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Spatial variability of Late Pleistocene–Early Holocene soil formation and its relation to early human paleoecology in Northwest Mexico

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ABSTRACT

In Sonora, northwest Mexico, we have recognized the existence of paleosol units of Late Pleistocene/Early and Middle Holocene age (13,000 to 4,250 Cal years BP) at several archaeological sites with Paleo-indian occupations (e.g. La Playa, Fin del Mundo, El Bajio, El Aigame and El Arenoso). The few paleoenviromental reconstructions from the region indicate that the end of the Pleistocene was dominated by temperate climate that promoted the establishment of the first people in coexistence and interaction with the Pleistocene megafauna. The study of the spatial distribution of various soil units developed during late Pleistocene in the region provides information about local environmental settings of the initial peopling of Sonora. Several pedosedimentary sequences were analyzed in the different parts of Sonora, the age control in which was provided by archaeological and paleontological findings and/or by the radiocarbon dating of carbonates and paleosol humus.

Two trends of the Late Pleistocene pedogenesis have been identified. The profiles located in the south, center and north of the state are dominated by red soils (earlier referred as Big Red in the archaeological literature) whose characteristics are represented by the Red San Rafael Paleosol (SRP). The properties of SRP in the lower part of the profile (rubification, clay accumulation, hig magnetic susceptibility, illuvial carbonates, and redoximorphic features) are indicative of a more humid environment. Above them is a late Holocene polycyclic sequence of soils with morphological characteristics displaying a more incipient development.

In contrast with the sequence described above, El Arenoso, north of Caborca, show a sequence of gray soils. Two paleosols were formed in alluvial sediments. At the Cantera profile (CTP) and El Arenoso profile (ARP) paleosols are represented by Bgk horizons and evidence of weathering and clay neo-formation, redoximorphic processes and illuvial accumulation of carbonates. We explain the differences of north-western profiles by specific geomorphic conditions which imply limited soil drainage and the possibility of over-wetting. These processes indicate alternating a humid environment (weathering, rubification, clay formation and redoximorphic processes); and dry periods (carbonates accumulation). Despite regional differences of the late Pleistocene paleosols, the comparison with the Holocene soils demonstrates clear trends towards desertification in the region. The first people that inhabited Sonora during the late Pleistocene found a more temperate and wetter climate than they encountered further to the north, but subsequent generations witnessed a rapid desiccation of the region with the formation of the Sonoran Desert in the early Holocene.

1. Introduction

Northwest Mexico and adjacent regions of the U.S.A. southwest is a fundamental region for investigating the climatic changes that

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occurred during the late Quaternary. These are well documented by a number of multi-proxy paleoenvironmental records obtained from lake sediments in Arizona, California, and Chihuahua (Haynes, 1987; Waters, 1989; Ortega-Ramírez et al., 1998; Lozano-García et al., 2002; Metcalfe et al., 2002), alluvial stratigraphy –Southern Arizona, Chihuahua, and Sonora– (Mehringer and Haynes, 1965; Waters, 1986, 1991; Nordt, 2003; Haynes, 2008; Pigati et al., 2008; Ballenger, 2010; Ballenger et al., 2011), packrat middens in Arizona (Anderson and Van Devender, 1995; Elias, 2007; Holmgren et al., 2003) and ocean sediments –Guaymas Basin– (Dean, 2006). These records show the Late Pleistocene (Last Glacial maximum and late Glacial – MIS2) in the region was a period of humid and colder climate, whereas the transition to the Holocene is characterized by a unidirectional trend to aridity lasting until today. A wetter Late Pleistocene reconstructed for Northwest Mexico and Southwest U.S.A., opposes the general global paleoclimatic tendencies. Loess-paleosol sequences in Tadjikistan, China and India (Bronger et al., 1998; Dodonov et al., 2006), Argentina and the Great Plains, U.S.A. (Kemp and Zárate, 2000; Jacobs and Mason, 2007; Fucks and Deschamps, 2008), Europe (Antoine et al., 2003) – indicate a strong pedogenesis during the interglacial intervals including the Holocene, and the LGM is characterized by depositional and erosional sequences linked to cold and dry climatic conditions. These differences indicate that although some major climatic changes have global control, climatic processes at the regional level can modify the local record. Studying the unique characteristics of each region provides better understanding of the history of the terrestrial climatic system.

People came to the American Continent during the terminal Pleistocene, when climatic variations played an important role shaping the landscape and consequently human adaptations. Humans began to inhabit Northwest Mexico at about ~ 13,500 cal BP, at that time Sonora together with Texas, Arizona and New Mexico was the most populated region of the continent. The Aubrey site, Texas, has been dated to ~11,565 ^{14}C BP (~13,400 cal BP), Blackwater Draw, New Mexico to 11,300 ± 235 ^{14}C BP (~13,142 cal BP); and Fin del Mundo Site in Sonora at 11,550 ± 70 ^{14}C BP (~13,390 cal BP) (Ferring, 2001; Haynes, 2008; Sanchez et al., 2013, 2014). These three sites as well as many of the Clovis sites located in Northwest Mexico, Southwest U.S.A., and the Great Plains also had remains of Pleistocene proboscidians that became extinct at the end of the Pleistocene/Early Holocene. In the Sonoran Desert, there are at least a dozen sites with important evidence for studying the first Clovis people and the paleoenvironment, including the San Pedro Valley sites in southern Arizona, U.S.A. (Murray Spring, Lehner, Naco, Escapule), and several sites in Sonora: the Fin del Mundo site, La Playa, El Bajío, El Gramal, El Aígame and El Arenoso (Holliday et al., 1994; Villalpando and Carpenter, 2004, 2005and, Villalpando et al., 2007; Terrazas Mata and Benavente, 2006; Terrazas Mata, 2007; Gaines et al., 2009; Sánchez et al., 2009; Carpenter et al., 2009; Sanchez, 2010).

The paleoclimatic history of the Sonoran Desert (Arizona and Sonora) has been reconstructed using a multi-proxy data from packrat (neotoma) middens in the region and surrounding areas (Van Devender, 1990; Van Devender and Spaulding, 1979). These records, combined with sparse pollen profiles from lakes and alluvial sequences from the region, along with a recent study of carbon (δ^{13}C) and oxygen (δ^{18}O) isotopes from mammalian fossils recovered from Sonora (Nuñez et al., 2010), provide the base for a preliminary interpretation of the climate and plant successions during the last 16,000 years. Macrofossils show forest vegetation associated with mild and wet climates, but the mammal fossils indicate a mixed vegetation of plants C3/C4, also associated with a more humid climate regime than today. The paleoenvironmental inferences for the western U.S.A. and Northwest Mexico are summarized in Table 1. Records indicate variable conditions and in some cases very contrasting: in some regions wetter conditions in the Late Pleistocene and Early Holocene, while at other conditions are drier (e.g., Martin, 1963; Mehringer and Haynes, 1965; Long, 1966; Haynes, 1969; Irwin-Williams and Haynes, 1970; Van Devender and Spaulding, 1979; Waters, 1986, 1989, 1991; Davis and Anderson, 1987; Nordt, 2003; Haynes, 2008; Pigati et al., 2008; Ballenger, 2010; Ballenger et al., 2011; Barron et al., 2012).

Table 1
Summary of Late Pleistocene to Holocene paleoenvironmental records in Western United States and Northwestern Mexico.

Period	Age	Paleoenvironments in Western United States	Paleoenvironments in Northwest Mexico	
			Guaymas Basin, Sonora	Babicora, Chihuahua
Late Holocene	4.5–1 ka Cal BP	Cooler and wetter than today; aggradation of stream valleys; formation of cumulic Mollisols on floodplains; renewed speleothem growth; Audubon Neoglaciation in Colorado; rejuvenated springs; sagebrush steppe and pinyon pine woodland expand on Colorado Plateau; expansion of woody shrubs in deserts; increased El Niño frequency.	(5.6–2.5 ka Cal BP). Warm period. Changing winter conditions to summer conditions, however weak southeasterly winds that bring warm water. In the Chihuahuan Desert dominated desert scrub.	
Middle Holocene aridity	7–4.5 ka Cal BP	Hot and dry; Antevs' Altithermal; pluvial lakes and alpine ponds dry up; spring flow ceases; arroyo cutting in many valleys; previous sagebrush steppe replaced by desert grassland; soils become more alkaline; salt-tolerant shrubs invade grasslands; lunette dunes form downwind from dry playa basins; forests reach highest elevation in mountains with diminished alpine tundra.		Warmer and dryer
Early Holocene	11.7–7 ka Cal BP	Rapid warming at end of Younger Dryas; begins cool and wet and becomes warm and dry; speleothem growth ceases; sagebrush steppe diminishes in southern areas; isolated trees die off in southern deserts; ponderosa pine and oak expand on lower montane slopes; progressive decrease in spring flow and wet meadow formation; soils that formed previously across the region begin to erode with warmer climate.	Warm and wet period. Conditions characterized by strong winds from the NW. In the Sonoran Desert (Arizona and Baja California) is already desert scrub.	Increasing warmth and dryness
Younger Dryas	12.9–11.7 ka Cal BP, Northern Hemisphere	Cold and wet although less-so than full-glacial climate; peak spring-flow, wet meadow-black mat formation; glaciation	Cold and humid period, no formation of black-mats.	Colder and wetter

Table 1 (*continued*)

Period	Age	Paleoenvironments in Western United States	Paleoenvironments in Northwest Mexico	
			Guaymas Basin, Sonora	Babicora, Chihuahua
		in Sierra Nevada but not yet documented in SW mountains; speleothem growth; sagebrush steppe persists across plains, basins, plateaus. Increased winter precipitation. In Sonora and Chihuahua Deserts, very dry conditions.		
Bølling-Allerød	14.6–12.9 ka Cal BP	Warmer and drier than full-glacial but cooler and wetter than today; speleothem growth; sagebrush steppe vegetation.	Warm and humid period, similar to today, with upwelling caused by northwest winter winds.	Drying
Full-glacial and Late-glacial	26–14.6 ka Cal BP	Cold and wet; major alpine glaciation on SW peaks above 12,000 feet; rivers wide with large bed load; speleothem growth; thick soil development; sagebrush steppe across plains, basins, plateaus; isolated pine-oak-juniper trees on Chihuahuan and Sonoran desert escarpments.	Cold period.	Cold and wetter

Paleosols, both buried and exposed on the present day surface dating to the Late Pleistocene/Holocene, have potential as an additional paleoecological proxy. Of particular importance is the San Rafael paleosol (SRP) (Fig. 1) identified at La Playa site and that apparently begin to form in Late Pleistocene with a continuous development until the middle Holocene (before 14,910–4600 cal BP). The paleopedological indicators suggest that SRP was developed predominantly under slightly more humid environment than the present; with marked seasonal changes (Cruz-y-Cruz et al., 2014). Drier episodes are supposed to occur within the SRP formation period; however, they did not leave clear signals in the “soil memory”.

Pleistocene-age red paleosols frequently are mentioned in published work because these were the surfaces that Clovis people inhabited. In a handful of Sonora sites, Clovis and Archaic artifacts have been found resting on the red soil “Big Red” (Sanchez, 2010). At the La Playa site we were able to characterize the SRP soil from Late Pleistocene/Holocene times as a Bw/BCk horizon (Cruz-y-Cruz et al., 2014).

Soils (paleosols) can provide proxy data for local environmental reconstruction through interpreting their “soil memory” —the morphological, physical and chemical characteristics indicative of past pedogenetic processes— (Targulian and Solokova, 1996; Targulian and Goryachkin, 2004; Bronger et al., 1998). Being a proxy with high spatial resolution (Targulian and Goryachkin, 2004) paleosols could provide a unique insight into regional variability of paleolandscape conditions, through the study of the composition of paleosol mantle and ancient soil diversity. The purpose of this work is to compare the key profile with the buried SRP soil at La Playa site, with other paleosols that have been identified and recorded at different localities in Sonora in order to evaluate the distribution of this soil in the region and determine if we can use it as a marker for finding paleoenviromental trends, Late Pleistocene archaeological sites, and megafauna localities.

2. Regional setting

The state of Sonora is located in Northwest Mexico, bordered to the west by the Gulf of California and Baja California Norte, to the east by the state of Chihuahua, to the south by Sinaloa and to the north by Arizona, U.S.A. (Fig. 2). The geology of Northern Mexico is characterized by the presence of a combination of very old Proterozoic crystalline basement of intrusive igneous rocks, gneisses, and schists as well as folded sedimentary rocks (Valencia Moreno, 2007). These rocks outcrop on mountaintops, while the plains are covered by extensive fluvial sediments. The study area is predominantly located in the Sonoran Desert biome, with a climate predominantly BS0h '(h) x' (dry semi-warm), the average annual temperature ranges from 18 to 22 °C. Average annual precipitation is 200–400 mm, with rainfall intermediate between summer and winter (Vidal Zepeda, 2005). One small portion of the study area, in the south of state (Huebampo), is in the Central Pacific climate region, with a climate predominantly BS0(h')w (dry with warm summer rains), average annual temperature is about 22 °C and the average annual rainfall is 300–700 mm. The predominant vegetation is desert scrub type (Pérez, 1985; INEGI, 2002).

The major part of the study area belongs to the Concepción River basin, covering the rivers Alisios, Magdalena, Altar, Asunción, Boquillas and Concepción (Pérez, 1985). It includes the archaeological site El Arenoso, north of Caborca, the site of La Playa, north of Trincheras, the NW of Magdalena de Kino, and the Rancho Los Alamitos. In the south of the state, the site of Huebampo is located in the Mayo River basin, whose tributaries come from the Sierra de Alamos and Huebampo (Escárcega, 1985; Pérez, 1985).

Sonora is today a semi-arid region. However, buried and surface paleosols showing well developed structure, accumulation of iron oxides and clay, evidences redoximorphic processes and illuviation, are indicative of more humid environments in the past. These paleosols often have red colors of different intensity. Investigations carried out over the last 15 years in Northern Sonora have demonstrated that in the archaeological sites of Fin del Mundo, La Playa, El Bajío, El Gramal, El Aígame and El Arenoso, among others, the materials of very early human occupation are often associated with these paleosols.

The reference profile of the buried red Late Pleistocene–Early Holocene paleosol was extensively studied in La Playa where it was called the San Rafael Paleosol (SRP); similar profiles (buried and exposed on the surface) were described also in other localities The age of this paleosol is supposed to be marked by the AMS date of pedogenic carbonates: between 14,910 and 14,230 cal BP, and a set of quite close AMS dates of humus: 4440–4250 cal BP (charcoal in A horizon in La Playa) and other sites of Southern Arizona and Chihuahua (Mehringer and Haynes, 1965). SRP in la Playa shows moderate accumulation of clay and the presence of illuvial carbonates with minimum contents in Bw and maximum in BCk and 2BCgk horizons which indicate leaching. Similar properties were documented in a very similar profile of surface paleosol found in the site Magdalena de Kino. This paleosol was classified as a Cambisol, according to the WRB (2006). The properties of SRP (rubification, accumulation of clay, higher values of magnetic susceptibility, illuvial carbonate, and redoximorphic features in the lower profile) are an indicator that a more humid environment than today was present during the Late Pleistocene. Development of SRP was abruptly terminated in the middle Holocene, when the environment drastically changed and erosion/sedimentation intensified.

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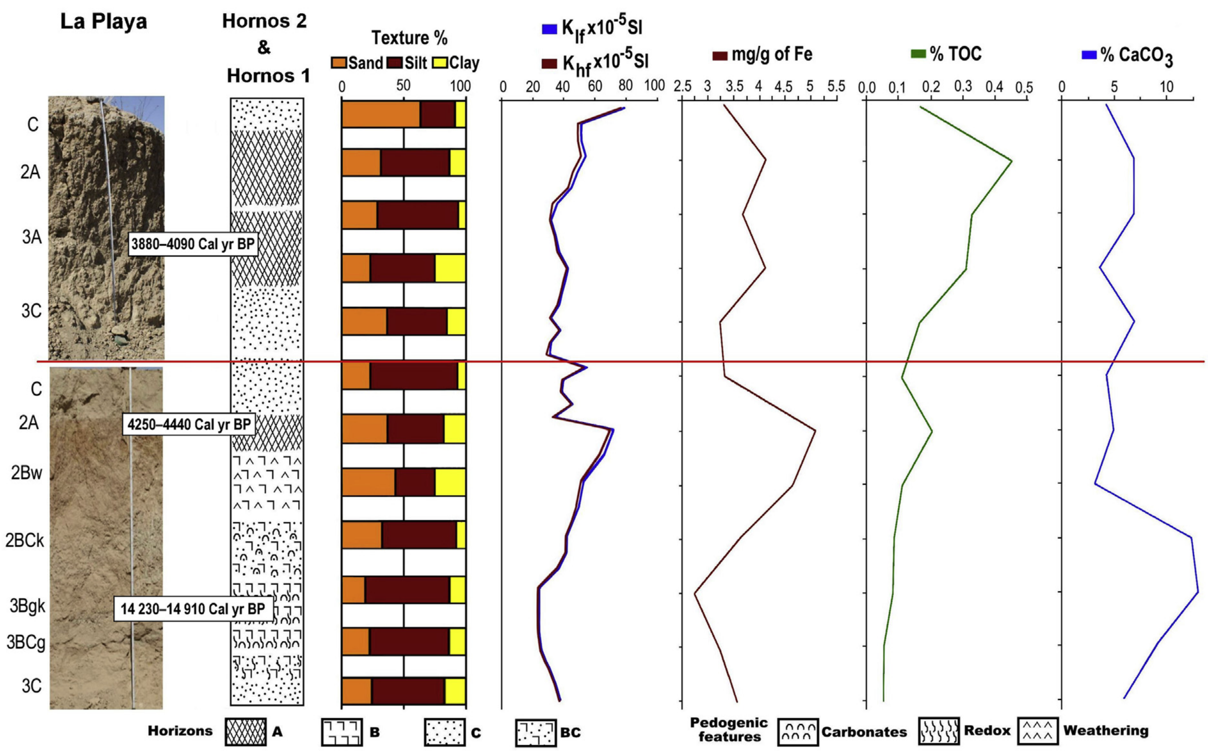

Fig. 1. Stratigraphy, dating and pedogenetic properties at San Rafael Paleosol reference profile (based on Cruz-y-Cruz et al., 2014).

The Late Holocene pedogenesis is characterized in La Playa by The Boquillas paleosol (BOP); the organic matter of horizon A has been dated to 3660 cal BP. It is an alluvial synsedimentary soil composed of several incipient Ah horizons separated by alluvial sediments. BOP shows incipient accumulation of humus and a weak development of the pedogenic structure, so it is classified as a Fluvisol according to WRB (2006). The soil development is weak and strongly affected by fires, triggered by both natural and cultural processes, indicating a very unstable landscape created by changing weather and human impact (Cruz-y-Cruz et al., 2014).

3. Materials and methods

The methodology consisted on field and laboratory work which included 2 major blocks:

1) Identification, description and further laboratory study of the new profiles of Late Pleistocene paleosols in different parts of Sonora, and comparison with the key sections of La Playa and Kino.
2) Revision of the earlier site descriptions within archaeological and paleontological investigations to identify Late Pleistocene paleosol units associated with the archaeological findings.

We assume that these two sources will provide an assessment of the spatial distribution and variability of the Late Pleistocene – Early Holocene paleosols and contribute to their interpretation as a record of paleoenvironments of Late Pleistocene megafauna and first humans in Sonora.

3.1. Field research

The field strategy consisted of a field recognition survey to look for road cuts, erosional gullies, and arroyo walls, with the purpose to identify and register paleosols. The main areas for the survey were those where earlier Paleo-Indian archaeological remains and Pleistocene megafauna were documented. Where possible, we tried to establish stratigraphic relation of the paleosol units and archaeological/paleontological materials. The original profile already described at La Playa was used as a reference to be compared with the new profiles. Based upon diagnostic traits observed at the San Rafael paleosol (SRP), we were able to select several profiles with Pleistocene paleosols for dating using ^{14}C, or showing a clear association with paleontological remains of Pleistocene age, and/or associated to Paleo–Indians artifacts.

Paleosols were described at the field using the established field description by the WRB (2006). The FAO-UNESCO (1994) manual was used for the identification, description and classification of horizons (depth, limits, color, texture, compaction, porosity, organic matter, presence of cutains, stains, spots and concretions). Several samples from key genetic horizons were collected for several laboratory analysis and micromorphology.

3.2. Laboratory analysis to characterize paleopedological features

Granulometric analysis followed USDA (2004). The abundance and distribution of clay fraction in the paleosols are indicative of pedogenetic processes of weathering and clay illuviation, whereas composition of sand and silt fractions is informative for the sedimentological aspects in alluvial sequences. After removal of the cementing agents: humus (with 30% H_2O_2), carbonates (with 0.5N HCl) and iron oxides (with citrate-bicarbonate-dithionite reaction), sand fractions were separated by sieving, and silt and clay by gravity sedimentation. The obtained fractions were dried at 105 °C and weighed to obtain the percentage of each sample.

Rock magnetic properties are widely used to detect and quantitatively estimate effects of pedogenesis in the sedimentary sequences and to correlate paleosol units. Various soil forming processes strongly impact the pool of magnetic minerals in soils; thus magnetic characteristics could be also indicative of type of

Fig. 2. Study Area, isohyets and rivers are included. The points indicate the studied sites.

pedogenesis. Magnetic susceptibility (χ) was measured in all sections studied by using a MS2B Bartington system at two frequencies (0.47 and 4.7 kHz).

Dithionite-extractable iron (Fe_d) is an integral evaluation of fine-grained iron oxides in the paleosol horizons. Most of them are of pedogenetic origin, and thus the content of Fe_d also shows an integral characteristic of weathering. For this analysis, free iron oxides were extracted following Mehra and Jackson (1960) in the dithionite-citrate-bicarbonate solution. The filtrate was analyzed using an atomic absorption spectrometer (Perkin Elmer Model 3110).

Organic carbon content (Corg). Although part of the organic matter in the paleosol is decomposed after burial, the position and intensity of the Corg maxima in the profile, could be used to measure the accumulation of humus in the past and characterize organic horizons. Soil samples were analyzed in using an elemental analyzer CHNS/O Perkin Elmer 2400 series II, to obtain the abundance of CHN under the following analytical conditions: helium was the carrier gas at a combustion temperature of 980 °C and reduction temperature of 640 °C, with a thermal conductivity detector (Schlichting and Blume, 1966).

Pedogenic carbonates in the soil are a direct signal of the local environment; in arid climates where evaporation exceeds precipitation, secondary carbonates tend to accumulate at certain depth. The content, shape and location of pedogenic carbonates can be related to specific environmental conditions. For this work, the dry sample was weighed and HCl 0.5M solution added until the carbonates were completely dissolved. Subsequently, the sample was washed and dried in an oven for re-weighing. The percentage of carbonates was determined by weight difference from the original weight of the sample and the weight after the treatment with 0.5N HCl.

Stable isotopes of C ($\delta^{13}C$) in soil organic matter provide a direct isotopic signature of the dominant vegetation when soil was been developed (Smith and Epstein, 1971; Guerrero and Berlanga, 2000). C3 plants have $\delta^{13}C$ ratio of −20 to −35‰, C4 plants ranging from −10 to −14‰; and CAM plants contain intermediate values between C3 and C4. The $\delta^{13}C$ mammalian tooth enamel is about 14‰ more positive, so that the values for C3 are about <−10‰ while to C4 have values between −1 and 3‰ (Cerling, 1999; Nuñez et al., 2010). Isotopic composition of pedogenic carbonates is controlled by vegetation: however, during the carbonate synthesis, C suffers isotopic fractionation (Cerling, 1984, 1999). For this reason, to obtain the vegetation isotopic signature from carbonates, −15‰ units must be added to the original $\delta^{13}C$.

For radiocarbon dating (AMS), two types of samples were sent to the Beta Analytics laboratory: 1) material of the paleosol humus horizons, for dating the soil organic matter and 2) calcitic neoformations from calcic horizons (concretions, crusts) for dating pedogenic carbonates. All dated carbonates come from vermicular concretions formed within the pores of the paleosols, due to pedogenesis.

4. Results

We have located, described and analyzed several profiles from four localities. The localities with Pleistocene paleosols are: Rancho El Arenoso, Caborca (three arroyo walls profiles –La Cantera, Los Poceaderos and El Arenoso–); Alamitos Profile, Hermosillo–Santa Ana Highway; and at the locality of Huebampo (Don 1 and Don 2 profiles) in the southern end of the state of Sonora. All the studied paleosols are developed on alluvial fans of Quaternary age, apparently under similar climatic conditions that trigger comparable processes and similar degree of soil development. In the majority of the places, the Late Holocene sequence is missing and the Pleistocene paleosols are exposed at the surface, probably due to recent erosional episodes. We have identified two main varieties of Pleistocene paleosols; one is red and the other is gray.

4.1. Description and analysis of the Late Pleistocene red paleosols

Paleosols belonging to this group look very similar to the soils described in the key profiles of la Playa and Kino and were thus associated with the SRP. They were described at Rancho Los Alamitos and Huebampo, developed on alluvial fan deposits. At Rancho Los Alamitos, the main flow comes from the Sierra de la Lámina, east of the locality. The alluvial sediments have been incised by a seasonal stream which also flows from the Sierra, and was further intersected by a road. The locality has an almost plain pediment with a gentle slope running NE to SW. The profile consists of three soils alternating with alluvial sedimentary deposits (Fig. 3a). The upper is a well-developed paleosol exposed at the surface, consisting of horizons A/AB/Bw/BCk/Ck, whit reddish brown A, AB and Bw horizons. The second is a paleosol underlying the first, with light development and reductomorphic features, with a 2Bg/2C sequence. The third is also a paleosol with stagnic properties, formed by 3Bg/3C horizons. Near Huebampo, in Southern Sonora, we observed, in a section of the road, red paleosols with similar features. At this locality, we studied two profiles in an alluvial fans oriented NE–SW. The Don 2 profile has a sequence: Bgk/Ck/2Btgk/2BCk/3Ck (Fig. 3b), and Don 3 profile has a sequence Bk/Ck/2C (Fig. 3c). Don 2 profile contained two paleosols; in the upper paleosol, the Bgk horizon shows evidence of redox processes and accumulation of carbonates and Ck horizon has few pedogenic features; while in the deeper paleosol, the 2BCk horizon indicates a major alteration of the material parental, and clay-illuvial horizon 2Btgk with stagnic features. Underneath these paleosols is a layer of alluvial sediment with coarser texture and enriched carbonates 3Ck. The Don 3 profile is located a few meters from 2 and shows a paleosol exposed on the surface with a Bk/Ck sequence. In this profile, below the paleosols a fossilized tortoise was found in sandy–silt sediment.

Analytical and morphological results of the sequence of Los Alamitos indicate that the clay fraction is high throughout the sequence, even in C horizons, with the maximum in the Bw and BCk and minimum in 2C and 3C horizons (Fig. 4). Higher values in magnetic susceptibility were obtained in the 3Ck and minimum values in the BCk and 2Bg; while the Fe_d has the maximum in the upper horizons A and AB and the minimum in 3Bg, indicating that 3Ck contains magnetic Minerals not produced by pedogenesis. TOC is generally low, with a maximum in A and AB, and decreases towards the base of the profile. All horizons contain carbonates and leaching between A, AB, Bw, BCk and Ck is observed, with the minimum in A and AB and maximum in Ck, although the underlying paleosoils also show significant accumulation of carbonates. The features of the paleosols of Don 2 and Don 3 profiles are similar to Alamitos profile paleosols.

4.2. Description and analysis of Pleistocene gray paleosols

In contrast with the red soils found in several regions of Sonora, at the Rancho El Arenoso locality, 60 km north of Caborca, we described three profiles containing gray paleosols in alluvial sequences (Fig. 5). The three profiles are located on an alluvial plain limited by the Sierra San Manuel at the NW and Sierra del Humo to the NE. The alluvial plain has a gentle slope NE–SW and is filled with deposits of Quaternary age. The stream El Arenoso (that originates in the Sierra del Humo to the NE) dissects the alluvial plain, and other minor streams also cut into the alluvial sediments. The Poceaderos and Arenoso profiles are associated with the Arenoso stream. The Cantera profile is located along the El Segundo stream, which begins at Sierra San Manuel to the NE.

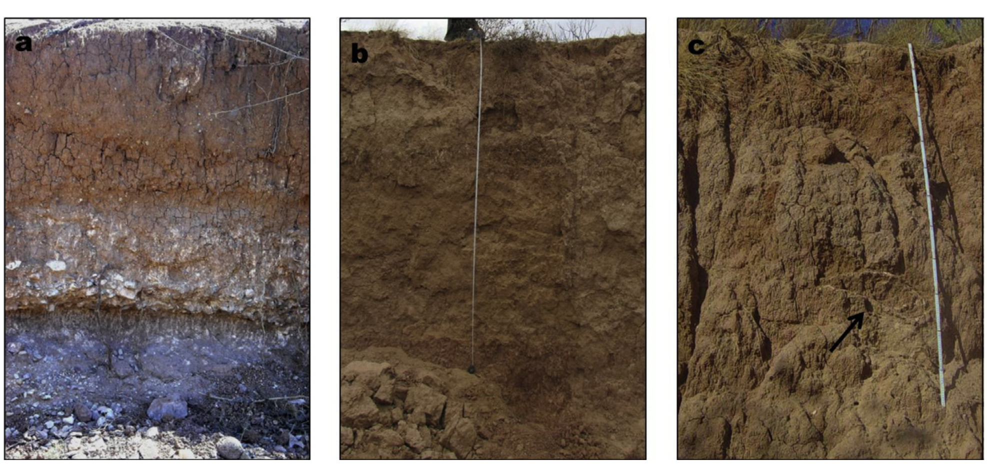

Fig. 3. Red Soils in natural context: a) Alamitos profile, b) Don 2 profile, and c) Don 3 profile. A fossilized tortoise in the 2C horizon is observed. Photos by Tamara Cruz.

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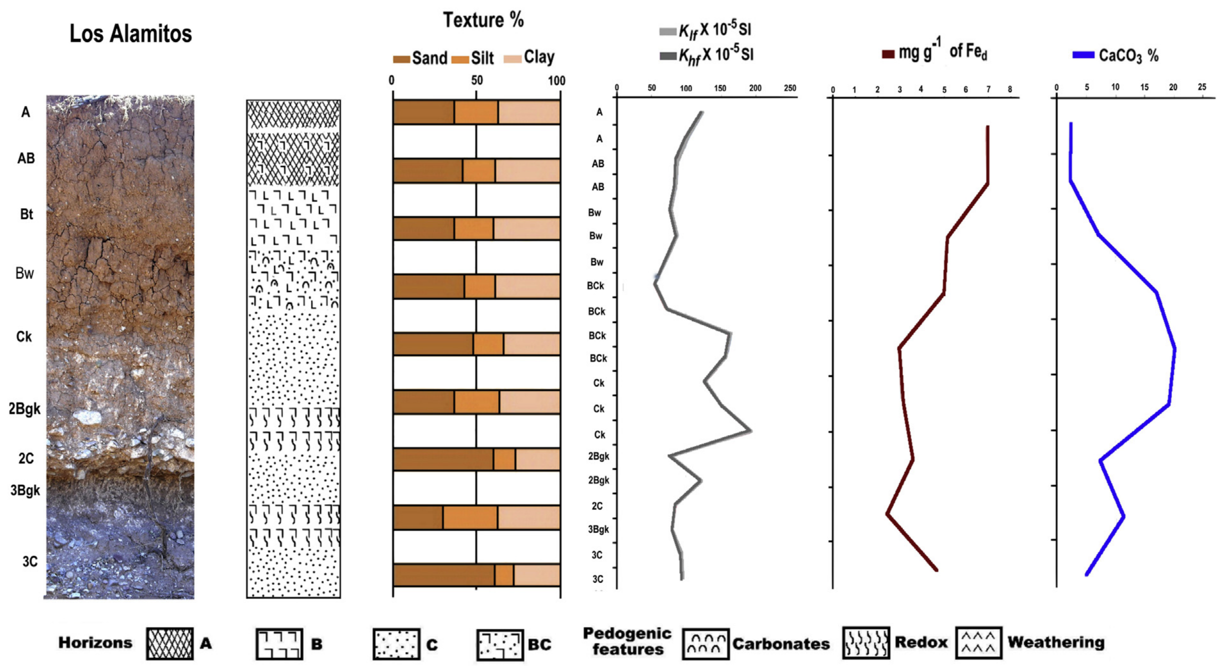

Fig. 4. Analytic results of the Los Alamitos profile.

The Cantera profile (Fig. 6a) is located at 548 m asl. The stratigraphic sequence is C/2Bgk$_1$/2Bgk$_2$/3C/4Bk/4Ck/5Bgk/5BCk/5Ck/6Bk/7Bg with several soil formations. The Arenoso profile (Fig. 6b) is located in an arroyo cut near the Cantera locality. The sequence of stratigraphic horizons is C/2Ck/3Ck/4C/5C/6Bgk/7Bk/7BC/8C/9Ck. Following the stream to the northeast, the Poceaderos profile (Fig. 6c) was found in which a sequence of horizons C/2Bg/3Bg/3BC/4Bt/5C/6C was described. The Cantera profile had the more complete pedologic sequence: here we were able to date the pedogenic carbonates in three sections of the sequence. Paleontological remains (tortoise) were found in the profile (Fig. 6d).

The analytical and morphological results of the gray paleosol represented at the Cantera profile (CTP), display a predominantly silty texture, with high contents of clay even at the C horizons. 6Bk, 4Ck and 4Bk have the highest contents of clay. The highest magnetic susceptibility and Fe$_d$ is at 3C followed by 2Bgk$_1$, 2Bgk$_2$, y 4Bk, and the lowest are C, 4Ck and 5Ck (Fig. 7). Maxima in the B horizons indicate that the magnetic minerals were produced by pedogenic process. The amount of TOC is very low, as is expected in soils without humic horizons. At the bottom of the profile, a drastic increase is observed in unit 5Ck and 6Bk, probably indicating the presence of an illuvial organic matter OM (the peds have black dots in the surface, perhaps a lixivial OM). All the horizons displayed abundant carbonates in various quantities, and leached horizons are absent, with the exception of 5Bgk and 5BCk that shows migration between horizons, with the minimum in 5Bgk and the maximum in 5BCk.

The micromorphological analysis shows that the paleosol groundmass is dominated by coarse sand-silt material with angular and irregular particles of various sizes. Rounded peds are common in several horizons, indicating redeposition and erosion. The 2Bgk$_1$ horizon present a heterogeneous distribution of carbonates in matrix and pores (Fig. 8a and b). The carbonate-free zones contain well developed illuvial clay coating in pores and Fe–Mn nodules (Fig. 8c and d). 3C has a fine groundmass with large crystals, the distribution of carbonates is heterogeneous: areas with abundant micrite alternate with reworked blocky peds free of carbonates. Illuvial clay coatings were observed inside carbonated zones, indicating that the carbonate formation occurred after the clay illuvial phase (Fig. 8e and f). In the carbonate free zones, dendritic manganese nodules were observed (Fig. 8g and h). These features are indicative of at least two different periods of pedogenesis: one under relatively humid conditions for illuviation of clay, iron and manganese, followed by a drier period that promoted carbonate formation. 4Ck has a coarse groundmass, with sand grains from volcanic rocks with plagioclase, rich in carbonates, with pores filled with neoformed calcite. Small ferruginous nodules and illuvial clay coatings surrounding the pores are present. Volcanic rocks with plagioclase, potassium feldspar, and sedimentary lithic fragments are present. The 5BCk horizon has similar groundmass characteristics, however some redeposited ped fragments free of carbonates with clay coatings. A specific feature of this horizon is the abundance of opaline phytoliths and presence of siliciofied plant tissues.

The micromorphological analysis shows a matrix composed of round and reworked peds, showing two types of different soils: one with high carbonate accumulation, in the groundmass and pores; and another without carbonate but with well-developed illuvial clay coatings. The clays, Fe$_d$ and magnetic susceptibility observed in 3C (Fig. 7) have a pedogenetic origins, but in this context they are products of an earlier pedogenesis. These early soils were transported from higher ground and were integrated into the alluvium, becoming parental material of the paleosols that we studied. In general, there are features of wet pedogenesis prior to dry conditions that promoted carbonate formation, as much of the material was leached and some redeposited fragments contain well developed illuvial clay coatings and redoximorphic features.

Three sections of the sequence were radiocarbon dated using pedogenic carbonates. The lower part of the profile (5Bgk) was dated to 30,730–31,120 cal BP, the middle section (4Bgk) dated to 19,320–19,430 cal BP, and the top section of the profile was dated to 16,800–16,920 cal BP (Table 2). The isotopic composition of the carbonates was −3.4‰ (5Bgk), −3.4‰ (4Bgk), and −5.7‰ in the top (Table 2). These readings indicate mixed vegetation, possibly grasses with bushes.

Table 2
Radiocarbon dating and isotopic values of Pleistocenic paleosols in Sonora.

Profile/depth (cm)	Horizons	Dated material	^{14}C conventional age	^{14}C calibrated age (2 sigma)	Laboratory code	$\delta^{13}C$‰ (MO)	$\delta^{13}C$‰ ($CaCO_3$)	MIS
Hornos 2 (BOP)								
20–70	2A	Organic matter				−18.94		
70–110	3A	Organic matter	3660 ± 40 BP	3880–4090 Cal BP	Beta–277563	−17.51		MIS1
	$3A_1$	Organic matter				−16.95		
Hornos 1 (SRP)								
0–11	2A	Charcoal	3930 ± 40 BP	4250–4440 Cal BP	Beta–300442			MIS1
	2Bw	Organic matter				−19.8		
115–160	3Bgk	Carbonates	12,490 ± 60 BP	14,230–14,910 Cal BP	Beta–277564		−6.40	MIS2
Kino								
80–130	$2BCk_1$	Carbonates	10,990 ± 50 BP	12,720–12,970 Cal BP	Beta–328552		−8.9	MIS2
130–150	$2BCk_2$	Carbonates	10,760 ± 50 BP	12,590–12,690 Cal BP	Beta–328553		−8.1	MIS2
Cantera (CTP)								
50–60/80	$2Bgk_2$	Carbonates	13,750 ± 60 BP	16,800–16,920 Cal BP	Beta–328549		−5.7	MIS2
60/80–100	4Ck	Carbonates	16,160 ± 60 BP	19,320–19,430 Cal BP	Beta–328550		−3.4	MIS2
130/140–165	5Bgk	Carbonates	26,230 ± 150 BP	30,730–31,120 Cal BP	Beta–328551		−3.4	MIS2
Don 2								
400		Carbonates		27,500 Cal BP				MIS2
Don 3								
0–45	Bk	Organic matter				−17.36		MIS2

The gray paleosols are closely associated to the La Cantera archaeological site, defined by the distribution of surface artifacts. No buried deposits have been discovered in the site. The site is located in an alluvial fan, and in the farther section there is a layer of a brown coarse sandy–clay with unsorted pebbles and gravel from distant alluvial fans. Under this layer, fine sediment with extinct vertebrate fossils was observed. On the surface, lanceolate bifaces of probable Late Paleo-Indian age (11,600–8000 ^{14}C BP) were collected. In addition, early and later Holocene projectile points (Jay and San Pedro) were registered, as well as ceramic period Trincheras artifacts.

Concerning paleontological findings at El Arenoso and La Cantera, Arredondo–Antúnez (unpublished data) identified *Equus excelsus*, *Equus mexicanus*, *Equus conversidens* and *Bison* sp. In this work this list was reduced to only two species: *E. mexicanus* and *E. conversidens*, because *E. excelsus* is invalid according to Alberdi et al. (2003), who recognized only three species of horses for the Pleistocene of Mexico, the largest is assigned to *E. mexicanus*, the medium–size as *E. conversidens*, and the smallest is unnamed. We add to that list *Mammuthus* sp. and a giant turtle of the Family Testudinidae (Gopherus or Hesperotestudo). The fossil association suggested an arid climate, probably a mixed environment with

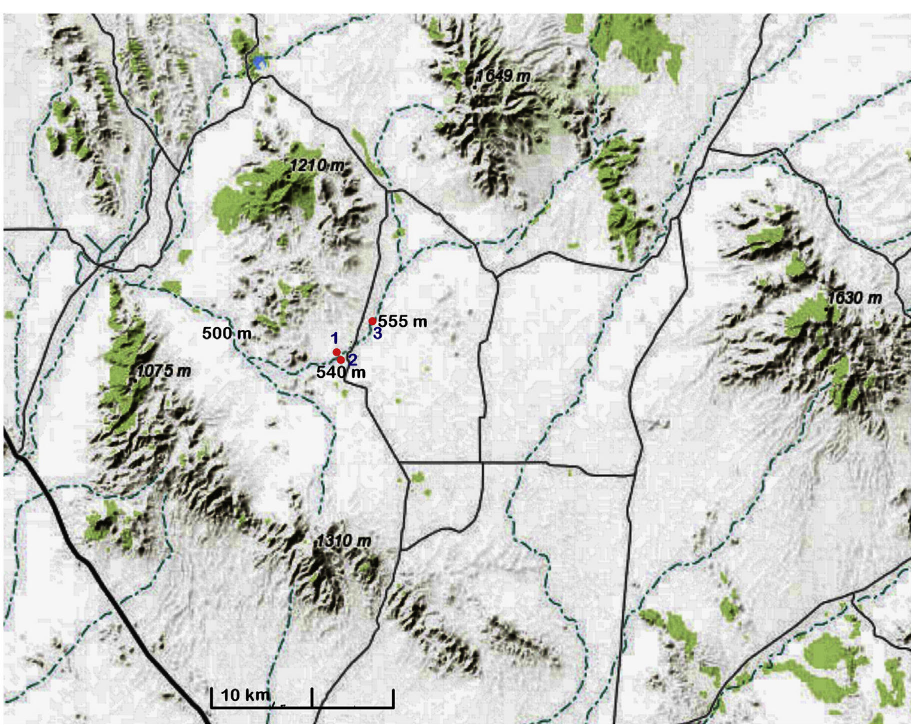

Fig. 5. Relief of the archaeological site El Arenoso Paleosol profiles are located in the lowest part of the basin formed by the Sierra El Humo (northeast), the Sierra de San Manuel (northwest) and the Sierra El Álamo (south). 1. Cantera profile, 2. Arenoso profile, and 3. Poceaderos profile (based on Digital Map of Mexico, INEGI 2014).

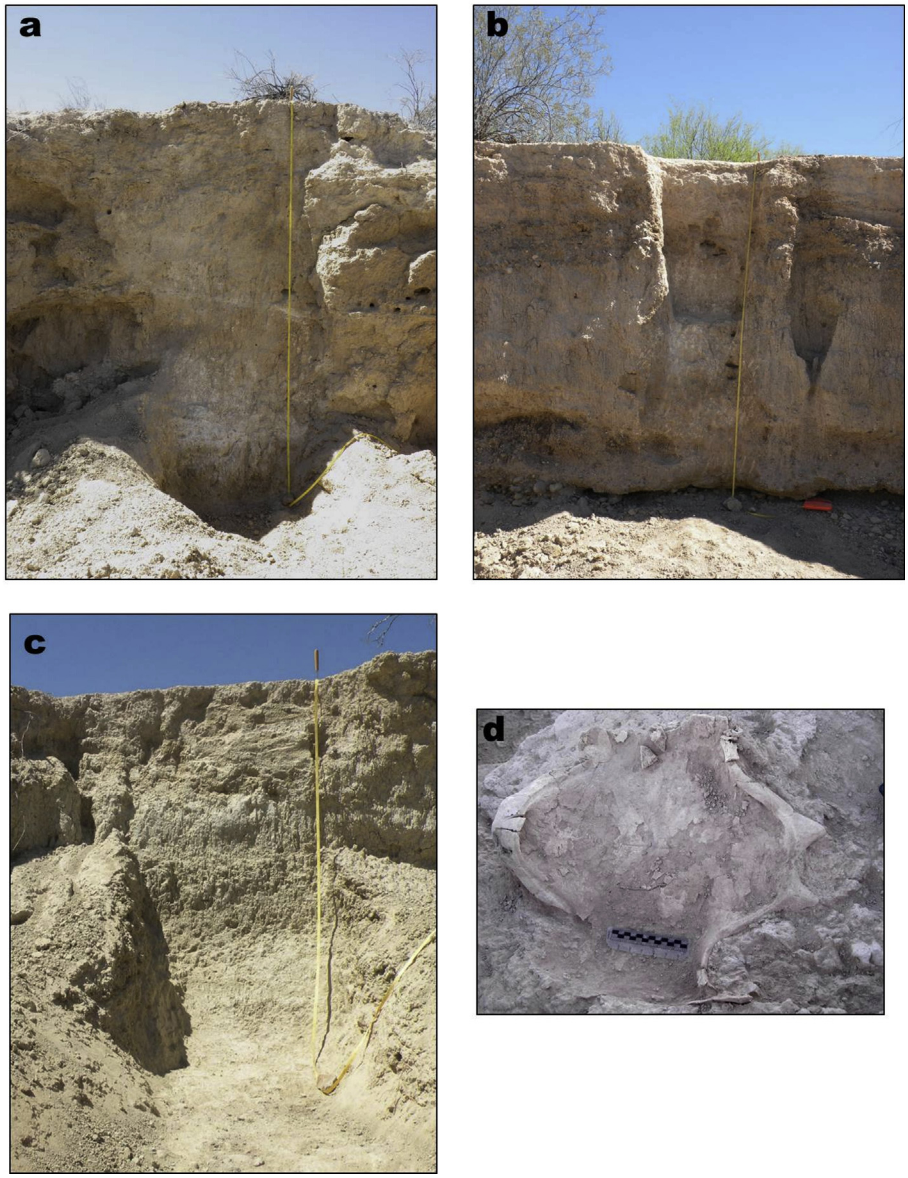

Fig. 6. Gray soils in the "Rancho El Arenoso" locality. a) Cantera profile, b) Arenoso profile, c) Poceaderos profile, and d) fossil tortoise excavated in La Cantera, associated with $2Bgk_2$ horizon. Photos a–c y Tamara Cruz, photo d by Alejandro Terrazas.

grassland and xeric shrubland, based on the ecological requirements of the fauna.

4.3. Archaeological and paleontological contexts and the Late Pleistocene/Holocene red paleosols

Archaeological investigations carried out during the last 15 years indicate that some of the first peoples that came to American continent during the Late Pleistocene (13,500 cal BP) discovered in Sonora the perfect place for hunting Pleistocene fauna and gathering plants. These first social groups that made Sonora their home are known as Clovis groups. About 10,000 years ago, human groups in the Sonoran Desert adopted an archaic way of life based on the edible desert plants, succulents and cactus, and hunting middle size animals (deer and peccary). Archaeological sites of Late Pleistocene/Holocene times are numerous in Northern Sonora, and apparently archaeological contexts and artifacts in many sites are directly related to the Pleistocene paleosols that comprise the living surface of the Clovis peoples and later archaic forager groups. Clovis is classically associated with Late Pleistocene megafauna, although only ~14 sites with Clovis/mammoth associations are known, and other megafauna (mastodon, horse, bison) associations with Clovis are rare (Grayson and Meltzer, 2002). Fin del Mundo is the only human/gomphothere association in North America and the only one in Sonora (Sanchez, 2010).

At Fin del Mundo, excavations yielded the remains of two juvenile Gomphotheres (Cuvieronius) with Clovis artifacts (Locus 1). Evidence for prolonged or repeated use of the area is indicated by the extensive camp, found 500–1000 m around Locus 1 on the stable uplands to the southeast, south, and southwest, where 10 Clovis points (two heavily reworked; the rest point bases), 25 point preforms, 38 end scrapers, 39 large blades, and 7 blade cores and core tablets were recovered from an extensive surface lithic scatter. The majority of the artifacts outside of the kill site were found on the surface of a red paleosol (Fig. 9a) dated to 11,550 ± 70 ^{14}C BP

(~13,390 cal BP) (Sanchez, 2010). Paleontological findings at Fin del Mundo include Gomphotheres *(Cuvieronius*), Mastodont, Equus, Bison, Gopherus, and Tapir (Sanchez, 2010; Sanchez et al., 2013, 2014) (Table 3).

The El Bajio site extends over 4 km^2, with a low-to-moderate distribution of artifacts observed throughout, and with 22 distinct loci defined. These loci are found distributed along the pediment, in the low-lying terrain of the Bajio, and upon the hilltops. The most

Table 3
Summary of sites with red and gray Pleistocene paleosols. Archaeological and paleontological information is included.

Site	Profile	Coordinates N	Coordinates W	Altitude	Horizon	Pleistocene fauna	Cultural artifacts (surface and buried)
La Playa	Hornos 1	30° 29′58″	111° 31′44.6″	510 m	C/2Bw/2BCk/3Bgk/ 3BCgk/3Ck	*Equus*, *Camelops*, *Mammuthus*, *Bison Antiquus*, *Sigmodon*, cervids and *Antilocapra*, and tortoises (*Gopherus* or *Hesperatudae*), (Sanchez, 2010).	Clovis, Early Archaic, Middle Archaic, Early Agricultural Period, Trincheras (Carpenter et al., 2005).
Magdalena de Kino	Kino	30° 42′23.75″	111° 07′52.42″	748 m	AB/2Bw/2BC/2BCk/3Ck/ 4C	Not reported	Not reported
Los Alamitos	Alamitos	30° 23′38.5″	111° 05′39.3″	721 m	A/AB/Bw/BCk/Ck 2Bg/ 2C/3Bg/3C	Not reported	Not reported
Huebampo	Don 2	26°42′02.4″	109°15′48.9″	54 m	Bgk/Ck/2Btgk/2BCk	Tortoise	Not reported
	Don 3	26°42′01.1″	109°15′47″	54 m	3Ck/Bk/Ck/2C		
El Bajío		29°56′50.48″	110°46′31.16″	722 m	Bw or Bt/Bk	Proboscidean, mastodon (Sanchez, 2010).	Paleoindian (Clovis, in archaeological context with red soil), (Sanchez, 2010).
Fin del Mundo		29°45′29.39″	111°40′46.82″O	633 m	Bw or Bt/Bk	Gomphotherium, mammoth, American mastodon, tapir and tortoise, (Sanchez, 2010).	Paleo-Indian (Clovis, in archaeological context), (Sanchez, 2010).
El Gramal		28°30′22.65″	111°18′20.53″	28 m	Bw or Bt/Bk		Clovis (Sanchez, 2010).
El Aigame		28°45′18.07″	110°27′22.53″	420 m	Bw or Bt/Bk	*Mammuthus* sp, *Equus*, and *Hesperotestudo* (Sanchez, 2010; White et al., 2010).	Clovis, (Sanchez, 2010).
El Arenoso	La Cantera	31° 02′26.23″	112° 03′15.22″	548 m	C/2Bgk$_1$/2Bgk$_2$/3C/4Bk/ 4Ck/5Bgk/5BCk/5Ck/ 6Bk/7Bg	Tortoise *Equus excelsus*, *E. Conversidens*	*Trincheras phase (1650 −1150 BP)*. San Pedro phase (ca. 2000 BP). *Jay* points (7000 BP). *Plainview-Meserve-Milnesand (10,000 − 8000 BP)*.
	Los Poceaderos	31° 03′43.9″	112° 01′37.8″	555 m	C/2Bg/3Bg/3BC/4Bt/5C/ 6C	*Equus* sp. *Mammuthus* sp.	*Trincheras phase (1650 −1150 BP)*. San Pedro phase (ca. 2000 BP). *Jay* points (7000 BP).
	El Arenoso	31° 02′16.2″	112° 03′5.4″	551 m	C/2Ck/3Ck/4C/5C/6Bgk/ 7Bk/7BC/8C/9Ck	*Equus* sp. *Mammuthus* sp.	Not reported

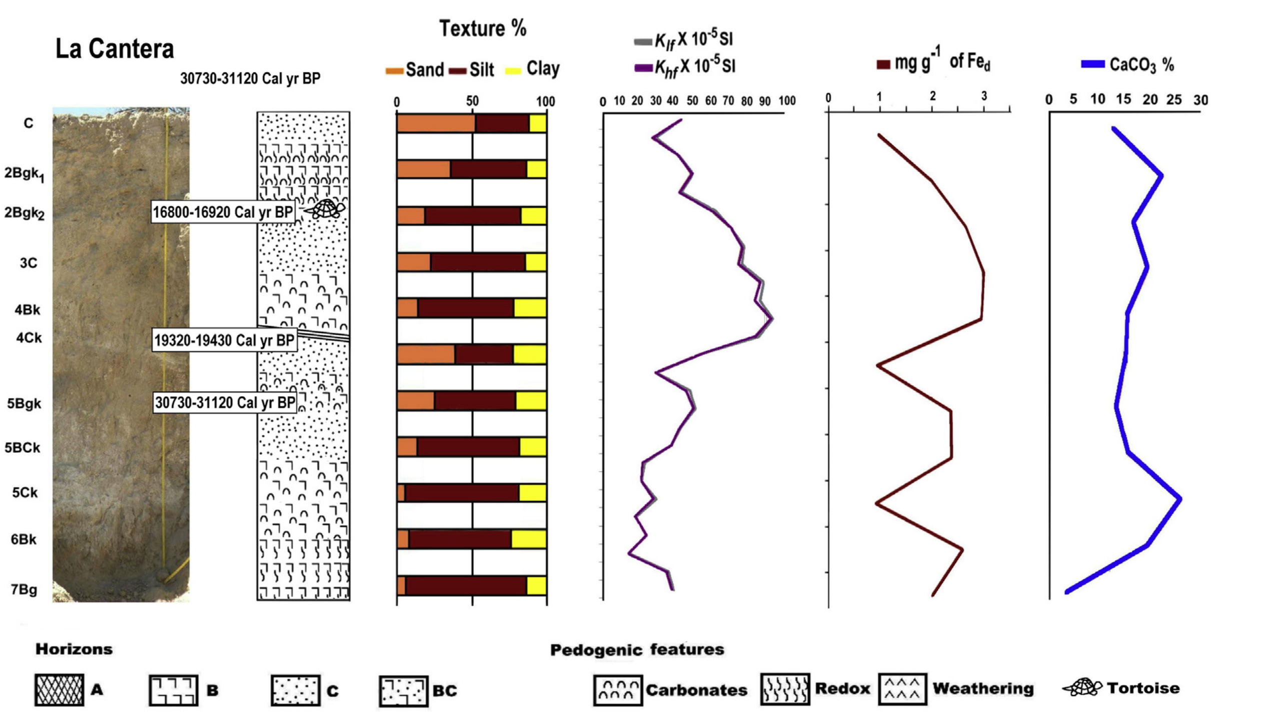

Fig. 7. Analytic results of the La Cantera profile, at the archaeological site of El Arenoso.

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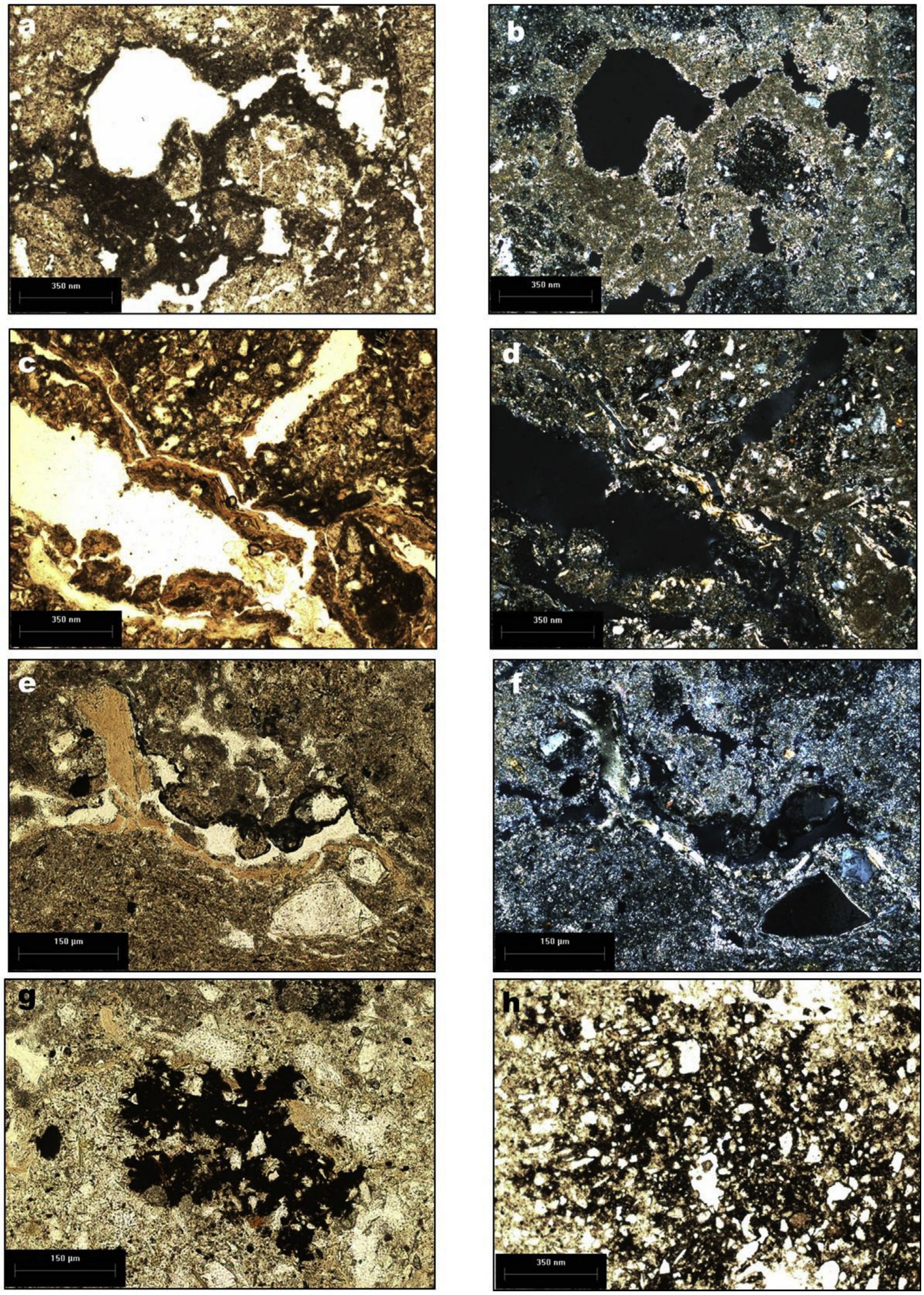

Fig. 8. Micromorphological features of gray paleosols. a and b) pedogenic carbonates in pores in $2Bgk_1$; c and d) clay coatings with interference colors, associated with Mn concretions in $2Bgk_1$; e and f) clay coatings "trapped" in a carbonate rich groundmass; g and h) dendritic Mn nodules in the soil groundmass; a, c, e, g and h plain polarized light; b, d, and f under crossed polarizers. Micrographs by Sergey Sedov. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

important locus, probably responsible for attracting human groups to visit this area originally, is the raw material source of vitrified basalt on Cerro de La Vuelta in the southwestern portion of the site. A total of 333 artifacts affiliated with Clovis people have been collected from the loci. Red paleosols (Fig. 9b) are exposed at the surface all around the site, and Clovis artifacts are eroding out from them (Sanchez, 2010). Future investigations of the red paleosol at El Bajio are needed in order to learn more about the Clovis/Paleosol relationship.

Archaeological site SON O:3:1 (El Áigame) encompasses an area 2.5 km N/S by 1.5 km E/W. We identified at least 28 different loci, demonstrating this to be a very complex site that was occupied for a long period of time. Ten loci had a Paleo-Indian affiliation only, six yielded both Paleo-Indian and Archaic artifacts, nine produced only archaic diagnostics, three seemed affiliated to the Early Agriculture period, and one contained ceramic artifacts. The presence of four Clovis points, bifaces, 30 end scrapers, blades, together with bifacial thinning flakes of fine materials at Loci 1 and 3 appear to represent one or more Clovis encampments. At least in these two localities the artifacts are eroding out from a red paleosol that covers an extensive area of the site (Sanchez, 2010). One radiocarbon date from charcoal collected at horizon A of the top of the red paleosol (Fig. 9c) is 4009 ± 42 BP (AA66509) (4406–4585 cal BP) and it is similar to the dates obtained at La Playa site (Sanchez et al., 2013). At Rancho El Aigame, *Mammuthus* sp, *Equus*, and *Hesperotestudo* have been reported (Sanchez, 2010; White et al., 2010).

5. Discussion

The soil cover of Late Pleistocene/Holocene time in Sonora shows two pedogenetic trends that conformed red soils and gray soils. The red paleosols are widely distributed in Sonora, mainly in the northern portion of the state, as shown by the profiles described at La Playa, Kino, Alamitos, El Bajio, and Fin del Mundo, among others. It is also possible to find them in the center of the state (El Aigame, El Gramal) and even in the south (Huebampo). These soils correspond to the Late Pleistocene/Holocene transition, from 20,000 years to 5000 years ago (Table 2).

Radiocarbon dates have been obtained in several profiles. At the Alamitos profile, we were unable to find datable materials, but it is possible to correlate it with the other sites because they share the same morphological features and pedogenic processes. The Alamitos paleosols show well developed soils formed under stable environmental conditions, alternating with periods of instability. The oldest paleosol shows a well-structured 3Bgk horizon with redoximorphic features, indicative of humid conditions during soil formation, followed by a dry period that allowed the accumulation of carbonates. Soil development was interrupted by a period of instability that removed the organic horizon and deposited sediments; the second paleosol showing similar features, indicative of humidity for their formation. This pedogenesis was interrupted by a new period of instability followed by a new pedogenesis which formed the uppermost paleosol. This paleosol is well developed, well structured, with clay accumulation, but not redoximorphic features, indicative of pedogenesis under a humid environment with oxidizing conditions. Clay formation periods, intercalated with periods of carbonate formation, indicate alternating environmental conditions, similar to those observed in other studied paleosols.

The characteristics of the Pleistocene red paleosols are represented in the San Rafael paleosol (SRP), a Chromic Cambisol (WRB, 2006). We observed two phases of pedogenesis. The grayish phase with 3BCg and 3Bgk horizons developed under conditions of water saturation for long period of time that caused reducing conditions and removed the iron and formed gley features. These types of paleosols developed in sandy arroyo sediments interbedded with gravels, probably an old stream bed. The gleying process was the result of hydromorphic processes related to fluctuations in the stream. The overlying 2BCk, 2Bw and 2A horizons indicate a pedogenesis period under oxidizing conditions that favored the

Fig. 9. Red paleosol in archaeological context; the morphological features observed are similar to SRP. a) Fin del Mundo, carbonate concretions are observed in the red soil. b) El Bajío, artifacts associated with the red soil that is exposed in superficie. c) El Áigame. We observed a humic horizon on red soil with gradual contact, so it may be the same soil. The charcoal dating on the bottom of the humic horizon (4406–4585 cal BP) is very similar to pedogenesis period of SRP. Photos by Guadalupe Sánchez.

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weathering of primary minerals and formation of secondary minerals, including iron oxides that provided red colors, clays and humus formation. Another important process in SRP is the accumulation of carbonate concretions in the pores, which typically happens in semiarid environments where evaporation is greater than precipitation. In this process, leachate carbonates migrate by gravity to the deepest units and precipitate and accumulate as coatings and concretions. The formation of SRP probably indicates a prolonged environmental stability period, which began during Late Pleistocene time and ended during Middle Holocene (14,910 to 4250 cal BP). The soil signal appear to indicate that a humid environment was present and persuade chemical weathering, but with a sufficient rate of evaporation that allow the accumulation of carbonates in the underlying horizons.

Field observations of soils morphological features suggested the existence of illuviation processes in some horizon that were identified as Bt horizons. Further micromorphology laboratory analysis of the clay illuviation revealed that none of the clay coatings fill the pores or wrap ped surfaces: instead moderate weathering of primary minerals and in situ clay formation were observed. Based on these observations, we assume that the units are cambic horizons (Bw). Although only a few red paleosols found at the archaeological sites have been analyzed at the laboratory, it is very probable that the "Big Red" identified as Bt/Bk horizons, could be Bw horizons. Further laboratory analysis of these units will be necessary for their accurate identification.

The properties of the gray paleosols at El Arenoso and La Cantera are similar, both showing moderate development. The principal processes observed are weathering of primary minerals, formation of secondary minerals, and redox processes and carbonate precipitation, the latter more developed. The gleying process indicates that the soil was saturated with water for long periods of time, producing acidification and anoxia, together with reduction and dissolution of iron, and providing the grayish colors. There is no evidence of clay illuviation at this soil, but carbonates leached to the underlying horizons are very common. Carbonate formation indicates periods of low humidity that permit the accumulation of carbonates alternating with wet periods. The interstratification of paleosols and sediments also indicate the alternation between periods of environmental stability for the formation of well-developed B horizons (over 15 cm), with periods of instability and erosion that removed the surface horizons (A horizons) and favored the accumulation of sediments in the lower parts, buried the paleosols and created a new surface on which a new soil was developed. This dynamic alternation of the environmental conditions, prevailed for long periods, as shown by similar soils formed during different periods, ranging from 31,120 cal BP (in pedogenic carbonates of 4Bgk) to 16,800 cal BP (in pedogenic carbonates of $2Bgk_2$).

The pedogenetic processes appear to indicate that the environment was different to that of today. The pedogenic clays and values of $\delta^{13}C$ were very similar in all the profile (Table 2) indicating a stable vegetation cover with few variations, which probably consisted of mixed vegetation between C3 and C4 grassland and xeric shrubs type plants, probably a semiarid environment but more humid that today with a marked seasonality. Possibly, cooler summers than today resulted from less insolation. Differences in the paleosols morphology are not products of significant differences in regional bioclimatic characteristics They are caused by local geomorphological variations: red paleosols developed on alluvial fans with a slight slope with better drainage, whereas paleosols of El Arenoso were formed in the lower part of a semi-enclosed basin bounded by the surrounding hills, where temporary water flows join together. To our knowledge, the formation of soils with these features is restricted to this basin.

The paleopedogenetic proxy data appear to correlate with the few available paleontological data for La Playa and El Arenoso sites. Mead et al. (2010) reported the presence of *Cynomis ludiviciaanus* at La Playa collected at the red paleosol, the first found at Sonora, because in general they are found at higher elevations associated with grassland/woodland vegetation. According to the macrobotanical record of the large and diverse sequences of neotoma fossil middens analyzed by Van Devender (2007), milder winter temperatures coupled with cooler summers created a more steady climate for the region, and Pleistocene elephants as well as prairie dog grazed at the bottom of the valley at the alluvial fan at La Playa.

The paleoenvironmental records in the SW U.S.A. indicate that the climates at the LGM were much wetter than today (Van Devender, 1973, 1990, Van Devender et al., 1994; Hall et al., 1988; Anderson and Van Devender, 1995; McAuliffe and VanDevender, 1998; Metcalfe et al., 2002, Metcalfe, 2006; Holmgren et al., 2007). Values of $\delta^{18}O$ in New Mexico indicate that during the Bølling-Allerød (BA) the climate was warm and dry. The Younger Dryas (YD) had a cold and wet environment with increased winter moisture, and towards the end of the YD environmental conditions become dry, coinciding with the increase in summer insolation (Ballenger et al., 2011). In Nebraska, YD moisture is registered in the Brady Soil developed in this period (Jacobs and Mason, 2007). In the Chihuahua uplands (Nordt, 2003), Babícora, Chihuahua (Ortega-Ramírez et al., 1998; Metcalfe et al., 2002) and in central and northern Baja California, the Pleistocene–Holocene transition and the Early Holocene were more humid than today (Anderson and Van Devender, 1995; Metcalfe et al., 2002; Metcalfe, 2006; Ortega-Rosas et al., 2008).

A clear marker of increased moisture during the YD are black organic layers formed under conditions of high humidity, such as marshes, swamps, and even histosols or mollic horizons, that developed in several points of the SW of U.S.A. during this period, to which Clovis evidence and remains of Pleistocene megafauna are associated, known generically as "black mats" (Haynes, 2008; Ballenger et al., 2011). In northern Mexico, and especially in our study area, we have not found strata and/or horizons rich in organic matter correlated with YD. The 2A horizon of the SRP, whose development covers that period, shows low humidity. It is likely part of the development of horizons 2Bw and leaching of carbonates forming Bk, CBk and Bgk horizons, relates to the cooler and moister environment of YD, which could be due to the more intensive carbonate illuviation observed during this period. The generalized climatic tend in Mexico appears to be increasing humidity in the Late Pleistocene (MIS3), with a tendency to aridity in MIS2, as suggested by humic horizons of alluvial sequences in Huexoyucan, Tlaxcala, and Santa Cruz Nuevo and Axamilpa, Puebla (Tovar et al., 2013.), contrary to global trends of aridity recorded in loess-paleosol sequences (Bronger et al., 1998; Dodonov et al., 2006).

6. Conclusions

The paleoenvironmental studies in the region indicate that wetter conditions during the Late Pleistocene, with a clear trend to aridification during the Holocene, were not general to Western North America. During the LGM, the migration of the Polar Front south allowed the Westerlies to establish a regime with mainly rain showers in winter (Metcalfe, 2006; Arroyo-Cabrales, 2008). During retreating glaciation, about 18,000 years ago, the climate in the region began to be arid while the influence of the increased North American Monsoon, although this did not occur uniformly. Barron et al. (2012) suggest that during the Early Holocene, before 8000 cal BP, the high pressure cells allowed North Pacific moisture flow promoted by the monsoon take a more direct path to the northwest (west of 114° W) causing increased precipitation in the southwestern United States. However, to the east of 114° W, including Sonora (111° W), increased summer precipitation associated with the North American Monsoon effect happened after 7500 cal BP. This could account for the discrepancy between the records of the SW United States and NW Mexico.

In the Sonoran Desert region, the paleo–indicators show that from the Late Pleistocene (about 20,000 cal BP) and up to the middle Holocene (4000 cal BP) a long period of stability in the landscape prevailed, that allowed the formation of well–developed soils under a predominantly semiarid climate with marked seasonal changes. The pedogenic processes occurring in the Pleistocene and Holocene paleosols are practically the same, but different intensity. The pedogenic development that began in the Pleistocene apparently lasted for 10,000 years, in contrast to the soils formed during the Holocene with shorter developmental process. These features indicate a somewhat more humid environment during the Late Pleistocene than today. However, the Sonoran Desert was not as wet as has been registered in Baja California and other surrounding regions. SRP did not record in its memory the climatic oscillations of the Bølling-Allerød/Younger Dryas. The only drastic climate change that left a signature in the soils occurred during Middle Holocene times and probably is equivalent to the Altithermal period defined by Antevs (1948, 1955) as a climate oscillation that lasted for several millennia characterized by very warm weather and very little precipitation that occurred between 7000 and 4500 BP.

The soil cover of the Late Pleistocene/Early and Middle Holocene is represented by the Red Unit (Cambisols) and the Gray Unit (Gleysols). The Red Unit is the most predominant form in Northwest Mexico, especially Sonora. The red paleosol could be used as a chronologic marker for finding Late Pleistocene paleontological specimens that are common in these soils; archaeological remains of the first people that came to the American Continent (especially Clovis) are also correlated to these soils. Geoarchaeological investigations that combine paleopedology, paleoenvironmental reconstructions, and paleontology will contribute greatly to learning about the colonization of the American continent and human adaptations to the changing landscapes of Late Pleistocene/Holocene times.

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