Médanos 2 area begins in one of the meanders of River Santa María (Fig. 3a), south of the previous section, and extends to the north of Tolombón. It is also composed of ancient and active dunes. The cumulative forms cross the river along a section of about 5 km (Fig. 1). It is possible in the interdune spaces to identify old alluvial sediments composed of sand and clays associated with floods (Fig. 3c). In several places, aeolian sands occur as yardangs. There are also remnants of dry vegetation (phantom forest) left after the passage of the dunes (Fig. 3c). The northerly and easterly parts of the dune field are more active, while the SW section has more relict dune forms.

During 2003 it was also possible to find wind corridors showing cross-sections of ancient dune accumulations. Two samples were taken near National Road 40 (Fig. 6a and b) (CTE-5 and CTE-6). The aeolian deflation corridors reached archaeological levels under the sandy cover. It was possible to identify several ceramic potsherds with sharp edges lying in situ and several pieces were partially reconstructed. This material was photographed, analysed, and classified to establish its cultural affiliation and relative chronology — and finally returned to its original place.

4.2. Cafayate dune sediment characteristics: grain size, mineralogy and grain morphology

The partial preservation of sand bodies eroded by deflation processes permits outcrops (1.5 to 2.5 m in thickness) to be observed (Figs. 4a, 5c, 6b). Close examination of the inner structure allows first and second order surfaces to be identified (in the sense of Hunter, 1977). Medium-scale (decimetre-thick) sets of cross-laminae are very common. Dip direction is towards the south, coherent with the present wind regime. Structures indicative of reverse winds have not been observed. Dunes with straight crests oriented perpendicular to the mean flow lines (2D dunes, in the sense of Southard and Boguchwal, 1990). Horizontal bounding surfaces reflect erosion of previous dunes although the partial preservation of the sets implies that erosion of the stoss surface was commonly

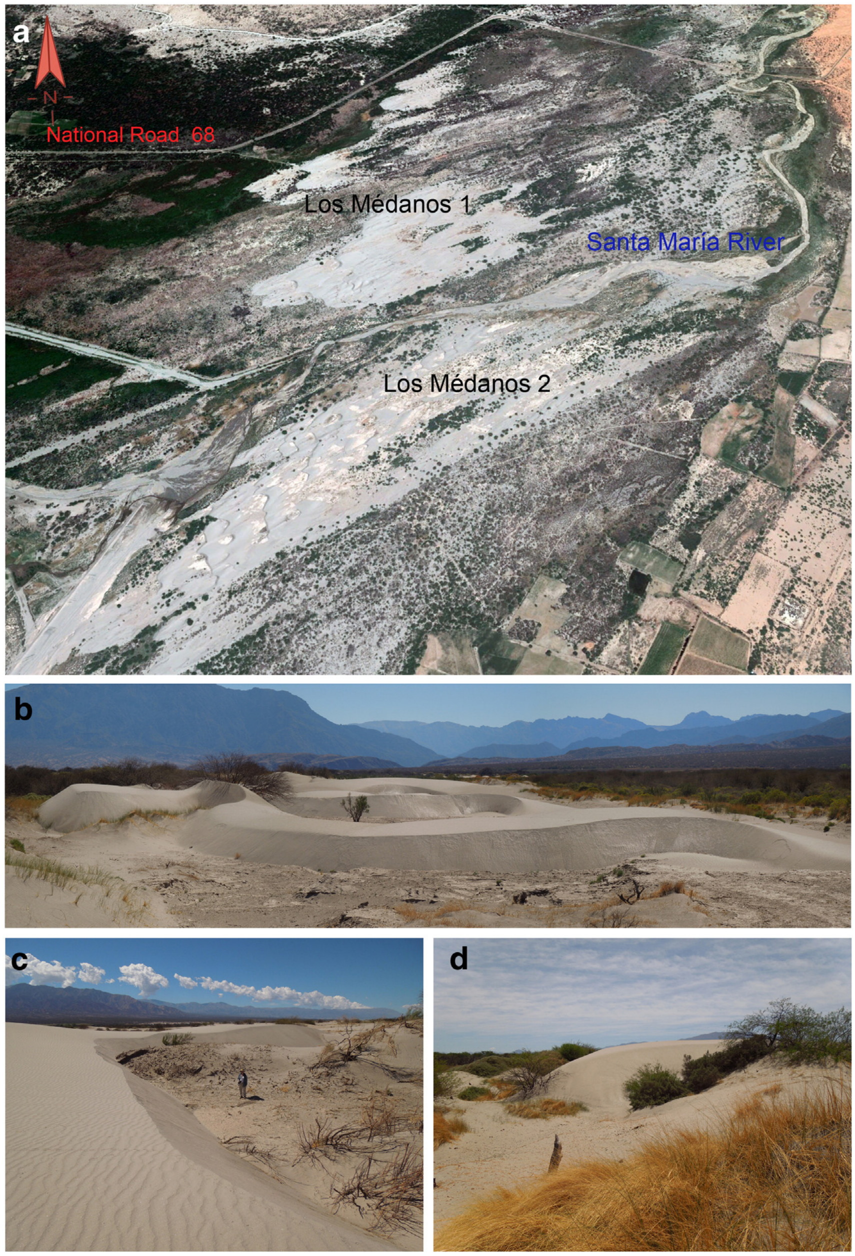

Fig. 3. Different types of active dunes from the Cafayate depression: (a) oblique image of active dune fields (Google Earth, 2009); (b) barchanoid ridges at Los Médanos 2 area, next to the River Santa María; (c) brink and slipface of barchans advancing over a phantom forest; (d) slipfaces of parabolic dunes at Los Médanos 1, *Sporobolus rigens* at the front and *Gomphrena martiana* and *Heliotropium mendocinum* behind, with *Prosopis nigra* at the bottom.

lower than accumulation of the preceding dune. Moreover climbing ripples with a high angle of climb reflecting high sedimentation rates are present and, in some cases, the upper part of the dune (zone between the windward and the leeward slopes) seems to have been conserved. Towards the toe, subcritically climbing translational strata are related to dry interdunes (Hunter, 1977; Kocurek and Dott, 1981). Wet interdunes which were related to higher water level stages also developed, as reflected by thin indurated surfaces or adhesion surfaces (Kocurek and Fielder, 1982). Bioturbation traces, probably related to these wetter episodes, indicate temporary interruption of deposition.

Fig. 7a shows the size distribution of the analysed sand dune samples as cumulative distributions. Sands are well sorted as expected from aeolian deposits. Mean size values range from 98 μm to 153 μm (very fine to fine sands). As for the interquartile range (IQR), sediment sizes representing the 25% and 75% points of the population spanned from 177–200 (fine sands) to 88–105 μm fractions (very fine sands) — except for sample CTE-4 which showed an anomalous finer distribution. Modes in grain size corresponded to the 146–125 μm and 177–146 μm fractions (fine sands) or slightly smaller, as in CTE-1 and, especially, CTE-4. CTE-1 showed two modes for fractions 125–105 μm (very fine sands) and 146–125 μm (fine sands). Sample CTE-4 presented a polymodal distribution, with modes in 125–105 μm, 88–74 μm (very fine sands) and even in the smallest-size fractions (silt) — and so the distribution is skewed towards these values. This heterogeneity can be related with the specific part of the dune to which this sample belonged. In other respects, distributions in dunes are more or less symmetrical as medians are in the same fractions as modes. Neither the central tendency measures (mean, mode) nor the interquartile range are below 53 μm. Although the observed grain size distributions are in the range of aeolian dunes, they are finer than the average, which can be due to several factors, including a limited supply of coarse grains or a competency limitation on transport.

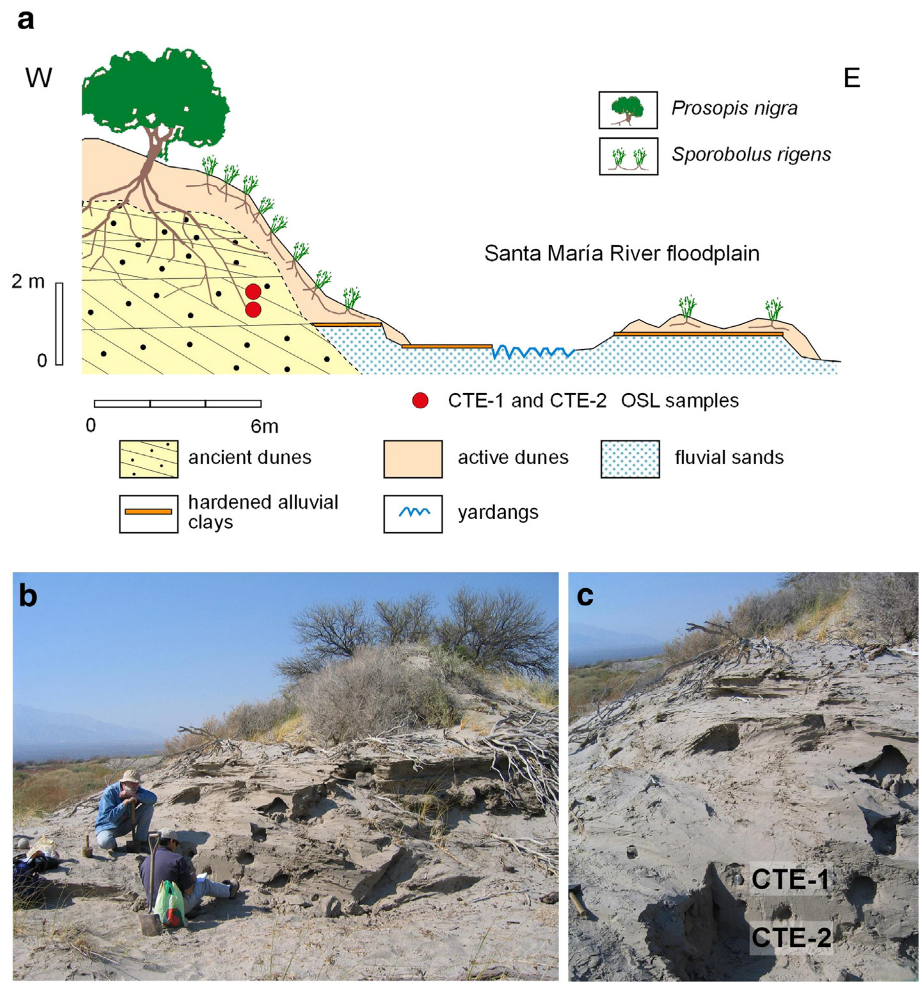

Fig. 4. (a) Schematic cross section of an ancient dune next to the River Santa María (northern area of Los Médanos 1) showing vegetation cover and location of CTE-1 and CTE-2 sampling points.

The mineralogical compositions of the bulk samples, as determined by XRD, share many similarities (Fig. 7b). In all samples, the main components are quartz, potassium feldspars, and plagioclase — with minor amounts of phyllosilicates (biotite and chlorite) and the occurrence of volcanic glass shards. Phyllosilicates were more abundant in samples CTE-3 and CTE-6 — which showed a polymodal distribution with modes in finer fractions than in other samples. Mineralogy of the most abundant fractions (146–177 and 125–146 μm) showed slightly different proportions for these minerals. This composition reveals, in general, a low degree of chemical maturity in the studied sediments (Muhs, 2004). Besides, and in spite of the lack of other data, this mineralogical composition of the aeolian deposits would be compatible with the material from the local Quaternary alluvial systems that drain basically unweathered granitic and metamorphic rocks.

There was a great variety of heavy mineral content — including augite, as the major component, with zircon, tourmaline and hornblende also well represented. Andalucite, garnet, epidote, sillimanite, kyanite, rutile and anatase only occur occasionally. This mineral association is typical of sediments with low chemical maturity and their frequency (less than 5%) is associated with rocks of low metamorphic degree (Chen et al., 2008; Garcia Giménez et al., 2012).

Sand grains have subangular shapes under low magnification (10×) (Fig. 7c and e). Surface grain micro-textures show similar mechanical features in all samples. Most grains show angular outlines and percussion marks (Fig. 7d). Cleavage preservation is a sign that few weathering processes have taken place. Particles of volcanic glass shards were identified showing the typical tubular shape of the vacuoles (Fig. 7e), with adhered particles (Fig. 7f). Most grains show medium to high relief; surface features include rounded pits that are probably related to aeolian processes (Garcia Giménez et al., 2012).

Coatings sometimes appear among the chemical features. Dispersive energy analysis indicates that coatings are made of: 1) clay minerals related to chemical alteration in feldspar grains; and 2) salt deposits (sulphates and chlorides) related to upward water movement caused by evaporation processes. These types of coatings have been described for dune grains in Australia (Pell and Chivas, 1995).

As a rule, mechanical features of surface grains are more significant than chemical features. Abrasion is scarce. Although pitting is present, its lack of density probably corresponds to a short transport distance.

In summary, the mineralogical study and grain morphology showed that the sands have short transportation, are not cemented, and have low chemical maturity, pointing to a close supply area. Moreover, mineralogical compositions are coherent with the fluvial system materials and the basement rocks present in the area.

4.3. Chronological information

Natural sections availability is scattered and scarce in the dune field of Cafayate. Due to that, the samples obtained for OSL datings might not be considered to be fully representative of the evolutionary dynamics of the area. However, obtained data are presented because they reinforce the initial general impression that all dunes belong to Holocene period, with a strong dynamism during the last millennium.

These samples displayed low quartz OSL signal sensitivity and relatively high thermal transfer values. Limited yields meant that only restricted numbers of aliquots could be measured, and these age

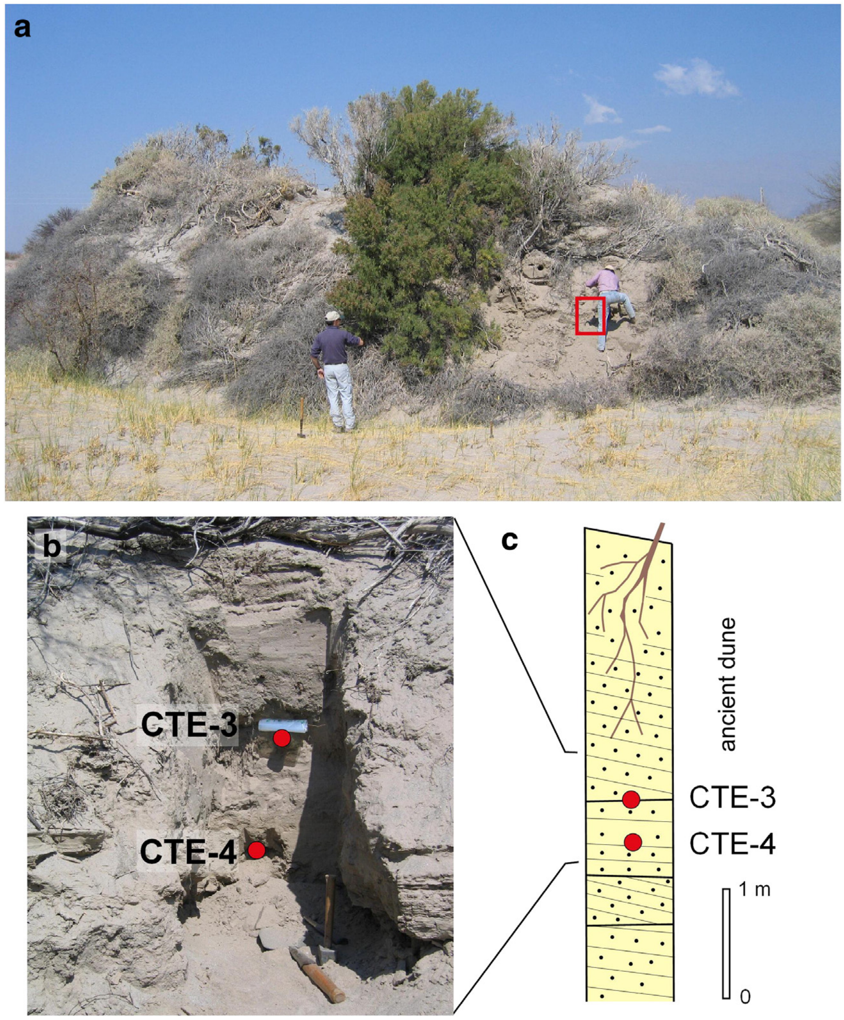

Fig. 5. (a) General photograph of the ancient dune, close to the bridge on National Road 68, indicating the location of CTE-3 and CTE-4 sampling points; (b) detail of the sampling points; and (c) profile stratigraphic column.

estimates are therefore considered preliminary. Although the samples displayed a relatively high degree of scatter between aliquots, equivalent dose (De) values formed discrete clusters within each sample. One sample, field code CTE1 (laboratory code K0159) displayed two clusters in De, corresponding to age estimates of AD 1010 ± 80 and AD 1780 ± 60 years. We note that all 12 measured aliquots have dose values corresponding to one of these two groupings, and interpret this as a sand that was originally deposited around AD 1010, but then reworked locally at around AD 1780. It is hard to explain the significant grouping of dose values by other processes. The observation of grouping for multiple grain single aliquot samples is expected where most grains are insensitive, but a small fraction of grains contribute the majority of the observed OSL signal (Rhodes, 2007). We therefore include both values in Table 1. Note that this effect is in direct contrast to partial bleaching, in which signals of grains are partially reduced by short light exposure; here signals are either fully bleached or retain a previous shared value.

For other samples, the age presented in Table 1 was based either on the minimum group of dose values, or a significant group within the range of values. The procedure used combined De values from well separated groups, as performed by Rhodes (2015) using the same basic approach as the central age model. In the former case, we interpret the few higher values as representing the effect of sensitive grains that were incompletely zeroed at the time of deposition. In the latter case, high values are interpreted as representing incomplete zeroing, and the few lower values as being caused by intrusive grains, probably introduced by bioturbation. The successful recognition of these processes depends on an advantageous OSL sensitivity distribution of the quartz grains that comprise samples from this region (Rhodes, 2007), the relative proportion of results in each group, and constraints from results of nearby samples. As mentioned above, sample volume was restricted, preventing us from further assessing these results. However, we note that the age estimates of each pair of samples (CTE-1 and 2; CTE-3 and 4; CTE-5 and 6) display a high degree of stratigraphic consistency, providing some increased confidence in these results.

According to that, the OSL age determinations show evidence of aeolian activity between AD 1010 ± 80 and AD 1780 ± 60 years (Fig. 8a). It is possible that this latest period of aeolian activity was preceded by earlier dunes which were reworked into the present dune field.

The chronology of the archaeological remains supports the OSL dating. The ceramic fragments found on the surface of an interdune deflation corridor at Los Médanos 2 (Fig. 6a) are fragments of a bowl belonging to the Late Formative period (Fig. 6c). The Formative period (ca. 500 BC 1000 AD) marks the beginning of sedentary settlements in the region (Olivera, 2001). In the study area, domestic settlements and cemeteries were dispersed in the valley bottom, piedmont, and gullies (Ledesma and Subelza, 2009). Among the common ceramic potsherds of those times it is possible to find polished grey and red, incised grey, and fine painted types (such as polychromed Guachipas) (Scattolin, 2006). The stylistic features of the ceramics found are similar to those described by Nastri (2003) at Morro del Fraile, and Scattolin (2003) at

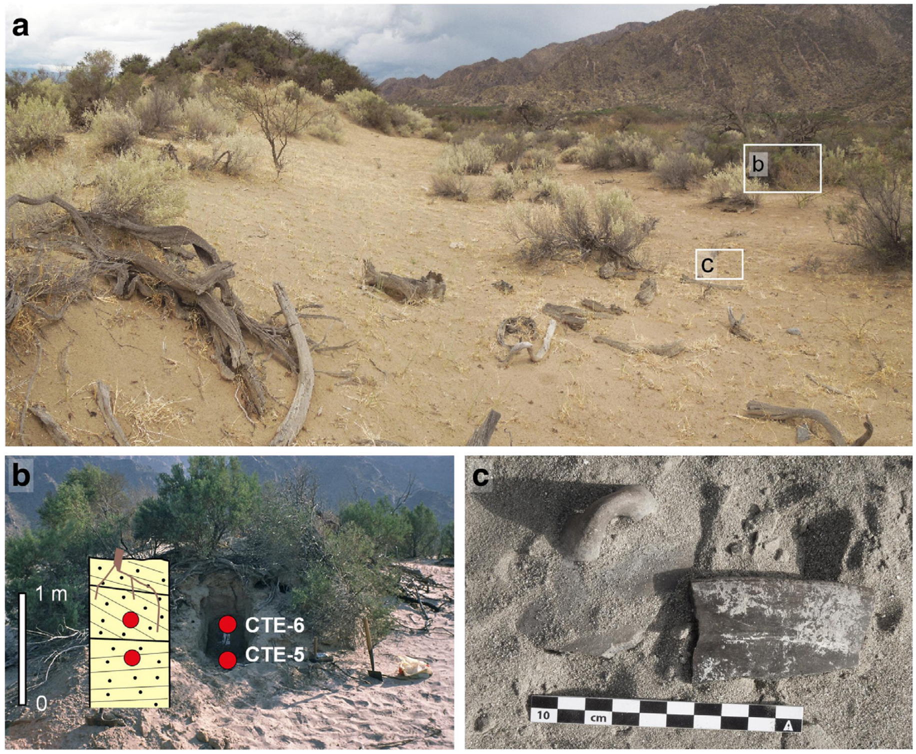

Fig. 6. (a) General view of one deflation corridor, next to Road 40, north from Tolombón; (b) detail of sampling points CTE-5 and CTE-6 with stratigraphic profile; and (c) Formative Period ceramic potsherds.

Morro de las Espinillas (710 to 1030 cal. AD; 680 to 1000 cal AD). As we noted previously, these archaeological materials were found in situ under the dunes dated around 1350 AD (samples CTE-5 and CTE-6, Table 1).

4.4. Paleoenvironmental issues

In general terms, it is accepted that in the centre of Argentina, a dry phase occurred from 3000–3500 BP and finished suddenly around 1000 AD (Carignano, 1999; Iriondo et al., 2009). However, in other regions, such as the Tafí Valley, Sampietro Vattuone (1999, 2002) pointed out the existence of a paleosol dated to 2480 ± 110 ^{14}C years BP and reflecting a wetter and warmer climate than present. This condition persisted until 875 ± 20 ^{14}C years BP (Garralla, 1999). This climate enabled the establishment of settlements of the Tafí culture (Formative Period, 2300 1100 BP) in the valley under favourable climatic and pedological conditions (Sampietro Vattuone and Neder, 2011; Sampietro Vattuone et al., 2011). Kulemeyer et al. (2013), the El Bolsón Valley (Catamarca) also indicates wet conditions between 750 BC and 500 AD. Thus we infer that the climate before 1000 AD was wet across the region.

Approaching the last millennium, Kulemeyer et al. (2013) proposed an arid phase in El Bolsón between 500 AD and 1275 AD, together with considerable evidence of anthropisation. From a regional perspective, during this time all Formative (ca. 500 BC–1000 AD) cultures, characterised by the adoption of farming and sedentism with dispersed settlement patterns, collapsed. The settlements in the next period (Fig. 8c), Regional Developments (ca. 1000–1500 AD) were characterised by population agglutination and the appearance of defensive structures (Sayago et al., 2003). Different altitudinal ecological niches over the piedmont of Tucumán were progressively exploited (Esparrica, 2003). In the Tafí Valley, Sampietro Vattuone (2010) identifies a drier phase with high levels of erosion from 1000 AD. In the Andes, there was a very dry climatic phase at this time. For example, the descent of the level of Lake Titicaca is recorded in the Bolivian plateau and the cultural consequence was the collapse of the Tiwanaku civilization (Ortloff and Kolata, 1993; Binford et al., 1997; Abbott et al., 2003). Inside this framework of regional aridity is located the sample CTE-1 (1010 ± 80 AD) (Fig. 8a; Table 1). During the second half of the MCA (ca. 1100–1300 AD) the presence of incipient soils in Central Argentina, as well as an increase in the extension of several lakes including Lake Mar Chiquita (Iriondo, 1999), greater fluvial dynamism (Iriondo and Kröhling, 1996), stabilisation of previous aeolian formations, and more extended subtropical forests.

There is much more regional information for the Little Ice Age. Pietro et al. (1995) made a climatic reconstruction using historical sources and established the existence of a dry period between 1580 and 1641 AD with catastrophic droughts in the decade of 1580 (Fig. 8b). Valero-Garcés et al. (2003), note in the record of Lago Peinado (Altiplano of Argentina) a dry phase before 1680 AD that could coincide with this arid event. The beginning of this phase coincides with the arrival of the Spaniards (1535 AD) and the period of indigenous resistance (Fig. 8c). Historical data recovered by López de Albornoz (1997) in the region shows important droughts between 1760 and 1800 AD, with a maximum intensity between 1780 and 1790 AD. Herrera et al. (2003) and Prieto and García Herrera (2009) also indicate a very dry phase between 1785 and 1805 AD in the region of Tucumán. These environmental conditions by themselves could explain the intense mobilisation of aeolian materials in the Cafayate depression. Moreover, this period coincides with the Spanish occupation (Fig. 8c) so it is possible that erosion was intensified by overgrazing in the lowlands of the region because the valley was used to breed mules for the Alto Perú (Rodríguez, 2008). These drier phases are coincident with the OSL results of the samples CTE-5 and CTE-6 at 640 ± 60 and 650 ± 70 years before 2000 AD (1360 ± 60 and 1350 ± 170 AD) (Fig. 3.1; Fig. 8b; Table 1) and the samples CTE-3 and 4 at 350 ± 50 and 410 ± 40 years before 2000 AD (1650 ± 50 and 1590 ± 40 AD respectively) (Fig. 3.2; Fig. 8b; Table 1).

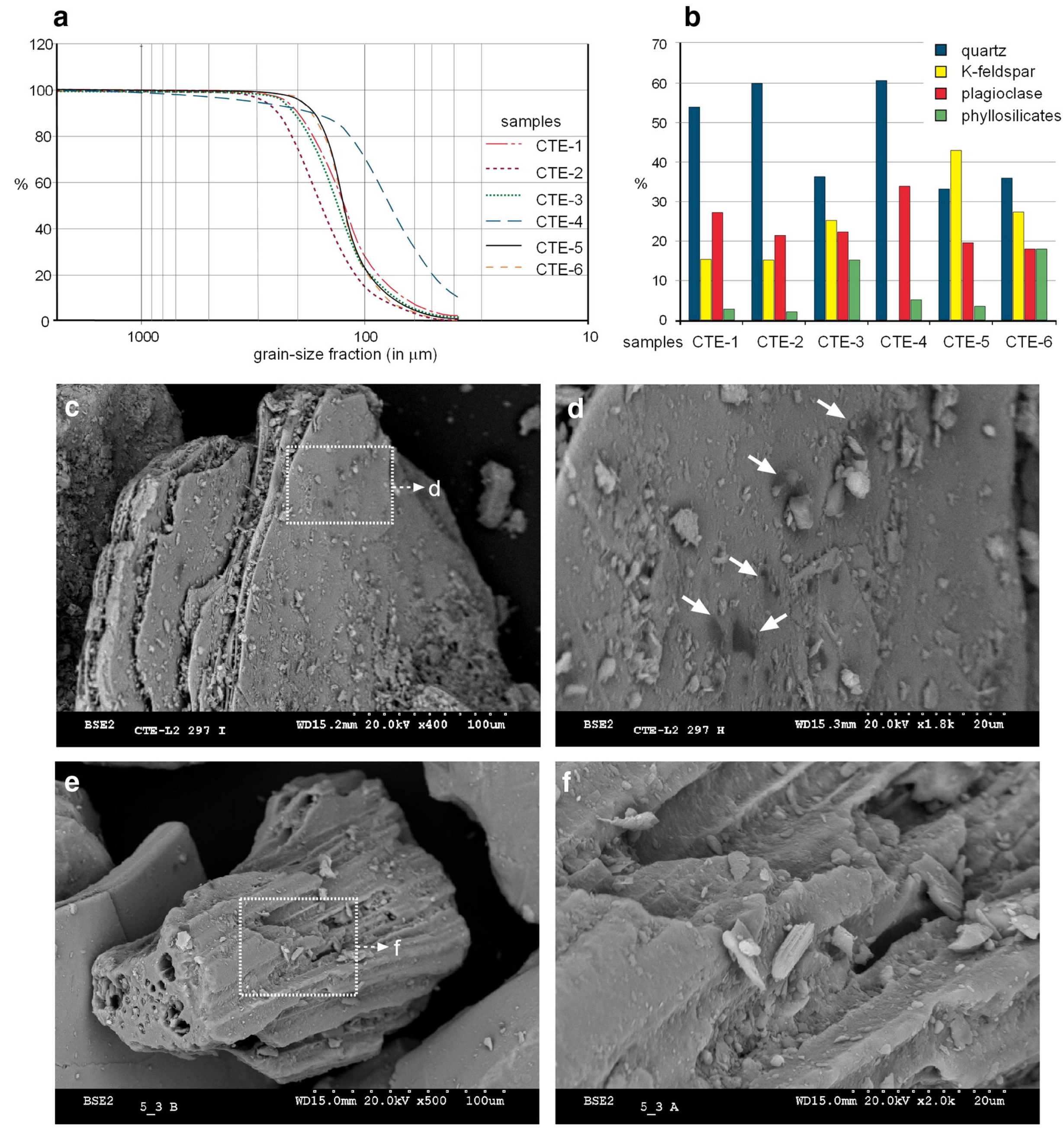

Fig. 7. (a) Cumulative curves of grain size of sand samples from ancient dunes (x-axis in logarithmic scale); (b) semi-quantitative mineralogical composition of bulk sand samples; (c) mmicrophotography of a subangular grain of weathered mica; (d) detail with percussion marks (arrows); (e) mmicrophotography of a volcanic glass shard; and (f) detail of adhered particles.

Table 1
OSL age estimates from dunes in the Cafayate area. All uncertainty values represent 1 sigma. Note that sample CTE-1 has two age estimates based on two distinct populations observed; see text for details. The numbers of aliqots measured are indicated between brackets next to field codes.

Field code (aliquot no.)	Lab. code	Depth (m)	D_e(Gy) ± 1 sigma	Dose rate (mGy/a) ± 1 sigma	Age (years before 2000 AD)	Age (years AD) ± 1 sigma
CTE-1 (12)	K0159	1.15	0.87 ± 0.24	3.87 ± 0.19	220 ± 60	1780 ± 80
CTE-1*	K0159	1.15	3.82 ± 0.24	3.87 ± 0.19	990 ± 80	1010 ± 80
CTE-2 (12)	K0160	1.50	0.89 ± 0.19	3.85 ± 0.20	230 ± 50	1770 ± 50
CTE-3 (6)	K0161	2.50	0.96 ± 3.40	4.55 ± 0.22	350 ± 50	1650 ± 50
CTE-4 (6)	K0162	3.00	2.06 ± 0.19	5.01 ± 0.24	410 ± 40	1590 ± 40
CTE-5 (12)	K0163	1.25	3.41 ± 0.28	5.33 ± 0.24	640 ± 60	1360 ± 60
CTE-6 (12)	K0164	1.00	3.46 ± 0.89	5.31 ± 0.24	650 ± 170	1350 ± 170

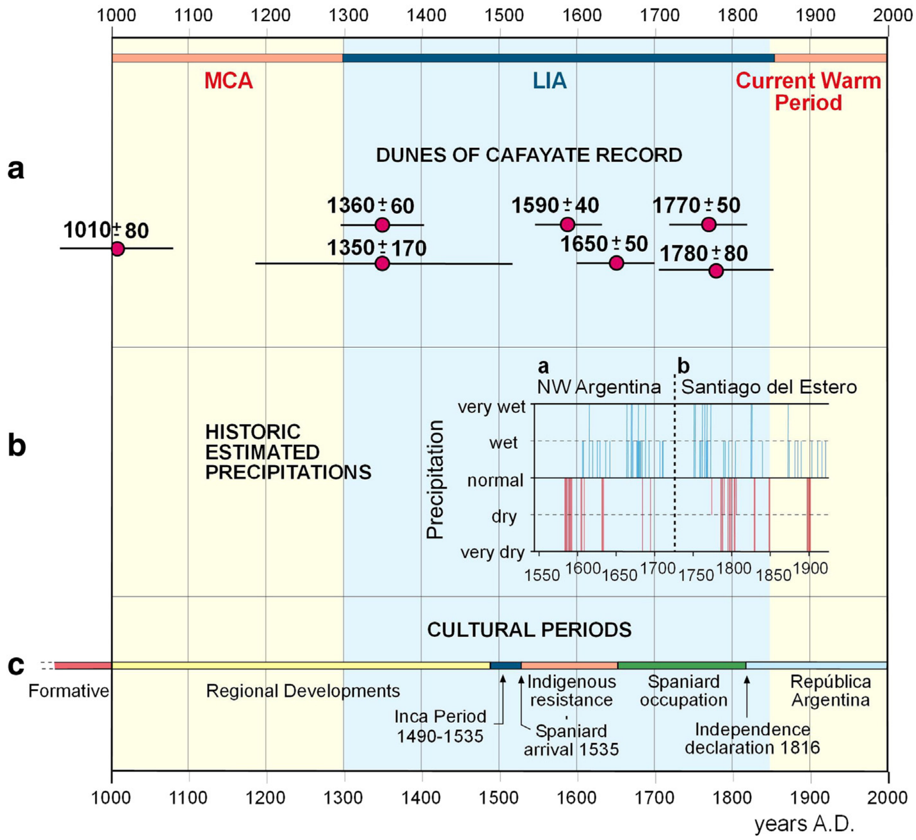

Fig. 8. (a) OSL ages related with climatic stages from the last millennium; (b) historic estimated precipitations in (a) Northwestern Argentina (Pietro et al., 1995) and (b) Santiago del Estero (Herrera et al., 2003) from documentary sources; (c) cultural periods from the Santa María valley.

Drier conditions were probably interrupted by wetter phases, although alluvial and aeolian records are absent in the Cafayate area. However, historical records show that the period between middle 17th to early 18th centuries was wetter, especially between 1663 and 1710 AD (Pietro et al., 1995) when floods and droughts caused high environmental variability (Prieto et al., 2000; Prieto and García Herrera, 2009; Herrera et al., 2003). Valero-Garcés et al. (2003) also showed a wet phase in the Argentinean Highland Plateau from the end of 17th century. Under these conditions, the vegetation could cover large areas of dune fields, including even carob trees, resulting in stabilisation of sand sheets.

The influence of anthropic activity on the dune sand mobilisation was probably related to the intensive pastoral exploitation of the area after Spaniards arrived, especially after the discovering of silver mines in the Alto Perú, between 1770 and 1805 AD (Mata de López, 1998, 2000), when there are reports of 70,000 mules grazing in Cafayate before being exported. Besides, there were cows, goats, and sheep grazing in the area whose number is unknown.

5. Conclusions

The Cafayate dune field in the northern area of the Santa María valley can be divided into two sectors: Los Médanos 1 and Los Médanos 2. Dunes are located following the direction of the dominant northeast wind. Dune types are barchans, barchanoid ridges, and parabolic dunes. Parts of the dunes are fixed by the typical vegetation of the area, while other sections are reactivated during strong wind events through deflation corridors and blowouts.

Sands come from the beds of the River Santa María. Bulk sample mineralogy reveals quartz and feldspar. Augite is the most common heavy mineral and this indicates a low degree of chemical maturity in the aeolian sediments. Subangular grain shape and mechanical surface features (abrasion and pitting) indicate a short transport distance. Salt coatings are formed by evaporation pumping during drier periods. Some volcanic glass shards were also identified.

The OSL age determinations obtained from the sampled sands only allowed determining that the aeolian processes remained active during the last millennium, with dates between 1000–1100 AD to 1740–1830 AD, being impossible to differentiate intermediate stabilised phases. These conditions of extreme regional aridity were also pointed through archaeological and documentary sources, as well as intermediate wetter periods, especially during the LIA.

The presence of human occupation in our study area is evidenced by the ceramic potsherds found under the dunes. Humans may therefore have influenced the environmental conditions of the area. Nevertheless, its influence over the region was only documented in the dune active phase of 18th century, contemporary with deep changes in land use of the territory documented by historical information.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.palaeo.2015.08.028. This data include Google map of the most important areas decribed in this article.

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