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Pleistocene paleosols associated with megafauna in Northwestern Mexico: Paleoecological inferences

Paleosuelos pleistocénicos asociados a megafauna en el noroeste de México: inferencias paleoecológicas
Paleossolos plistocénicos associados a megafauna no noroeste do México: inferências paleoecológicas

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ABSTRACT

The pedological cover of the state of Sonora, in northern Mexico, is predominantly composed of moderately developed red soils that evidence processes of weathering, humification, rubification, neoformation of clay, and carbonation, classified as Cambisols according to the WRB. These soils constitute a pedological unit denominated the San Rafael Paleosol (SRP). In contrast, gray soils are recorded in some sites located in semi-closed basins and are characterized by processes of weathering, neoformation of clay, reductomorphism and carbonation. These soils developed during the late Pleistocene under a semi-arid and cold climate, slightly more humid than the present one, with winter dominant rains, and marked seasonal changes. These paleosols are associated with remnants of Pleistocene Rancholabrean fauna of diverse composition, associated with arid and humid climates, demonstrating local climatic variations much more complex than at present. This paper evaluates the physical, chemical and micromorphological attributes of paleosols located in the San Francisco and El Arenoso ranches in the north of Sonora. The analyses are undertaken in order to identify the main pedogenetic processes and to establish the predominant environmental conditions during their formation, specifically the particular characteristics associated with semi-enclosed basins that allowed the accumulation of water and the formation of ponds. At both sites remains of Pleistocene megafauna have been found associated with paleosols. These results are contrasted with previous paleopedological studies and the paleontological record, permitting a broader discussion of regional paleoclimatic trends.

RESUMEN

La cubierta edáfica del estado de Sonora, en el norte de México, está formada predominantemente por suelos rojos de desarrollo moderado, con procesos de intemperismo, humificación, rubificación, neoformación de arcillas y carbonatación, clasificados como Cambisoles según la WRB, que constituyen una unidad edáfica denominada Paleosuelo San Rafael (SRP). Sin embargo, en algunos sitios se han registrado suelos grises formados en cuencas semicerradas, con procesos de intemperismo, neoformación de arcillas, reductomorfía y carbonatación. Estos suelos se desarrollaron durante el Pleistoceno Superior bajo un clima semiárido y frío, un poco más húmedo que el actual, favorecido por las lluvias invernales y cambios estacionales marcados. Estos paleosuelos se encuentran asociados a restos de fauna pleistocénica rancholabreana de composición diversa, asociada a climas tanto áridos como húmedos, lo que muestra variaciones climáticas locales mucho más complejas que en la actualidad. Con la intención de establecer las características particulares de los paleosuelos formados en cuencas semicerradas que pudieron permitir la acumulación de agua y la formación de estanques, se evaluaron las características físicas, químicas y micromorfológicas de los

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paleosuelos localizados en los ranchos San Francisco y El Arenoso, en el norte de Sonora, en los cuales también se han hallado restos de megafauna pleistocénica. Los análisis permitieron evaluar las características de los paleosuelos, identificar los procesos pedogenéticos principales y establecer las condiciones ambientales predominantes durante su formación. Estos resultados se contrastaron con los estudios paleopedológicos previos y los antecedentes paleontológicos, lo que permitió enmarcarlos dentro de las tendencias paleoclimáticas regionales.

RESUMO

A cobertura edáfica do estado de Sonora, no norte do México, é predominantemente composta por solos vermelhos de desenvolvimento moderado que evidenciam processos de meteorização, humificação, rubefação, neoformação de argila e carbonatação. Estes solos, classificados como Cambissolos de acordo com a WRB, constituem uma unidade pedológica denominada Paleossolo San Rafael (SRP). Em bacias semifechadas, foram identificados solos cinzentos caracterizados por processos de meteorização, neoformação de argila, hidromorfismo com carácter redutor e carbonatação. Estes solos desenvolveram-se durante o Plistocénico Superior sob clima semiárido e frio, um pouco mais húmido do que o atual, com chuvas dominantes de inverno e marcadas alterações sazonais. Estes Paleossolos estão associados a restos de fauna plistocénica rancholabreana de composição diversa associada a climas tanto áridos como húmidos, demonstrando variações climáticas locais muito mais complexas do que as atuais. Neste trabalho, avaliaram-se as características físicas, químicas e micromorfológicas dos Paleossolos localizados nos ranchos de São Francisco e El Arenoso, no norte de Sonora, com o objetivo de identificar os principais processos pedogenéticos e estabelecer as condições ambientais predominantes durante a sua formação, em particular as características associadas a bacias semifechadas que permitiram a acumulação de água e a formação de lagoas. Nos dois locais, foram encontrados restos de megafauna do Plistocénico associados aos Paleossolos. Os resultados obtidos contrastam com os estudos paleopedológicos anteriores bem como com o registo paleontológico, permitindo uma discussão mais ampla das tendências paleoclimáticas regionais.

KEY WORDS
Paleoenvironment, paleopedology, micromorphology, Sonora.

PALABRAS CLAVE
Paleoambiente, paleopedología, micromorfología, Sonora.

PALAVRAS-CHAVE
Paleoambiente, paleopedologia, micromorfologia, Sonora.

1. Introduction

Previous studies have shown the Late Pleistocene (late MIS2) paleoenvironmental conditions of northern Sonora, Mexico were semi-dry with cold climate that showed marked seasonal changes, from at least 15 ka. However, in some places such as El Arenoso and Fin del Mundo, pedosedimentary sequences have been found with evidence of reductomorphic processes (gleyzation) that indicate more humid conditions. These conditions arise mainly from local geomorphological characteristics (Sánchez et al. 2014; Cruz-y-Cruz et al. 2014, 2015), owing to location in the lower parts of semi-closed basins. This setting allowed moisture retention and, most likely, the formation of permanent and/or ephemeral water bodies. Sonora also is rich in paleontological remains of Pleistocene Rancholabreana fauna. This record evidences a very diverse composition with a mosaic of species, ranging from those typically associated with tropical moist climates, such as tapirs (*Tapirus* sp.) and mastodons (*Mammut americanum*), to those of desert climates, such as prairie dogs (*Cynomys ludovicianus*) and desert tortoises (*Gopherus* sp. and/or *Hesperotestudo* sp.) (White et al. 2010).

In short, multiple lines of data indicate regional climatic conditions were much more complex and variable than present conditions. To increase the knowledge of the habitats of the different Pleistocene fauna species and to understand this variability in the paleontological record, it is necessary to establish local environmental characteristics. Several studies have shown that paleosols are reliable indicators of environmental conditions. Based on the evaluation of the morphological, physical and chemical characteristics that constitute *soil memory*, it is possible to make inferences about the predominant environmental conditions during their formation (Targulian and Sokolova 1996; Foth 1997; Bronger et al. 1998; Targulian and Goryachkin 2004).

This paper presents the pedo-sedimentary sequences of two sites located in semi-enclosed basins with the objective of increasing the knowledge of paleopedological characteristics and climatic variations during the Late Pleistocene (MIS 3 and MIS 2). The first site is at Rancho San Francisco, located at the bottom of the Sierra La Jojoba, in the Sierra Madre Occidental province. The second site is Rancho El Arenoso, located at the foot of the Sierra de San Manuel, in the Sonoran Plain province. Both sites contain remains of Pleistocene fauna and show evidence of high humidity conditions in which water bodies (ponds) may have formed.

2. Materials and methods

2.1. Study area

The study area is located in northwest Sonora (**Figure 1**), in the Sonoran Desert biome, with a predominant climate BS_0h '(h)x' (dry semi-warm) (Vidal Zepeda 2005), and the average annual

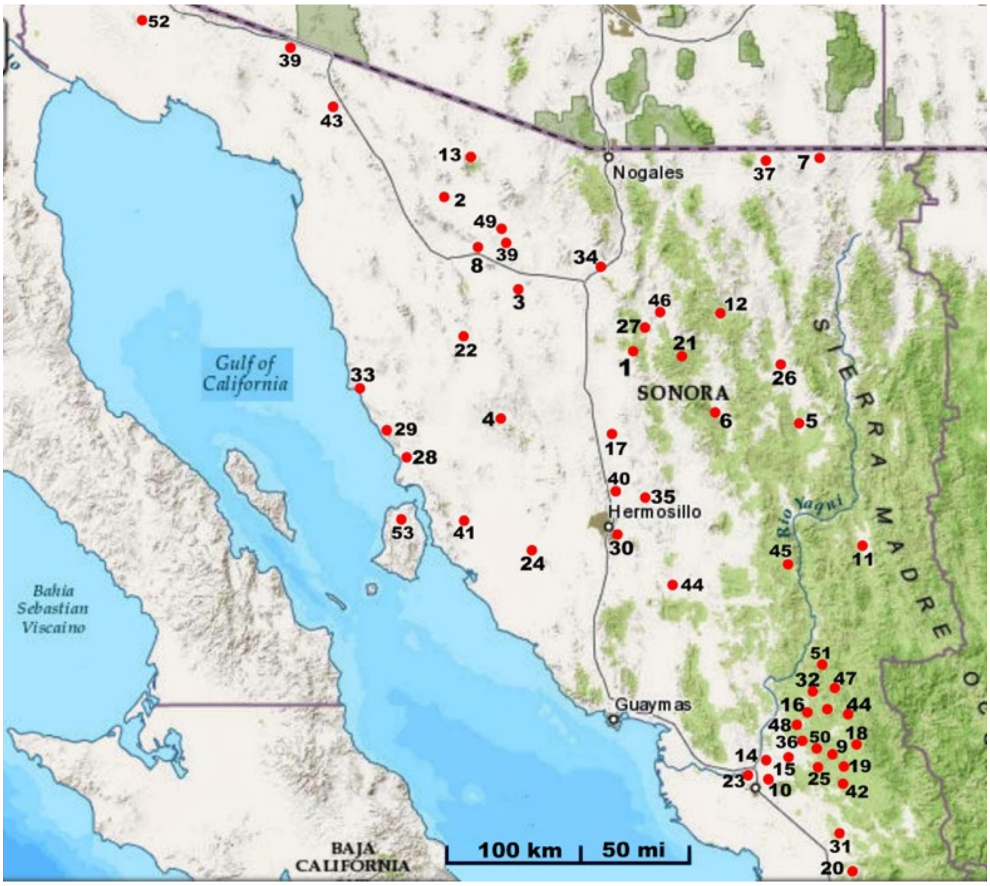

Figure 1. Study Area. The sites studied are: 1. Rancho San Francisco and 2. Rancho El Arenoso. Also, the approximate location of the sites with evidence of Racholabrean fauna is shown: 3. La Playa; 4. Fin del Mundo; 5. Térapa; 6. Aconchi; 7. Agua Prieta; 8. Altar; 9. La Angostura; 10. Las Areniscas; 11 Arivechi; 12. Arizpe; 13. Arroyo de Humo; 14. Bachoco; 15. Bajimari; 16. La Botana; 17. Carbó; 18. El Carrizal; 19. Cedros; 20. Chinobampo; 21. Ciénega del Cabo; 22. La Ciénega; 23. Cócorit; 24. Costa de Hermosillo; 25. Los Coyotes; 26. Cumpas; 27. Cucurpe; 28. Desemoboque de los Seris; 29. Desemboque del Río San Ignacio; 30. Hermosillo; 31. Jusibampo; 32. Llano Prieto; 33. La Libertad; 34. Magdalena; 35. La Mata de Carrizo; 36. Mutica; 37. Naco; 38. O´Neil Pass; 39. Oquitoa; 40. Pesqueira; 41. Playa San Bartolo; 42. Quiriego; 43. Quitovac; 44. Rancho Áigame; 45. Rancho Estribo; 46. Rancho La Brisca; 47. Rancho de Enmedio; 48. El Sahuaro; 49. Sangre Vieja; 50. Santa Ana; 51. Santa Rosa; 52. Sierra El Rosario and 53. Tecomate. Image from Digital Map of Mexico, INEGI, modified from White et al. 2010.

temperature ranges from 18-22 °C. The annual precipitation averages between 200-400 mm (Vidal Zepeda 2005). The principal vegetation is desert scrub (Pérez 1985).

From this extensive area, we present the results of the study of the paleosols of the paleontological sites Rancho San Francisco and El Arenoso (**Figure 1**). Both sites are located in the valleys of semi-closed basin, currently with seasonal water flows, with a semiarid climate (**Figure 2**). However, the pedosedimentary deposits associated with the remains of Pleistocene fauna show higher humidity conditions, which differentiate them from the red paleosols studied in other localities (Cruz-y-Cruz et al. 2015).

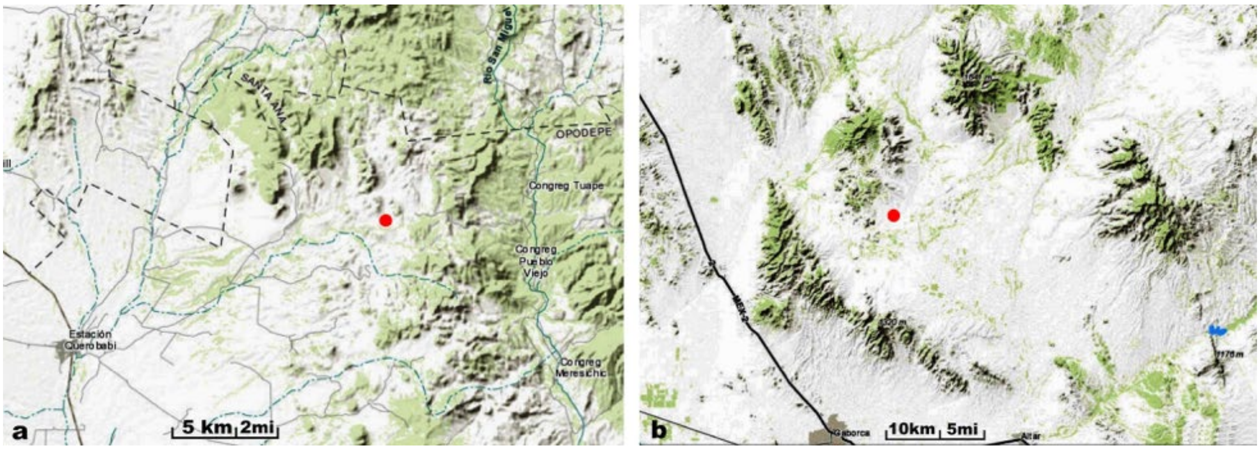

Figure 2. a) Rancho San Francisco and b) Rancho El Arenoso. Geomorphological characteristics of the sites are observed. The red points mark the location of the profiles. Modified images of the Digital Map of Mexico, INEGI.

The first paleosols profiles described, at Rancho San Francisco, Opodepe, Sonora, are associated with the remains of Pleistocene fauna. The site is located in a semi-closed basin bordered by low hills (**Figure 2a**). The paleosols are located in a flood plain formed to the southwest of the Sierra La Jojoba, with a gentle slope from NE to SW. The main alluvial contributions come from the Sierra La Jojoba. The San Francisco 3 profile has a sequence of AB/C/2B/2C/3B1/3B2/3C/4BC, and the Mamut de San Francisco profile, a sequence of C/2C/3C.

The San Francisco 3 (SF3) profile (**Figure 3**) is located at 30°07'54"N and 110°47'49"W, at 909 masl. A cut in the ground was described, to a depth of 3.3 m. The profile shows a pedosedimentary sequence composed of a modern low surface soil with AB/C horizons with thick texture and an abundance of gravels of different sizes. The C matrix is clayey and structured, with 40% gravel; this soil is carbonated. Underlying this C horizon is a more developed paleosol, with 2Bw/2C horizons that are not carbonated and have redoximorphic features (Mn concretions) with silty-loamy texture. Below is another paleosol with 3B/4B 4C horizons that have a better development and structure, clayey composition, without carbonates in the matrix. It is followed by a paleosol with a 5BC horizon of thicker composition, abundant gravel and a structured matrix of clay. At the base is a thick layer (6C) of colluvial-alluvial sediments containing bone fragments of Pleistocene fauna that are highly fragmented.

The Mamut de San Francisco (MSF) profile (**Figure 4**) is located at 30°07'49.73"N and 110°47'51.56"W, at 883 masl. This profile was described at the site of a mammoth fossil (site SON: G: 13: 1 from INAH), on the southern wall of the excavation unit (the mammoth has not yet been fully excavated), at a depth of 60 cm. The profile shows a colluvial-alluvial sedimentary sequence composed of three strata that overlie the remains of the mammoth. The sequence is C/2C/3C horizons. The C horizon has a reddish-brown color, a coarse texture with high gravels and small aggregates and evidences redoximorphic processes (yellow and dark speckles) with white spots on the aggregates. Horizon 2C has a coarse texture with a composition of 40% gravels, mainly large and angular and fewer semi-rounded, and a brown matrix with redoximorphic features (Fe and Mn stains and nodules). Horizon 2C and 3C contain a bone fragment. Horizon 3C is much thicker sediment, is brown in color, contains gravels up to 10 cm in diameter, and presents discontinuous carbonates and reductomorphic processes (brown and yellow speckles). This layer contained the bone remains of a mammoth with evidence of drag, although the bones are still in anatomical position.

Figure 3. San Francisco 3 profile. Photo by S. Sedov.

Figure 4. Mamut de San Francisco profile. Mammoth bones are seen at the bottom. Photo by T. Cruz.

The Rancho El Arenoso locality is located to the N of Caborca, in the Municipality of Altar. This locality includes the La Cantera profile, which is located in the alluvial plain delimited to the NW by Sierra San Manuel and to NE by the Sierra del Humo (**Figure 2b**). Alluvial deposits of the Quaternary that were affected by subsequent streams dominate this setting. The general slope of the plain runs from NE to SW, parallel to the El Arenoso stream that flows from the NE where the Sierra del Humo is located. The La Cantera profile is associated with the El Segundo stream with its flow from the Sierra San Manuel.

The La Cantera profile (**Figure 5**) is located at 31o 02´26.23”N and 112o 03´15.22”W, at 548 masl and consists of a trench to a depth of 2.55 m. The surface layer is silty sediment. The profile presents a sequence of five paleosols of inter-layered sediments with lost A horizons. The first paleosol is moderately developed with 2Bgk1/2Bgk2 horizons. The second paleosol, which underlies the former and a layer of sediment (3C), is also moderately developed with a well-structured 4Bk horizon and accumulations of carbonates. Below this horizon underlies a 5Ck of laminated caliche. The third paleosol is formed by 6Bg/6BCk horizons and presents reductomorphic and carbonation properties. Below, this there is a 7Ck horizon. The fourth paleosol is an 8Bk horizon that presents moderate carbonate. The last paleosol, 9Bg, consists of a horizon with much more developed redoximorphic features.

In this profile, a turtle fossil was found (possibly *Gopherus* sp.) in the 2Bgk2 horizon, as well as horse remains (possibly *Equus excelsus*) at the bottom. Bison (*Bison bison*), horse (*Equus conversidens*) and mammoth (possibly *Mammuthus columbi*) have also been identified on the site (Terrazas and Benavente 2013).

2.2. Palaeontological evidence from Northern Sonora

Sites of Pleistocene fauna of the Rancholabrean period (between 160 ka BP and 9.5 ka BP) are abundant in Sonora. The termination of this period coincided with the global extinction of a significant number of megafauna species (Savage 1951; Roy 2003; Benton 2005; Montellano-Ballesteros and Jiménez-Hidalgo 2006; Bell et al. 2004; Arroyo-Cabrales et al. 2008; Benton and Harper 2009; Ferrusquía-Villafranca et al. 2010; Ceballos et al. 2010). The list of paleontological sites with rancholabreana fauna in Sonora is summarized in the **Table 1**. Locations are listed in accordance with **Figure 1**.

Figure 5. La Cantera profile. Photo by T. Cruz.

2.3. Laboratory analysis

The principal objective of the analytical process was to study the properties related to *soil memory*, constituted by the set of pedogenetic characteristics enduring through time (Targulian and Goryachkin 2004). This was accomplished through analyses of grain size composition, dithionite-extractable iron, total organic carbon content (TOC), carbonate content, radiocarbon dating, and soil micromorphology as detailed below.

Grain size composition was based on the United States Department of Agriculture (USDA 2004) guidelines. The particle size was quantified by separating fractions after the elimination of the principal cementing components (humus, carbonates and iron oxides). Particle size characteristics influence several soil properties

Table 1. Localities reported in Sonora with paleontological evidences of the late Pleistocene

Location number	Locality	Paleontological evidences
1	Rancho San Francisco	Mammoth and other Pleistocene fossils.
2	Rancho El Arenoso	Bison (*Bison* sp.), horses (*Equus conversidens* and *Equus excelsus*), mammoth (*Mammuthus columbi*) and tortoises (*Gopherus* sp.) (Arredondo 2013).
3	La Playa	Prairie dogs (*Cynomys ludovicianus*), bison (*Bison*), mammoths (*Mammuthus*), camels (*Camelops*), berrendos (*Capromeryx* sp.) and tortoises (*Gopherus* sp.) (Villalpando et al. 2007; Carpenter et al. 2009; Mead et al. 2010).
4	Fin del Mundo	Gomphotheres (*Cuvieronius* sp.), mastodons (*Mammut americanum*) and tapirs (*Tapirus* sp.) (Sánchez et al. 2014).
5	Térapa	Birds, fish, amphibians, crocodiles (cf. *Cocodrylus acutus*), bison (*Bison*), horses (*Equus*), gophers, ground sloths (*Paramylodon harlani*), tapirs (*Tapirus* sp.), deer (*Odocoileus virginianus*), Pleistocene pronghorn (*Stockoceros* sp.), boars (*Platygonus* sp.), llamas (*Hemiauchenia* sp.), capybaras (*Hydrochoeridae*), gliptodons (*Glypotorherium cylindricum*), pampatheres (*Pampatherium* cf. *P. mexicanum*), bobcats (*Lynx rufus*), racoons (*Procyon lotor*), wolves (*Canis dirus*) and rodents (Mead et al. 2006; Nunez et al. 2010; Bright et al. 2010).
6	Aconchi	Mammoth (*Mammuthus*) (White et al. 2010).
7	Agua Prieta	Mammoth (*Mammuthus columbi*) (White et al. 2010).
8	Altar	Mammoth (*Mammuthus*) (White et al. 2010).
9	La Angostura	Mammoth (*Mammuthus*), bison (*Bison*), horse (*Equus*), camels (*Camelops*) and gomphothere (*Cuvieronius* sp.) (White et al. 2010).
10	Las Areniscas	Bison (*Bison*), gomphotheres (*Cuvieronius*) (White et al. 2010).
11	Arivechi	Bison (*Bison*) (White et al. 2010).
12	Arizpe	Mammoth (*Mammuthus*) and gomphothere (*Cuvieronius* sp.), wild turkey (*Meleagris gallopavo*), horse (*Equus*), bison (*Bison* sp.) (White et al. 2010).
13	Arroyo de Humo	Bison (*Bison*) and proboscidiean (White et al. 2010).
14	Bachoco	Horse (*Equus*), camel (*Camelops*), bison (*Bison*), mammoth (*Mammuthus*), gomphothere (*Cuvieronius* sp.) (White et al. 2010).
15	Bajimari	Horse (*Equus*), bison (*Bison*), Odocoileus, peccaries (*Platygonus*) (White et al. 2010).
16	La Botana	Horse (*Equus*), bison (*Bison*), mammoth, (*Mammuthus*), glyptodont (*Glyptotherium*), camel (*Camelops*), (*Odocoileus*) (White et al. 2010).
17	Carbó	Mammoth (*Mammuthus*) (White et al. 2010).
18	El Carrizal	Horse (*Equus*), bison (*Bison*) (White et al. 2010).
19	Cedros	Horse (*Equus*), bison (*Bison*), mammoth (*Mammuthus*) (White et al. 2010).
20	Chinobampo	Bison (*Bison*), camel, horse (*Equus*), and glyptodont (*Glyptotherium*) (White et al. 2010).
21	Ciénega de Cabo	Mammoth (*Mammuthus*) (White et al. 2010).
22	La Ciénega	Proboscide (White et al. 2010).
23	Cócorit	Mammoth (*Mammuthus* sp.), gomphothere (*Cuvieronius* sp.) (White et al. 2010).
24	Costa de Hermosillo	Horse (*Equus*) (White et al. 2010).
25	Los Coyotes	Proboscide (White et al. 2010).
26	Cumpas	Mammoth (*Mammuthus*) (White et al. 2010).

27	Cucurpe	Proboscide (White et al. 2010).
28	Desemoboque de los Seris	Tortoise (*Gopherus*), lagomorph (White et al. 2010).
29	Desemboque del Río San Ignacio	Tortoise (*Gopherus*) (White et al. 2010).
30	Hermosillo	Mammoth (*Mammuthus*), horse (*Equus*), tortoise (*Gopherus*) (White et al. 2010).
31	Jusibampo	Horse (*Equus*) (White et al. 2010).
32	Llano Prieto	Mammoth (*Mammuthus*), bison (*Bison*), horse (*Equus*), glyptodon (*Glyptotherium*) (White et al. 2010).
33	La Libertad	Tortoise (*Gopherus*) (White et al. 2010).
34	Magdalena	Mammoth (*Mammuthus*) (White et al. 2010).
35	La Mata de Carrizo	Proboscide (White et al. 2010).
36	Mutica	Bison (*Bison*) (White et al. 2010).
37	Naco	Mammoth (*Mammuthus*), horse (*Equus*) (White et al. 2010).
38	O´Neil Pass (Puerto Peñasco)	Tortoise (*Hesperotestudo*) (White et al. 2010).
39	Oquitoa	Gomphothere (*Cuvieronius*) (White et al. 2010).
40	Pesqueira	Proboscide (White et al. 2010).
41	Playa San Bartolo	Camel (*Camelops*), horse (*Equus*), tortoise (*Gopherus*) and lagomorph (White et al. 2010).
42	Quiriego	Bison (*Bison*), horse (*Equus*) and mammoth (*Mammuthus*) (White et al. 2010).
43	Quitovac	Antilocapridae, camel (*Camelops*), horse (*Equus*), and mammoth (*Mammuthus*) (White et al. 2010).
44	Rancho Áigame	Horse (*Equus*), tortoise (*Hesperotestudo*) and proboscide (White et al. 2010).
45	Rancho Estribo	Mammoth (*Mammuthus*) (White et al. 2010).
46	Rancho La Brisca	Fifty-one species, including fish, amphibians, reptiles, birds and mammals (White et al. 2010).
47	Rancho de En-medio	Bison (*Bison*), camel, horse (*Equus* cf. *E. conversidens*) and mammoth (*Mammuthus*) (White et al. 2010).
48	El Sahuaro	Bison (*Bison*) and horse (*Equus*) (White et al. 2010).
49	Sangre Vieja	Proboscide (White et al. 2010).
50	Santa Ana	Horse (*Equus*) (White et al. 2010).
51	Santa Rosa	Mammoth (*Mammuthus*) (White et al. 2010).
52	Sierra El Rosario	Pack rat (*Neotoma* spp.), owl (*Strix brea*) (White et al. 2010).
53	Tecomate (Isla Tiburón)	Sea lion (*Zalophus californicus*), bison (*Bison*) (White et al. 2010).
54	Mina El Yeso (without location)	Proboscide (White et al. 2010).
55	Piedra de Malpaís (without location)	Horse (*Equus*) (White et al. 2010).
56	La Puercera (without location)	Mammoth (*Mammuthus*), bison (*Bison*), horse (*Equus*) (White et al. 2010).

such as structure, density, compaction and pore size, moisture retention, air capacity, and specific surface area.

Dithionite-extractable iron (Fe_d) was assessed through the extraction and quantification of free iron oxides following Mehra and Jackson (1960). The filtrate fraction was analyzed by atomic absorption spectrometry using a Perkin Elmer Model 3110 at the Soil Science Department in the Institute of Geology, UNAM.

Total Organic Carbon content (TOC) was obtained using an elemental analyzer CHNS/O Perkin Elmer 2400 series II at the Department of Soil Science, Institute of Geology, UNAM (in accordance with Schlichting and Blume 1966).

Carbonate content was assessed by first weighing a dry sample and then adding 5M HCl solution until all carbonates were destroyed and the reaction stopped. Subsequently, the sample was washed and dried in an oven, and then re-weighed. The percentage of carbonates was determined by weight difference between the initial sample and the post treatment with HCl sample.

Radiocabon dating was achieved through assays of the humic acids and pedogenic carbonates of the paleosols. The AMS dating was performed in the laboratories of Beta Analytic.

Soil micromorphology was performed on undisturbed samples with preserved structure. The collection method recorded the original orientation. Subsequently thin sections were prepared, and observed under a petrographic Olympus America BX51 microscope. Thin sections were analyzed with polarized and crossed polarized light to identify the characteristics of the soil matrix and pedogenetic processes (Stoops et al. 2010).

3. Results

3.1. Laboratory analysis

In the San Francisco 3 profile (**Figure 6**), the granulometric analysis showed that the clay fraction was abundant in all horizons, with a maximum in 5BC (43.7%) and 2Bw (39.46%) and

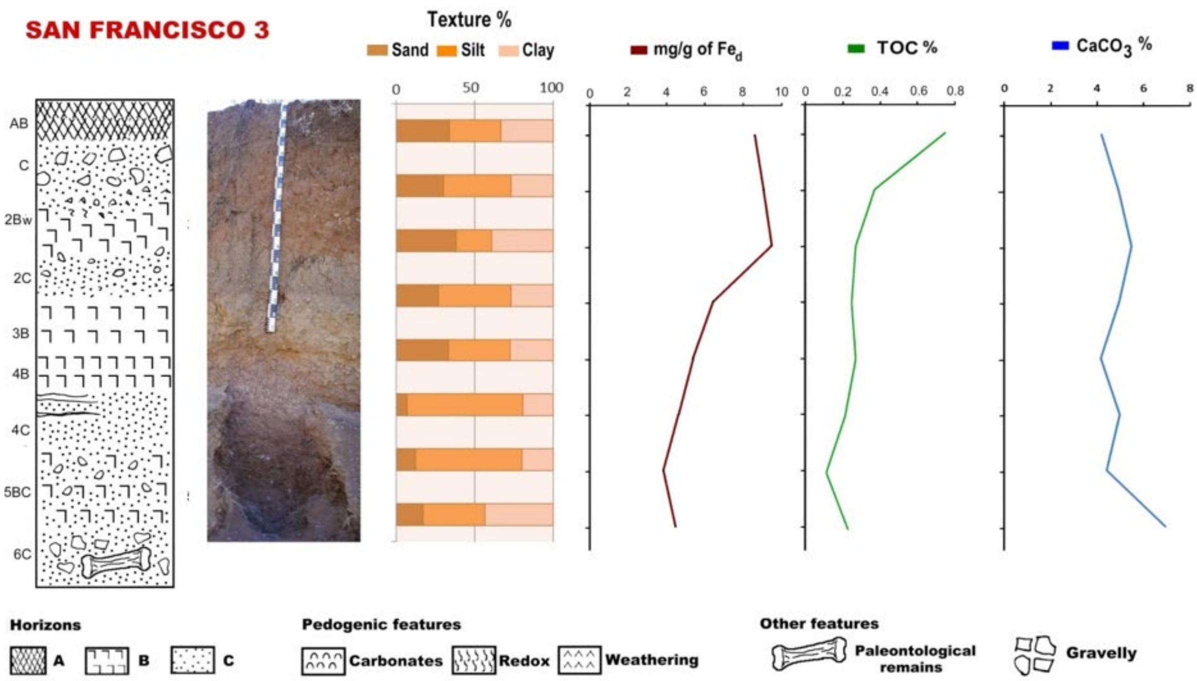

Figure 6. Analytical results of the San Francisco 3 profile. The 6C horizon was not analyzed and is only included in the scheme to show the location of the fossil remains.

the minimum in 4B (19.73%), which indicates paleosols are composed of pedo-sediments. The silt fraction presented maximum values in 4B (73.2%) and 4C (67.2%) and lowest values in 2Bw (22.5%). The highest percentage of sand was found in 2Bw (38%) and 3B (33.2%), and the minimum in 4B (7%). The highest extractable free iron content with sodium dithionite (Fed) was observed in 2Bw (9.48 mg/g), followed by C (9%) and AB (8.61 mg/g); a decrease towards the lower part of the profile was observed, with the minimum in 3Ck (3.84 mg/g). The TOC was low throughout the sequence (less than 1%). The highest value of TOC was found in AB (0.74%), and decreased in the lower part of the profile in the C horizon (0.24%) with the minimum content in 4C (0.11%). All the horizons were carbonated with more than 4% of $CaCO_3$. A leaching process of AB (4.19%) towards the underlying horizons C and 2Bw (5.48%) was observed with a decrease in 2C (4.94%) and 3B (4.15%). Carbonates increase slightly in 4B (4.98%), decrease again in 4C (4.42%) and reach their maximum value in 5BC (6.97%) at the base of the profile.

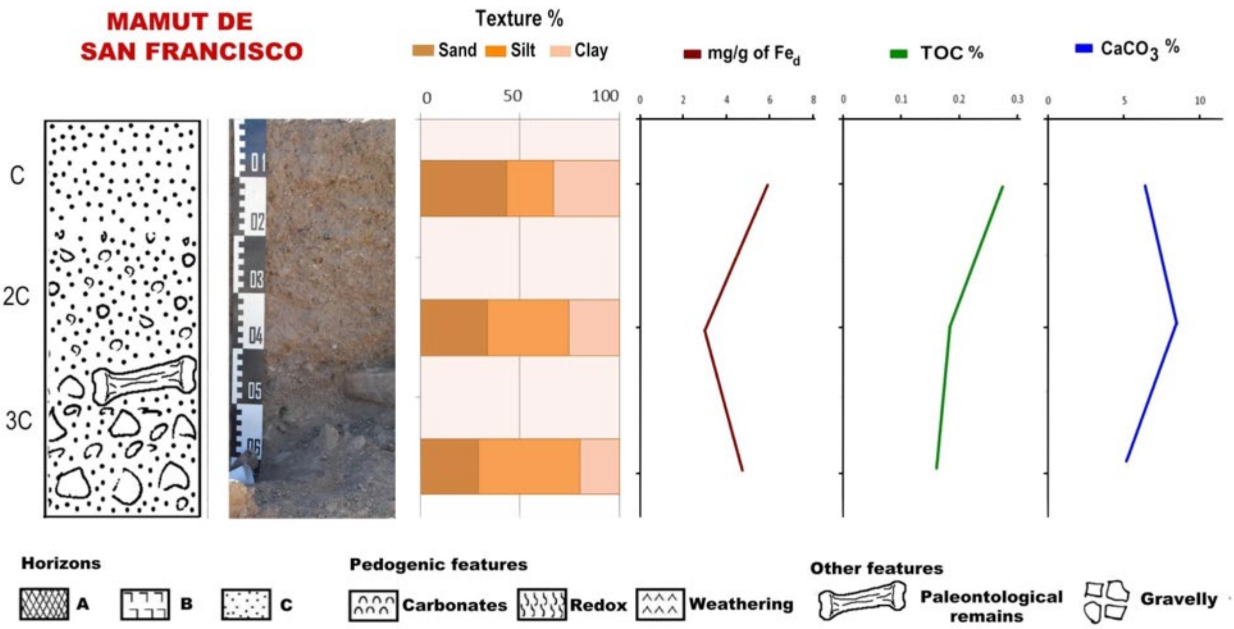

Figure 7. Analytical results of the Mamut de San Francisco profile.

In the Mamut of San Francisco profile (**Figure 7**) the sand fraction was higher in the C horizon (43.30%) and decreased in 2C (33.75%); the minimum content was observed in 3C (29.21%). The maximum silt content was observed in 3C (51%) and decreased in 2C (40.65%); the minimum content was found in C (23.36%). The clay fraction had maximum values in C (33%) and decreased in 2C (25.59%); 3C (19.7%) contained the lowest fraction. The highest Fe_d content was recorded in C (5.81 mg/g), followed by 3C (4.78 mg/g), and the lowest content was obtained in 2C (3 mg/g). TOC was very low with a maximum in C (0.27%), average presence in 2C (0.18%) and a minimum in 3C (0.16%). $CaCO_3$ had maximum values in 2C (8.45%), medium in C (6.43%) and minimum in 3C (5.25%).

In the La Cantera profile (**Figure 8**), the largest amount of sand was found in the C horizon (52.14%), which shows a clear lithological discontinuity with the other horizons. The predominant fraction in all other horizons was silt, with a maximum in 9Bg (79.9%) and minimum in C (35.6%). The highest percentages of clay are found in the 8Bk (24%), 4Bk (22.13%) and 6Bg (21%) horizons, although all horizons contain clays, including 5Ck (22.67%). This pattern indicates that the sediment may be derived from soils eroded from the upper horizons. The content of the Fe_d was very low, due to the reducing conditions that predominate in the paleosols. The maximum Fe_d was found in the 3C (3.28 mg/g) and the 4BK (2.98 mg/g) horizons; the amount decreased drastically in 5Ck (0.96% mg/g), then increased again in 6Bgk (2.52 mg/g) and 6BCk (2.63 mg/g), decreased again in 7Ck (1.03 mg/g) and increased slightly in 8Bk (2.24 mg/g) and 9Bg (2.15 mg/g). All horizons are carbonated in considerable proportions. The minimum content was found in the 9Bg horizon (3.62%), located at the base of the profile, while the maximum value was found in 7CK (26.19%).

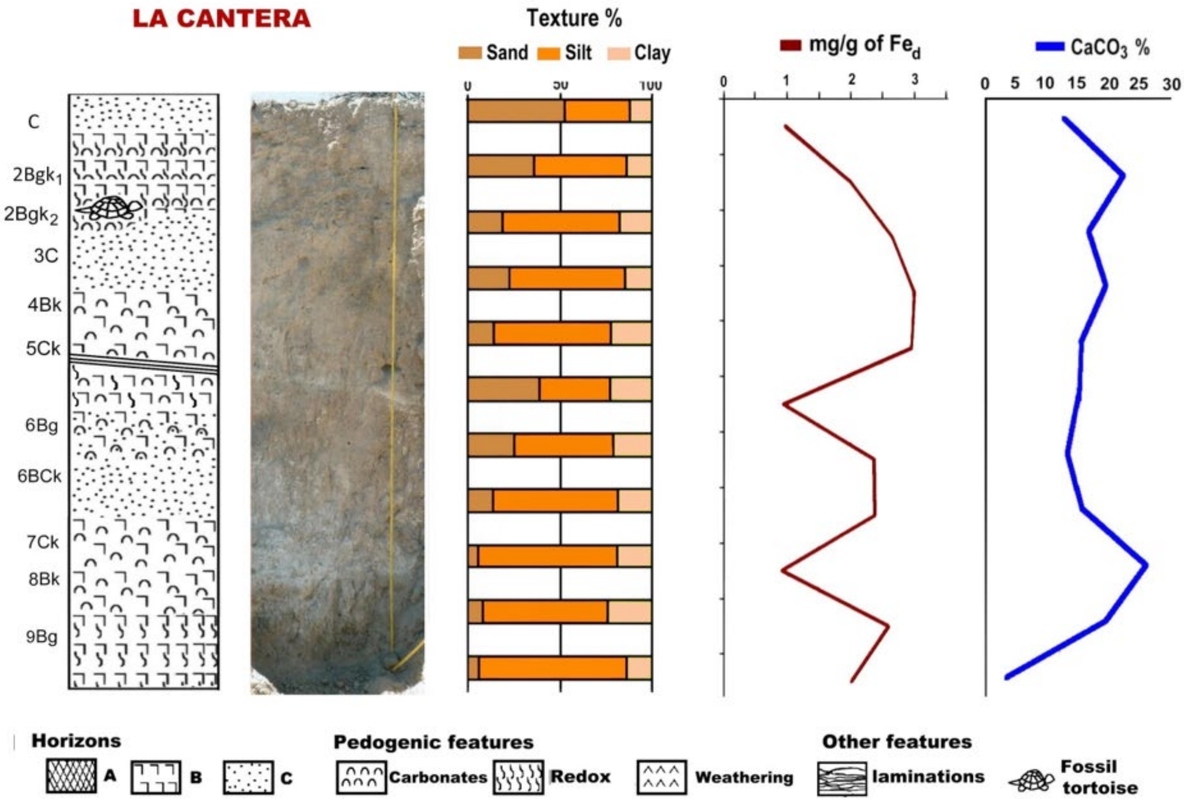

Figure 8. Analytical results of the La Cantera profile.

3.2. Micromorphological features

This section describes the micromorphological characteristics of the Mamut of San Francisco and La Cantera profiles.

In the Mamut de San Francisco profile, the micromorphology demonstrated that the matrix was composed of reworked soils. Areas with coarse particles were observed mixed with zones of finer composition and aggregates of finer composition (**Figure 9a**) and lithic fragments (**Figure 9b**). Iron and manganese accumulations were observed in the matrix of the three horizons (**Figures 9c and 9d**), evidencing conditions of water saturation, which is corroborated by the abundant presence of diatoms throughout the profile (**Figure 9g**). Carbonate accumulations in the matrix and in pores (**Figures 9e and 9f**) evidence periods of aridity, most probably associated with the modern climate. In addition, plant remains provide evidence of more recent pedogenetic processes (**Figure 9h**).

In the La Cantera profile, the soil matrix is composed of reworked soil aggregates with different morphology; some aggregates show high carbonate content, both in the matrix and

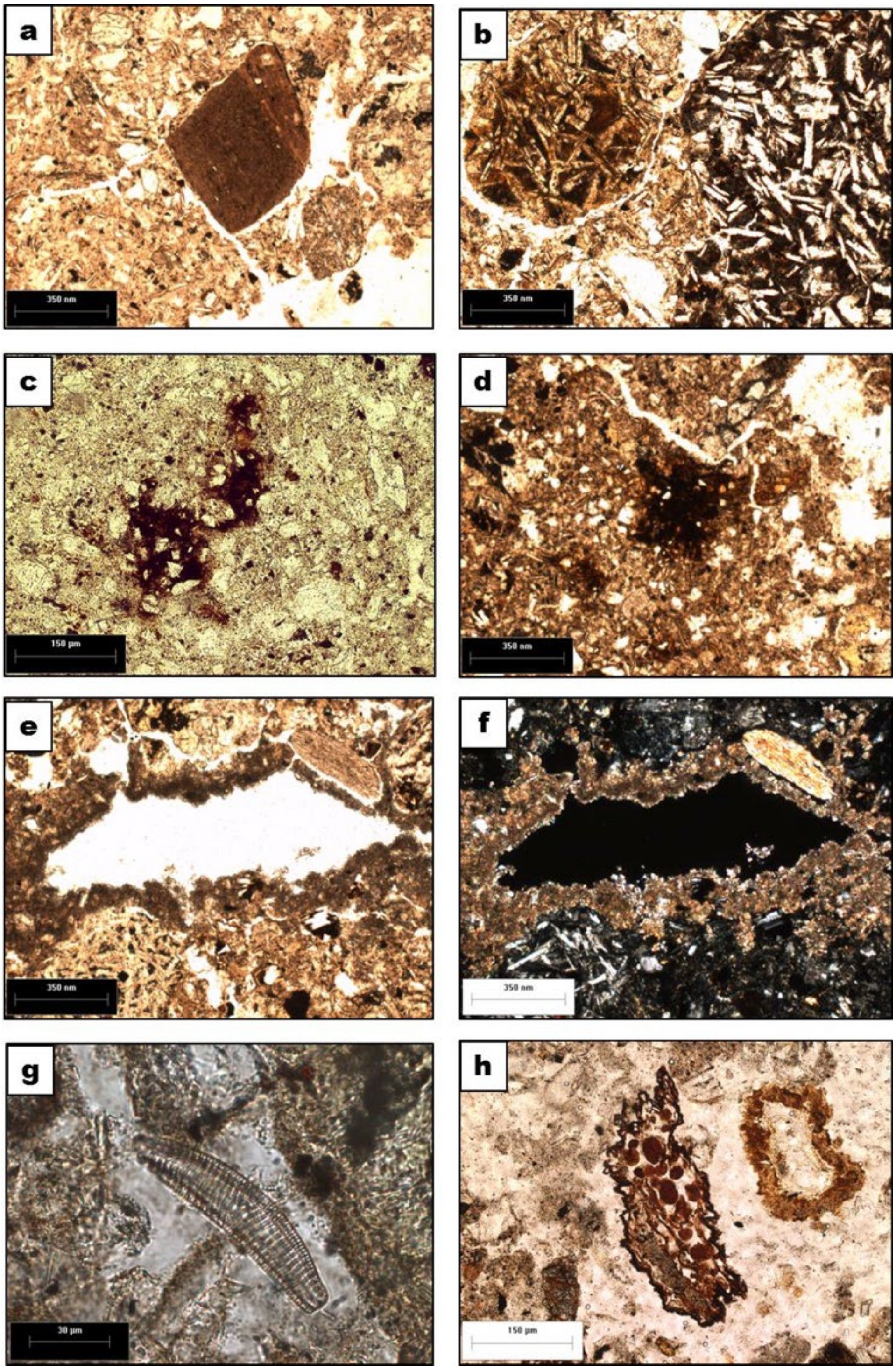

Figure 9. Micromorphological features of Mamut de San Francisco profile: a) soil aggregate in the matrix, PPL; b) lithic fragments in the matrix, PPL; c and d) accumulation of iron in the matrix, PPL; e and f) carbonate coatings in the pores, PPL(e) and Nx (f); g) diatom in the matrix, PPL; and h) plaint remains, PPL. Photos by T. Cruz.

in pores (**Figures 10a and 10b**); while others show illuvial clay coatings (**Figures 10a, 10b and 10c**) and redoximorphic features (**Figures 10d and 10e**). Silicified plant tissues were identified in some horizons (**Figures 10f and 10g**). We associate their development with abundant Si release from weathered volcanic minerals found in the same strata. The sample also contains diatoms, many of them fragmented (**Figure 10h**). This indicates ancient soils formed under moist conditions. In general, traits of humid pedogenesis were observed and much of the sediment was leached. In some horizons, soil fragments with well-developed illuviation cutans, indicative of redeposition, were observed. At the base, redoximorphic features and amorphous silica neoformations predominate, and a very intense and multiphasic secondary carbonation was also observed.

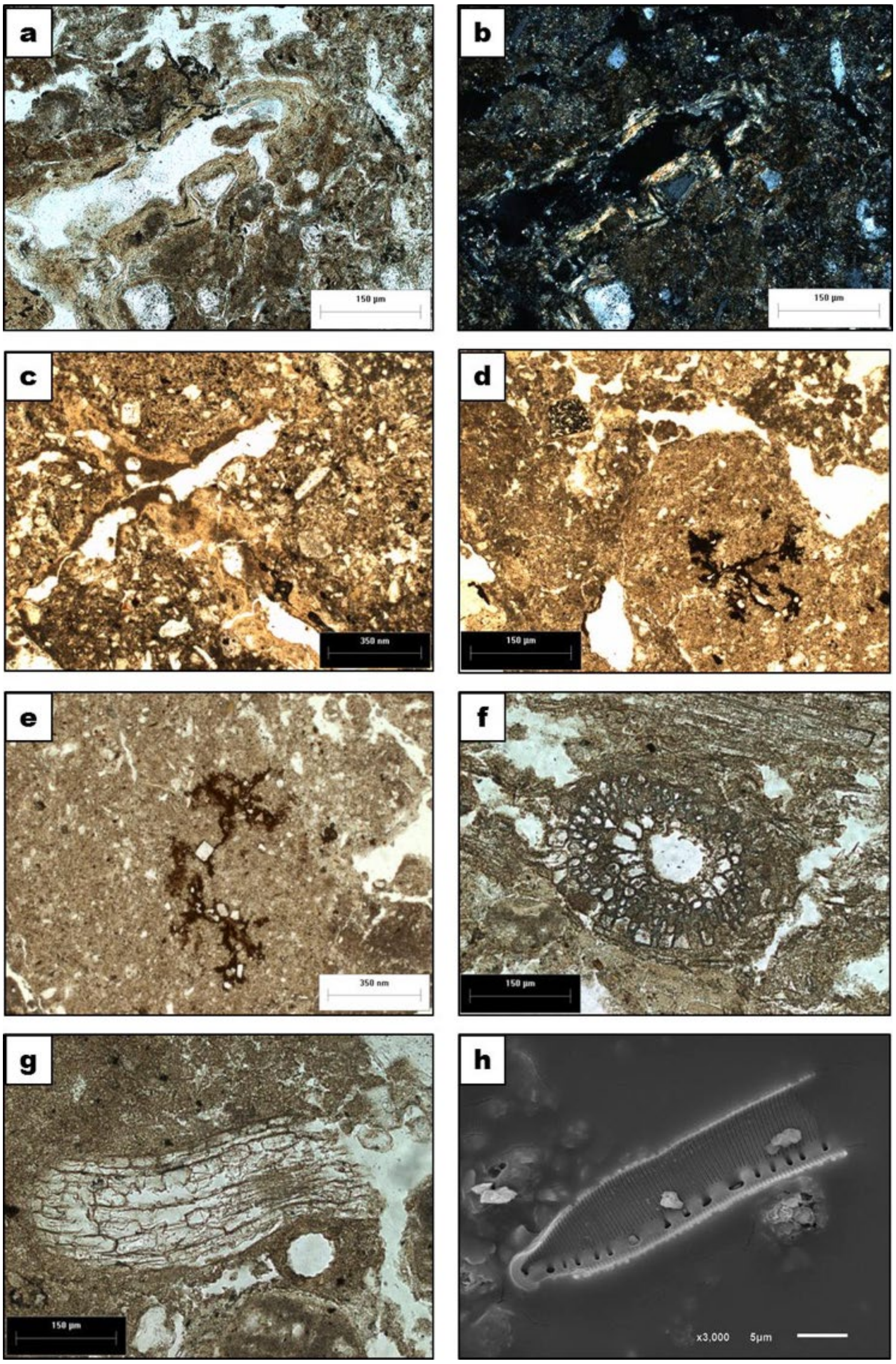

Figure 10. Micromorphological features of La Cantera profile: a and b) clay coating, associated with accumulations of carbonates, PPL (a) and Nx (b); c) clay coating on the pore, PPL; d and e) dendrite of manganese in the matrix, PPL; f and g) silicified plant tissue, PPL; and h) diatom in the matrix, observed with SEM. Photos a-g by T. Cruz and S. Sedov; photo h courtesy of A. Golyeva.

3.3. Radiocarbon dating and $\delta^{13}C$ values

The ages and isotopic composition of the paleosols are shown in **Table 2**. The organic matter (humic acids) from the 4B horizon of the San Francisco 3 profile was newly dated by radiocarbon for this work. The La Cantera dates previously were published (Cruz-y- Cruz et al. 2015, 2016), but are included in the table for comparative purposes to correlate the sequences analyzed with regional trends.

The isotopic carbon values obtained with the dates were also included, since they will be used to make paleoenvironmental inferences.

Table 2. Radiocarbon ages of paleosol carbonates and humus of selected horizons in the two profiles

Site	Profile	Horizon	Material	^{14}C Age BP	^{14}C Calibrated age (2σ) BP	$\delta^{13}C$ $^0/_{00}$ (MO)	Laboratory code
Rancho San Francisco	SF3	4B	Organic matter	10320 ± 40	12380 – 12005	-19.8	Beta – 377619
El Arenoso	La Cantera	2Bgk2	Carbonates	13750 ± 60	16800 – 16920	-20.7 (*)	Beta – 328549
El Arenoso	La Cantera	5Ck	Carbonates	16160 ± 60	19320 – 19430	-18.4 (*)	Beta – 328550
El Arenoso	La Cantera	6Bg	Carbonates	26230 ± 150	30730 – 31120	-18.4 (*)	Beta – 328551

(*) With enrichment factor 150/00 to adjust to equivalent ratios for organic matter (according to Cerling and Quade 1993).

4. Discussion and Conclusions

4.1. Correlation of the San Francisco and El Arenoso paleosols with regional paleopedological records

As mentioned in the introduction, red paleosols predominate in Sonora. These soils constitute a pedological unit (Red Unit) formed by Cambisols that represent the late Pleistocene-Holocene surface. Soils of this age are also represented by a pedological unit of Gleysols (Gray Unit) present in Rancho El Arenoso -La Cantera, El Arenoso and Los Poceaderos profiles- (Cruz-y-Cruz et al. 2015). The characteristics of this pedological unit are also represented in the San Rafael Paleosol (SRP), described at the La Playa archaeological site. These soils developed between the late Pleistocene and the Middle Holocene (14.9-4.2 ka cal BP). The characteristics of this pedological unit are moderate development; good structure; weathering of primary minerals and neoformation of secondary minerals, such as clays and iron oxides; carbonation and humification (Cruz-y-Cruz et al. 2014).

In Rancho San Francisco, the paleosols evaluated in the SF3 profile show similar morphological characteristics, including moderate development, good structure, weathering, new formation of clay and iron oxides, and carbonation. These characteristics are similar to the other red paleosols. The red coloration is given by the formation of pedogenic iron oxides, indicated by the Fe_d content, which exhibited maximum values in 2Bw. The dating obtained from the organic matter of the 4B horizon (**Table 1**) indicates the final (or near to final) period of the development of this soil was between 12.3-12 ka cal BP. Thus the overlying paleosol, formed by the 2Bw/2C horizons, can be considered an analogue of the SRP.

As explained in the profile description, the deepest horizon of the SF3 profile (5BC) is on a layer of very thick sediments containing remains of Pleistocene megafauna, indicating that the paleontological deposit is much earlier than 12.3 ka cal BP. During a field survey of the site it was observed this rock layer continued to the bone bearing horizon of the Mamut de San Francisco profile. Thus this is the same layer containing the fossil remains (horizon 3C). These relationships demonstrate that the deposit containing the Pleistocene fauna remains formed many years before 12.3 ka cal BP.

At the site where the mammoth was located (MSF profile) no paleosols were found. The mammoth was buried by sediments composed of reworked soils mixed with thick sediments and large lithic fragments. The characteristics of the sediments, mainly the evidence of redoximorphic processes and the significant presence of diatoms, indicate the site was flooded for some period. This is likely indicates the formation of a local marsh (most likely a *ciénega*).

However, $\delta^{13}C$ of soil organic matter of paleosols of the SF3 profile (-19.8$^0/_{00}$) does not differ from the values obtained in previous studies for the other contemporary sites: -19.8$^0/_{00}$ in La Playa; 23.9$^0/_{00}$ and 23.1$^0/_{00}$ in Magdalena de Kino; -20.7$^0/_{00}$ in El Arenoso (Cruz-y-Cruz et al. 2016) and -17$^0/_{00}$ in Fin del Mundo (Sánchez et al. 2014), that indicate a mixed vegetation cover of C_3/C_4 plant during the development of the paleosols. Therefore, considering the other pedogenic features of the paleosols of the SF3 profile, environmental conditions similar to those of the SRP can be considered -semiarid and cold, slightly wetter than today, with winter rains and marked seasonal changes- (Cruz-y-Cruz et al. 2016). Thus, the formation of the pond in the lower part of the basin was mainly conditioned by its geomorphological characteristics, in the lower part of the basin, and by the low rate of evaporation due to a cold climate.

In Rancho El Arenoso the analytical results also indicate soils with moderate development with pedogenic characteristics very similar to those evaluated in the other sites for the same period (SRP). The exception is that redoximorphic processes are strongly developed imparting a gray coloration to the paleosols. The main pedogenetic processes are weathering, clay formation, redoximorphic processes and strong carbonation. Gleyzation indicates prolonged moisture saturation in the soil that caused anoxia and acidification, generated reduction and dissolution of the iron minerals, and imparted a gray coloration. The carbonation indicates periods of decreased humidity in which the carbonates accumulated, alternating with the more humid periods. The inter-stratification between paleosol and sediments also indicate alternation between periods of environmental stability and pedogenesis with periods of instability and erosion. The carbonate dates of the paleosols range between 30-16.8 ka cal BP (end of MIS3 into MIS 2). This includes the Last Glacial Maximum (LGM) -about 22 ka cal BP- during which very cold and dry environmental conditions prevailed at a global scale (Uriarte 2009). These conditions created environmental instability with a corresponding increase in erosion-redeposition processes of paleosols. This is evidenced by the pedo-sedimentary sequences described here.

The paleontological evidence in El Arenoso was found associated with the 2Bgk2 horizon (tortoise *in situ*), dated in 16.8 ka cal BP, and below it, so the fossil deposit must have been formed during the MIS2 period. Therefore, it is very likely that the formation of the paleontological site located in the Rancho San Francisco also happened during MIS 2 and is associated with the climatic oscillations of the LGM.

4.2. Paleoecological inferences

Although there are numerous localities with paleontological evidence, there are no specific studies on paleosols directly associated with Pleistocene megafauna, which is why most of the paleoenvironmental inferences have been made from the faunal association and its ecological requirements. However, the characterization of the paleosols formed during the Late Pleistocene (MIS 3 and MIS 2) in several localities in Sonora permits the description of principal pedogenic tendencies and the establishment of a correspondence with prevalent environmental characteristics.

In Térapa, the ecological requirements of the Pleistocene fauna present in the site and its isotopic carbon values ($\delta^{13}C$) indicates a humid and slightly warm period between 43-40 ka cal BP, corresponding to MIS 3 (Bright et al. 2010). Between 30 and 16.8 ka cal BP, in El Arenoso the faunal association and the isotopic values of fauna and paleosols indicate a mosaic of mixed vegetation (Cruz-y-Cruz et al. 2015). This is probably related to a predominantly cold and semi-arid environment that allowed the accumulation of carbonates in soils, alternating with periods of humidity corresponding to the development of gleysols. This period corresponds to MIS 2, which comprises the LGM (Uriarte 2009). At Fin del Mundo, the fossil record indicates of humid conditions existed before 13.4 ka cal BP (Sánchez et al. 2014; Cruz-y-Cruz et al. 2016). At around 14.9 ka cal BP (late MIS2) the La Playa site record (paleosols) indicates a semi-arid climate, although with more humidity than today characterized by marked seasonal changes and C_3/C_4 mixed vegetation cover (Cruz-y-Cruz et al. 2016). This period coincides with the end of the Oldest Dryas and the beginning of the Bølling interstadial (Ballenger et al. 2011). At 13.4 ka cal BP (end of MIS2) the Fin del Mundo record indicates a change to drier conditions with an increase in C_4 plants (Holliday et al. 2014). Between 12.9-11.8 ka cal BP (end of MIS2) the records (paleosols and $\delta^{13}C$) of Magdalena de Kino and La Playa again show a slight increase in humidity as evidenced by a decrease in evaporation during the cooler Younger Dryas (Ballenger et al. 2011; Cruz-y-Cruz et al. 2016).

Much of the synchronous variation in the morphology of the paleosols can be explained by differences in local geomorphological conditions. The red paleosols developed on alluvial fans with a slight slope, whereas the gray paleosols of El Arenoso formed in the lower part of a semi-enclosed basin. Something similar seems to have occurred at Fin del Mundo, which is also located in a semi-enclosed basin and shows evidence of the formation of a body of shallow water from which fossils of Rancholabrean fauna were recovered (Sánchez et al. 2014; Holliday et al. 2014).

The inter-stratification of paleosols and sediments indicates the alternation between periods of environmental stability sufficiently long for the formation of soils with more or less deep B horizons (more than 15 cm) and periods of instability in which erosive processes predominated and removed the surface horizons (A horizons). These periods favored the accumulation of sediments in low lying areas, burying paleosols and creating new surfaces on which new soils could develop. This dynamic cycle of alternating environmental conditions prevailed for an extended period of time, as shown by soils formed in different periods, covering the end of MIS3, MIS2 and half of MIS1 (to the middle Holocene) (Cruz-y-Cruz et al. 2014, 2015).

The information obtained during this study makes it possible to establish the formation of local marsh in places such as Rancho El Arenoso, Rancho San Francisco, and Fin del Mundo; all of them located in semi-enclosed basins. These ponds were the result of the prevailing environmental conditions at the end of the Pleistocene during which cold and semi-dry climates predominated. So that the characteristics of the paleosols could develop, the increase in humidity should have happened during the winter season, with an evaporation rate limited by the low temperatures that allowed the chemical weathering and the formation of B horizons. Those climatic conditions could also allow the formation of the ponds.

These ponds seemed to have proliferated in a great part of the territory of the modern day Sonoran Desert and Coastal Plain of Sonora. This landscape presumably allowed the establishment of fauna communities with diverse ecological requirements, as evidenced in the paleontological record.

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