Evaporitic paleosols in continental strata of the Carroza Formation, La Popa Basin, Mexico: Record of Paleogene climate and salt tectonics

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ABSTRACT

A succession of continental red beds in the Paleogene Carroza Formation, northeastern Mexico, contains an assemblage of evaporite paleosols previously unknown in pre-Neogene strata that record the syndepositional exposure of nearby diapiric evaporite and a climatic shift to increasing aridity. Carroza red beds were deposited in an ephemeral braided-fluvial system in a high-accommodation setting. Paleosols developed in nearly all depositional settings, including channels, crevasse splays, and floodplains, and contain salic/natric, gypsic, baritic, and calcic horizons. Calcic paleosols are limited stratigraphically to the lowermost part of the formation in oyster-bearing estuarine strata and yield upsection to evaporitic paleosols, thus providing a record of increasingly arid conditions as the Paleogene marine shoreline shifted eastward, toward the Gulf of Mexico Basin. The increase in aridity reduced vegetation and residue thickness on the exposed diapiric salt, consequently increasing the influx of evaporitic minerals into the basin, and driving the development of salic/natric, gypsic, and baritic horizons in all depositional environments. Evaporitic paleosols of the Carroza Formation have characteristics similar to soils forming today in climates with annual precipitation ranging from <80 mm/yr to as much as 450 mm/yr, in apparent conflict with estimates of subhumid to subtropical conditions from Carroza fossil leaf data. Because evaporitic paleosols are persistent throughout the Carroza section, we infer that a combination of spring-fed, high water tables, augmented by flood-basin inundation from high-discharge seasonal fluvial flood events sustained perennial woodlands, and sodium-caused clay dispersion created poor drainage in topographically low parts of a rapidly subsiding salt-withdrawal basin.

INTRODUCTION

Paleogene continental strata in the La Popa salt basin of northeastern Mexico contain an extraordinary, previously undescribed assemblage of evaporite and carbonate paleosols. The strata accumulated in a salt-withdrawal basin adjacent to an elongate salt diapir and contain detritus derived from the exposed diapir. Stratal geometry and distribution of depositional environments within the basin thus record sedimentation and pedogenesis influenced by salt diapirism. Moreover, stratigraphic analyses reveal a secular change from calcic to evaporitic paleosols and thus indicate that the strata constitute an important record of Paleogene climate change. Evaporitic paleosols are rarely recognized in pre-Neogene rocks, but are nevertheless important indicators of arid paleoclimates and in some instances can provide an important record of coeval salt tectonics (e.g., Lawton and Buck, 2006). In this paper we describe fluvial deposits and salic/natric, gypsic, baritic, and uncommon calcic paleosols in the Carroza Formation and stratigraphically subjacent strata of the La Popa Basin in order to document and evaluate the nature of salt-sediment interaction and pedogenic evolution in the salt-withdrawal basin. This extraordinary assemblage of paleosols was previously unrecognized in pre-Neogene strata. Evaporitic paleosols of the Carroza Formation provide evidence for an early Cenozoic arid climate in the region, and a temporal departure from more conventional calcic paleosols typical of arid climatic regimes (e.g., Gile et al., 1981); indeed, calcic paleosols are present in continental facies of limited geographic and stratigraphic extent in strata that underlie the Carroza Formation. We infer that the unusual paleosol assemblage resulted from a combination of climatic aridity and proximity to the exposed salt wall, which provided the ionic constituents for the paleosols. In addition to demonstrating an arid paleoclimate, the paleosols indicate protracted diapir exposure and demonstrate significant influence of salt tectonics on pedogenesis.

GEOLOGIC SETTING

Some of the best-exposed salt diapirs in the world occur in the La Popa Basin of northeastern Mexico (Fig. 1; Laudon, 1996; Giles and Lawton, 1999). The La Popa salt basin formed during crustal extension adjacent to the Gulf of Mexico in the Middle and Late Jurassic and accumulated thick (~2 km) evaporite deposits of the Minas Viejas Formation (Lawton et al., 2001). The basin fill, which includes the Jurassic evaporite, Upper Jurassic–Lower Cretaceous carbonate strata, and Upper Cretaceous–Eocene siliciclastic strata (the Difunta Group), has a total maximum thickness in excess of 6 km (Lawton et al., 2001). The Upper Cretaceous–Eocene section, widely exposed in the basin, is partitioned into three salt-withdrawal “minibasins” (e.g., Rowan et al., 2003) that subsided into the thick Jurassic salt (Fig. 1), and studies of stratigraphic geometry indicate that salt diapirism was concurrent with deposition of all exposed units (Laudon, 1996; Lawton et al., 2001). The structural development of the salt diapirs deformed and controlled depositional patterns in adjacent Lower Cretaceous through Paleogene strata (Giles and Lawton, 1999; Rowan et al., 2003). Laramide shortening during latest Cretaceous through Eocene time created NW-trending synsedimentary detachment folds within the La Popa Basin and large doubly plunging anticlines in pre-tectonic Lower Cretaceous strata beyond the margins of the basin (Fig. 1).

The Carroza Formation is the youngest formation of the Difunta Group, which ranges in age from early Maastrichtian through Eocene.
At least 900 m thick, the Carroza Formation exposed in the Carroza mini-basin consists of roughly equal proportions of red mudstone-siltstone and sandstone, and uncommon limestone and conglomerate of continental origin, with abundant evaporitic paleosols (McBride et al., 1974; Buck et al., 2003; Waidmann, 2004). The underlying Viento Formation consists dominantly of tan shallow-marine sandstone and olive siltstone; it attains an exposed thickness of 730 m (Figs. 1 and 2; McBride et al., 1974). Laterally extensive beds of tan heterolithic sandstone with combined-flow ripples gradational upon conglomerate with chert pebbles, abundant large oyster fragments, and subrounded mafic igneous clasts derived from the salt wall were deposited during protracted diapiric exposure that accompanied Viento deposition. Adjacent to the La Popa salt wall (Fig. 1), these shallow-marine beds contain beds of red siltstone with abundant calcareous nodules resembling extensive red intervals in the continental Adjuntas Formation, which underlies the Viento (Figs. 1 and 2). We regard the red siltstone intervals of the Viento Formation as lateral facies equivalents of adjacent marine strata, representing coastal-plain deposits with calcareous paleosols that developed where the local topography lay above sea level as a result of diapir-driven uplift. The Viento Formation overlies the Adjuntas Formation, which has a biostratigraphic age of early Eocene (Ypresian), and is considered middle Eocene in age (Vega and Perrilliat, 1989a, 1989b, 1992; Vega et al., 2007). The age of the Carroza Formation is not directly constrained, but its stratigraphic position above the Viento Formation indicates that it could be as young as middle Eocene.

Figure 1. (A) Location map of Mexico, with inset rectangle indicating La Popa Basin study area. (B) Geologic map of La Popa basin, modified from Lawton et al. (2001). Inset rectangle indicates geologic map of Figure 3. Laramide synclines: ChS—Chaparral syncline; CzS—Carroza syncline. LP—La Popa summit; PL—village of Puerto Luis; SJ de La Popa—village of San Jose de La Popa.
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blocks of mafic igneous rocks and fossiliferous micrite; these blocks resemble lithologies entrained in evaporite of the nearby El Papalote diapir (Fig. 1) and deposited as fragments in strata near the diapir (Garrison and McMillan, 1999; Lawton et al., 2001). Stratigraphically persistent diapir-derived detritus, including mafic igneous clasts, in the Paleogene strata indicate that the La Popa salt wall was exposed continuously during deposition of the Adjuntas, Viento, and Carroza formations (Figs. 1 and 2).

Figure 2. Stratigraphy of the upper part of the Difunta Group in La Popa Basin. Unit thicknesses are maximum exposed thicknesses; all units thicken into subsurface of Carroza minibasin. Abbreviation: w/d—width/depth.

Figure 3. Geologic map of part of the Carroza minibasin, indicating locations of measured sections. Measured sections: AC—Arroyo las Cabras; CG—Cerro el Gavilan; D—Diablo; LD1 and LD2—Lower Diablo 1 and Lower Diablo 2; LR—Lower el Rincon; P, Poza; UR—Upper el Rincon. La Popa summit indicated on upthrown block of salt wall.
Cerro el Gavilán (CG)
Upper El Rincon (UR)
Lower Diablo II (LD2)
Diablo (D)
Lower Diablo I (LD1)

Figure 4 (on this and following page). (A) Top: Measured stratigraphic sections of the Carroza Formation, including (B) Bottom: a geologic cross section indicating positions of one set of measured sections on limbs of the Carroza syncline. Abbreviations: vf ss—very fine sandstone; f ss—fine sandstone; m ss—medium sandstone.
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Figure 4 (continued).
deposition accompanied diapir rise (e.g., Rowan et al., 2003). Our mapping indicates that the narrow overturned stratal panel adjacent to the salt wall is present along the length of the wall (Fig. 3). A broader open syncline, termed the Carroza syncline, diverges from the salt wall and trends southeast obliquely across the minibasin (Figs. 1 and 3). A separate syncline, termed the Chaparral syncline, enters the minibasin from the west and ends at a plunge termination near the village of San Jose de la Popa (Fig. 1). Paleogene units thicken from surface exposures into the subsurface of the minibasin, such that it resembles salt-withdrawal basins of similar scale developed above allochthonous salt in the Gulf of Mexico (Rowan, 1995; Shelley and Lawton, 2005). We interpret the broad synclines in the minibasin to represent en echelon folds that resulted from superimposition of Laramide shortening on the elongate minibasin. In contrast, the narrow panel of overturned bedding containing angular unconformities near the salt wall represents growth strata created by rise of the adjacent diapir (e.g., Giles and Lawton, 2002; Rowan et al., 2003; Waidmann, 2004).

Laramide folding began in the La Popa Basin in the middle Maastrichtian. Constraints on deformation timing include stratigraphic growth geometries in and near detachment folds indicating that folding postdated deposition of the lower Maastrichtian Muerto Formation (Hon, 2001; Weislogel, 2001), but had begun by the time of deposition of carbonate strata low in the Potrerillos Formation (Fig. 2; Druke, 2005). Onset of Laramide deformation is important to diapirism because shortening causes increased diapir rise rates (Rowan, 1995). Although the Laramide folds of the Carroza minibasin affect most of the Carroza section, outcrops of the youngest part of the formation lie only near the salt wall in the en echelon offset of the two folds and preclude knowing whether the youngest 180 m of the section experienced or postdated Laramide deformation.

CARROZA FORMATION SEDIMENTOLOGY

To establish stratigraphy, lateral and vertical distribution of facies and distribution of paleosols in the Carroza Formation, we measured and described eight stratigraphic sections (Figs. 3 and 4), in which we recognized 197 paleosols. Due to east-west changes in depth of erosion along the west-plunging Carroza syncline and poor exposure of the lower part of the Carroza Formation on the south flank of the minibasin, none of these sections spans the entire formation. The Viento-Carroza contact at the base of our measured section at Arroyo Las Cabras (Figs. 4 and 5) consists of several beds of tan sandstone with whole and fragmented oyster shells, cm-scale clasts of light gray micrite, and chert pebbles interbedded with light yellowish-brown fissile shale that grades to purple and red shale. This interval of interfering lithologies typical of both the Viento and Carroza formations is interpreted as a gradational transition from Viento-style tidally influenced bay and marsh deposits, which include tidal channels (e.g., Lawton et al., 2001), to Carroza-style, subaerially exposed, coastal-plain deposits. Calcareous paleosols in this part of the section are indicated by the presence of in situ carbonate nodules and reworked pedogenic micrite nodules in the channels (Fig. 5).

Lithofacies Associations

The Carroza Formation consists of interbedded red and subordinate green shale (45%), siltstone (5%), sandstone (46%), and minor conglomerate and limestone (4%), in which we defined six lithofacies associations that correspond to different depositional settings within an ephemeral fluvial system.

Thick-Bedded Sandstone

Beds of red, and less commonly tan, sandstone 20–600 cm thick are dominated by horizontal lamination with parting lineation composed of striking black heavy-mineral streaks and associated climbing ripple cross-lamination. Subordinate trough crossbeds are present in the lower meter of some sandstone bodies (Fig. 6A). Sandstone fines upward from coarse-grained bed bases, locally with pebbles, red siltstone intraclasts, and wood fragments, to fine-grained bed tops. No evidence for lateral accretion was observed in this lithofacies association. Although generally composed of single stories that can be traced across the study area (Fig. 3), the sandstone beds stack two to three stories thick in the hinge of the Carroza syncline to form multistory sandstone bodies as much as 20 m thick (Fig. 6B). These multistory sandstone bodies thin and lose stories with distance from the hinge (Waidmann, 2004).

Abundant evidence exists for intermittent drying and exposure of individual sandstone story tops. Desiccation cracks occur in thin beds of siltstone separating the stories and locally on sandstone bed tops, which commonly contain paleosols with root traces. Ant nests observed on upper surfaces of thick sandstones consist of downward-radiating, branching networks of galleries and numerous chambers (Fig. 6C). Interconnected tunnels are 0.5–2.0 cm in diameter, and vertical galleries are as much as 25 cm long. Many chambers are partially filled with gypsum.

The thick-bedded sandstone bodies are interpreted as fluvial channels with high width/depth (w/d) aspect ratios in which deposition took place by unconfined upper flow regime processes to yield the observed horizontal lamination. Flow was ephemeral, and channels dried out completely for protracted periods of time between flow events as indicated by root traces, bioturbation, paleosol horizons, and desiccation cracks at the tops of stories. Stacking of stories in the hinge of the syncline resulted from deposition during Laramide folding as fluvial channels sought the lowest topography in the basin. Paleocurrent indicators measured in the lower mapped channel complex (Pc1) are generally directed to the northeast, whereas indicators in the next younger mapped channel complex (Pc2) are eastward, parallel to the long axis of the minibasin (Fig. 7). The northeast-directed sediment dispersal of the older channel complex is interpreted to have resulted from channel systems crossing from the Chaparral syncline (Fig. 1) into the Carroza syncline. It appears that the river system may have crossed the salt wall at the eastern end of the exposure of Pc1 (Fig. 7). Paleocurrent data also indicate that the channels had straight reaches for distances of several km, at the end of which they abruptly turned, causing sandstone bodies to end in map view in some instances.

Channel geometry in the Carroza Formation is difficult to measure precisely owing to the nature of the outcrop, but w/d aspect ratios of channels are consistently large. The lower mapped sandstone body (Pc1; Fig. 3) in the hinge of the Carroza syncline consists of two stories, a lower story 7.8 m thick and an upper one 6.7 m thick (Waidmann, 2004). The width of the sand body, measured perpendicular to mean paleocurrent direction (Fig. 7) is ~4400 m, yielding a potential w/d range for sandstone body Pc1 of 564–658, depending upon which sandstone story actually reaches the western sandstone body pinchout (Fig. 3). A similar calculation for three stories, each ~6 m thick, that comprise sandstone body Pc2 in the hinge of the Carroza syncline (Fig. 6B), in combination with a preserved minimum width of 600 m of the sandstone body (from Fig. 3 map), yields a minimum w/d of 100.

Thin Red Sandstone Beds

Thin beds of very fine to medium-grained sandstone 5–30 cm thick are interbedded with red siltstone, have sharp but unscoured bases, and are commonly rooted, with scattered leaf impressions and desiccation cracks penetrating into the underlying mudrock (Fig. 6D). Desiccation cracks are filled with very fine to fine-grained white sandstone that infiltrated from overlying...
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133 m of covered section. Scattered exposures and quarry 1 km to east indicate the interval is mostly ‘red’ shale with red sandstone interbeds in exposed areas. Most sandstone interbeds contain salic/natric horizons and a few contain carbonate nodules (replacing gypsum).

Weak red (2.5 YR 4/2) shale with interbedded sandstones. Sandstones have capping columnar structures with salic/natric and gypsic horizons, and carbonate nodules replacing gypsum.

Medium sandstone with mudcracks. Top is highly bioturbated. Color is gray (SY 5/1).

Medium sandstones fines upward with salic/natric horizons and vertical burrows capping each sandstone. Color is reddish brown (SY 5/3).

Crevase splay deposits with four or more soils containing salic/natric and gypsic horizons. Rare green (10Y 7/1) Az horizons are also present. Extensive vertical burrowing. Halite casts are on ped faces with reddish gray (SYR 5/2) colors. Soils are shallow and weakly developed with stage I snowballs and salic/natric horizons are not as well developed as in other units.

Planar bedded medium sandstone. Contains plant fragments. Color is greenish gray (10Y 8/1).

Fluvial channel with strong columnar structure at top and common gypsum snowballs and rare burrows. Color is light gray (1 gley 7/n) and gray (10R 5/1) to dark gray (SYR 4/1) at top.

Contains gray (SY 5/1) salic/natric horizon with columnar pedds at top. Gypsic horizon below is dark gray (SYR 4/1) and contains carbonate nodules replacing gypsum and burrowing from above.

Bottom sandstone bed is tidal channel with unconfineable base containing carbonate nodules present from churning of underlying soil. Contains laths that indicate carbonate is pseudomorphous after gypsum. Heavily burrowed. Fines upward to pale olive (SY 6/3) fissile shale. Oyster shells in sandstones. Sandstones are heavily burrowed. Colors of sandstones are pale olive (SY 6/3) and light olive gray (SY 6/2).

Sandstone with vertical burrows and extensive bioturbation. Carbonate is present as in situ nodules and transported rounded fragments. Colors are pale olive (SY 6/3) and light olive gray (SY 6/2). Contains halite casts (first evidence of salt). See Figure 6G.

Splay sands containing pedogenic calcium carbonate as nodules and root traces at contact with unit above. Mudcracks. Color is dark gray (7.5YR 4/1) (first Carroza ‘purple’).

Light yellowish brown (2.5YR 6/4) sandstone and shale of the Viento Formation.

Figure 5. Detailed section of lowermost Arroyo Las Cabras section illustrating abrupt change from calcic to gypsic, salic/natric, and baritic paleosols at ~20 m.
thin white sandstone beds that in some instances are not preserved. Bed thickness decreases with lateral distance from channel sandstone bodies, and sandstone beds tend to stack in upward-thickening bedsets separated by thin mudstone interbeds. Burrows of insects and their larvae are present in some sandstone beds. We recognized Diptera cases and Acorichnus isp. (e.g., Hasiotis et al., 2003) in some examples of this lithofacies (Figs. 6E and 6F). This lithofacies association is interpreted to represent crevasse-splay deposits formed during flood events, with flow directed from the channel toward the floodplain. Crack-fill sandstone is interpreted as eolian on the basis of its white—as opposed to red—color, grain size, and common absence of preserved overlying bed, which was removed as a result of deflation following crack infill.

Red Siltstone and Mudstone

Red to purple blocky shale and siltstone in beds a few cm to as much as 60 m thick comprise roughly one-half of the Carroza Formation. The mudrock is commonly interbedded with sandstone beds of the thin red sandstone association. Thin sandstone beds are commonly mottled and intermixed with mudrock intervals as a result of rooting by...
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plants, desiccation, and burrowing. We interpret the red mudrocks as distal floodplain deposits.

**Drab Mudrock**

Uncommon grayish brown to olive gray upward-fining silty shale intervals 5–100 cm thick contain plant fragments and scattered small freshwater gastropods [Pachychilus (Pachychiloides) lawtoni; Perrilliat et al., 2008]. Locally, particularly in steeply dipping stratal panels near the salt wall, white sandy mudrock intervals are present beneath 15-cm sandstone beds. Stumps of fossil wood 4 cm in diameter penetrate vertically through the sandstone and branch into spreading root networks in the mudrock. Leaf mats are abundant on surfaces of very fine grained sandstone beds. Rodríguez-Reyes (2008) reported leaf fossils of the families Myrtaceae, Anacardiaceae, Burseraceae, and Rutaceae, as well as cf. Salicaceae (willow) from sandstone bodies interbedded in the mudrock and the mudrock itself. The drab colors, root networks, and fossil leaves derived from trees that require perennial water (e.g., Amlin and Rood, 2002) suggest that this lithofacies association represents pond deposits, perhaps fed by springs on the flank of the basin near the diapir. Perrilliat et al. (2008) interpreted one example of this lithofacies association as an abandoned channel deposit.

**Pebble and Granule Conglomerate**

Near the salt wall, several granule-pebble conglomerate beds 10–500 cm thick with clasts of mafic igneous rocks, fragments of angular detrital gypsum, and carbonate clasts derived from the diapir are interbedded with red mudrock intervals. Clasts are suspended in a matrix of poorly sorted red and gray silty sandstone (Fig. 6G). The thickest of these conglomerates, at the base of the measured section at Lower Diablo II, consists of 5 m of tan gypsiferous siltstone with suspended sand grains, clasts of gypsum, and chert pebbles. The pebbly siltstone overlies 2 m of red shale and sandstone, also with fragments of gypsum. By textural comparison with gypsiferous residuum derived from weathering of active diapirs in the Persian Gulf region of Iran (Bosak et al., 1998; Bruthans et al., 2008, 2009), and its position above diapiric blocks described below, we interpret this single interval of pebbly siltstone as reworked diapiric residuum derived directly from the salt wall. The thinner conglomerate beds interbedded with red mudrock are interpreted as deposits of small debris flows likewise derived from the exposed evaporite and entraining clasts of material from the diapir and adjacent upturned strata (Waidmann, 2004).

**Limestone and Shale**

Two intervals of laterally restricted (~5 m length), 50-cm-thick limestone beds interbedded with green and red shale are present in the western part of the study area on and adjacent to the Cerro El Gavilan measured section. The carbonate consists of micrite with scattered gar scales, fish bone fragments, and disarticulated and articulated ostracodes (Fig. 6H). This lithofacies association is interpreted as deposits of ponds or small lakes, their narrow width suggesting that they might occupy abandoned channels.

The Carroza fluvial environment was a sand-rich, braided-fluvial system. Channel characteristics include extremely high width/depth aspect ratios (100–600), straight channel reaches, and exposure of channel deposits as...
a result of ephemeral flow. These characteristics are consistent with braided river attributes (e.g., Miall, 1977, 1985). The predominance of horizontal lamination and overall high sand content provides evidence for uncommon high-discharge flow events by analogy with Holocene sand-rich flood deposits in braided-river environments (McKee et al., 1967; Miall, 1977). The channel deposits resemble those of flashy, ephemeral sheetflow sandy rivers described by Miall (1996), differing from such river types primarily in the abundance of muddy overbank or floodplain deposits. The abundance of preserved mudstone and siltstone in the Carroza fluvial system likely resulted from high subsidence rates in the minibasin, which constituted a high-accommodation setting that favored preservation of fine sediment (e.g., Shanley and McCabe, 1995). Anabranching or anastomosing dry-land fluvial systems, although having some sand-rich representatives characterized by straight reaches, typically possess channels with width/depth values near 10–15; moreover, they are mud-rich with low resulting net to gross ratios, lack lacustrine deposits, crevasse splays, and sedimentary structures, and there is little textural contrast between channels and overbank deposits (North et al., 2007).

CARROZA FORMATION PALEOSOLS

Paleosols occur in all lithofacies associations of the Carroza Formation except the limestone and conglomerate. Paleosols are 40–190 cm thick, dominantly red or reddish (hues 2.5YR, 5YR, 5R, or 7.5YR), and characterized by one or more of the following types of horizons: (1) salic/natric; (2) gypsic; (3) baritic; (4) burrowed and/or rooted horizons lacking other indicators of pedogenesis; and (5) calcic. Because more than one type of horizon can be present in a single paleosol (GSA Data Repository Fig. 1), their combined occurrences described below exceed 100%.

Dominant salic/natric horizons are present in 68% of the 197 Carroza paleosols. These horizons are distinguished by marked columnar structure (Figs. 8A and 8B). Columns range from 1 to 10 cm in diameter with domed tops and common halite casts (Fig. 8H). Columnar structure is best preserved in horizons developed in fine-grained sandstone. The uppermost parts of the horizons are commonly burrowed, particularly in channel deposits. Root traces in

\[\text{Figure 8. Features of paleosols. (A) Columnar structure of salic/natric horizons in lower Diablo I measured section. (B) Columnar structure of salic/natric horizons adjacent to lower Arroyo las Cabras section. (C) Photomicrography of coalescing gypsum snowballs, with minor replacement by calcite from gypsic horizon in upper Diablo section. (D) Photomicrography of stage I gypsum snowball, mostly replaced by calcite, from gypsic horizon in upper part of Arroyo las Cabras section. (E) Coalescing stage I gypsum snowballs in upper Diablo section. (F) Stage II gypsum nodules in Diablo section; (G) Stage I barite snowballs in baritic horizon, Arroyo las Cabras section. (H) Halite casts, lower Diablo I section.}\]
Salic/natric horizons range from rare to abundant, less than one mm to greater than 10 mm in diameter, and are invariably vertical. Burrows are dominantly vertical, rare to common, 0.5–1.0 cm wide and up to 15 cm long. Locally, salic/natric horizons contain stage I gypsum snowballs (Figs. 8C–8E; e.g., Buck and Van Hoesen, 2002; Buck et al., 2006).

Salic and natric soil horizons, although differentiable in Holocene soils, are nearly impossible to distinguish in paleosols. Holocene salic horizons form at the surface or in the subsurface and contain pedogenic accumulations of salts more soluble than gypsum (Food and Agriculture Organization [FAO], 1998; Soil Survey Staff, 2006). Natric horizons are defined on specific percentages of clay, columnar structure, and high exchangeable Na	extsuperscript{+} (FAO, 1998; Soil Survey Staff, 2006). Columnar structure can form in both natric and salic horizons and requires alternating periods of wetting and drying and a salt source in which sodium is the dominant cation (McCahon and Miller 1997; Soil Survey Staff, 2006). Distinguishing between salic and natric horizons in the Carroza Formation is difficult because the features that survive into the rock record—strong columnar structure, halite casts, and stage I snowballs (Buck and Van Hoesen, 2002)—do not distinguish between the two horizon types. We therefore refer to these horizons as salic/natric horizons. The most extensive development of salic/natric horizons occurs in crevasse-splay deposits, but they are also commonly present at the tops of channels. In the case of soil development on the tops of channels or crevasse splays, upward wicking of saline waters concentrated halite and potentially other highly soluble Na	extsuperscript{+} minerals to form the columnar structure. In contrast, salic/natric horizons present beneath other horizons probably formed by downward leaching of soluble Na	extsuperscript{+} salts (Fig. 9).

Gypsic horizons are present in 43% of the 197 described paleosols. Gypsic horizons contain stage I snowballs and stage II gypsum nodules (Figs. 8C–8F; e.g., Buck and Van Hoesen, 2002; Buck et al., 2006). The snowballs range in diameter from 0.5 to 3.0 mm and commonly coalesce to form compound snowballs as much 8 mm in diameter (Fig. 8E). Stage II nodules are as much as 2 cm in diameter (Fig. 8F). Holocene gypsic soils form in arid to semiarid climates where there is a source of sulfate ions (Buck et al., 2006). Stage I snowballs are a defining characteristic of pedogenic accumulation of sulfate salt minerals: although most commonly gypsum, they may be formed by other soluble sulfate minerals (Buck and Van Hoesen, 2002; Buck et al., 2006). Root traces are vertical, rare to abundant, 0.3–1.0 cm wide, and as much as 4 cm long. Vertical burrows (0.5 × 4.0 cm) are common, and rare burrows up to 18 cm long are present. The structure in gypsic horizons varies from moderate to strong, fine to coarse, sub-angular blocky, and if a salic/natric horizon is also present, the structure is moderate to strong, medium to coarse columnar. Fifty-four of the 84 described gypsic paleosols also contain salic/natric horizons. Salic/natric horizons commonly overlie gypsic horizons, but salic/natric and gypsic features also occur together, or salic horizons may be found below gypsic horizons (Fig. DR1 [see footnote 1]). In a few locations and more commonly near the base of the section, stage I snowballs and some stage II gypsum nodules have been diagenetically replaced by calcite (Figs. 5 and 8D). Gypsic horizons occur in all paleosol depositional environments but are most commonly present in the crevasse-splay and distal floodplain deposits (Fig. 4).

Paleosols with baritic horizons are present only in the eastern part of the field area (Figs. 3 and 4). Of the ten paleosols (5%) containing barite, eight contain co-occurring gypsum, two contain only barite horizons, and five have salic/natric horizons overlying barite-gypsum horizons. Baritic horizons occur in channel, distal floodplain, and crevasse-splay deposits in sediment textures ranging from shale to medium-grained sandstone. Structure varies from weak, fine, angular blocky to moderate, fine, and columnar. Root traces and burrows are rare to common, 1–10 mm in diameter, and vertical to subvertical. Barite forms both stage I snowballs 1–3 mm in diameter and stage II nodules consisting of bladed crystals arranged in rosettes 0.5–7 cm across and locally elongated vertically (Fig. 8G). Diagenetic calcite and dolomite partially replace some barite nodules.

Holocene soils in arid to semiarid climates that contain barite form at locations with a source of sulfate and barium ions (Sullivan and Koppi, 1995; Buck et al., 2004; Brock, 2008; Brock and Buck, 2009), or in soils with high water tables and saline groundwater (Lynn et al., 1971; Stoops and Zavaleta, 1978). Although Carroza paleosols in which a salic/natric horizon overlies a baritic horizon indicate at least periodic or seasonal evaporative upward wicking of subsurface water (e.g., Buck et al., 2006), the widely dispersed snowballs and vertically elongated nodules, together with vertical root traces and colors indicating strong oxidation, suggest that the dominant pedogenic mechanism was downward movement of water.

Although burrows and root traces are present in some evaporitic paleosol horizons, 16% (31) paleosols in the Carroza Formation contain no evidence of salt accumulation and possess only burrowed or rooted horizons. Root traces vary from 1 to more than 10 mm in diameter. Burrows are very common, usually vertical, and are typically from 0.5 cm in diameter by 5.0 cm long. These paleosols are most common in channel or pond deposits. Lack of columnar structure and absence of evidence for accumulation of soluble salts suggest that these soils record very short periods of pedogenesis between aggradation events or formed in environments characterized by leaching of soluble salts.
Calcic horizons are present only in 2.5% (5) of the 197 paleosols, and these horizons are furthermore restricted to the base of the Carroza Formation (Figs. 4 and 5). Calcic horizons are composed of stage II nodules as much as 2 cm in diameter with angular blocky to subangular blocky structure (e.g., Gile et al., 1966). Vertical burrows are 3–4 cm across and 11–18 cm long. In contrast to the other paleosol horizons, calcic horizons are commonly pale olive to light olive gray (5Y6/3, 5Y6/2). Calcic horizons occur in the interfingerering contact between the Carroza and Viento formations in bay or salt marsh environments. Near the salt wall in the lowermost Carroza Formation, rare calcic horizons occur in distal floodplain and splay deposits. The nodules are composed of micritic calcite, sometimes accompanied by diagenetic veins of sparry calcite along shrinkage cracks.

Holocene calcic horizons form ubiquitously in arid and semiarid soils as a result of root respiration and Ca-rich rain and/or dust input (e.g., Gile et al., 1981; Cerling, 1984). However, the precipitation of calcium carbonate is suppressed when either gypsum is present or the surface is devoid of vegetation. Gypsum decreases the solubility of calcium carbonate, preventing it from migrating through the soil, and thus prevents or inhibits its formation (Reheis, 1987; McFadden et al., 1991; Buck and Van Hoesen, 2002; Buck et al., 2006). The decrease in solubility is caused by the common ion effect, whereby the solubility of any salt in equilibrium with a saturated solution decreases, if a surplus of one of its ionic components is present (Krauskopf, 1967).

In the presence of a supersaturated gypsum solution, the solubility of calcium carbonate is decreased 64-fold (Reheis, 1987). A second mechanism that can inhibit calcic soil formation is the absence of vegetation or microbial activity mechanism that can inhibit calcic soil formation. This occurs in climates <80 mm/yr, (Amit et al., 2006); however, all reported cases of arid and hyperarid soils that lack calcic horizons and vegetation also involve soils that contain gypsum and other soluble salts (Rech et al., 2003; Amit et al., 2006; Buck et al., 2006; Howell, 2009). Thus, a full understanding on the controls of calcic horizon formation is not yet available. Because the diapir was at the surface throughout the time of Carroza deposition, we infer that the absence of salic/natic and gypsic horizons at the base of the Carroza Formation indicates that any available soluble salts were leached from the soil profile, and the climate was sufficiently humid to promote root respiration and calcic soil formation.

Carroza paleosols exhibit four grades of paleosol maturity defined on the basis of salt morphology, and thus salt content (e.g., Reheis 1987; Buck and Van Hoesen, 2002). Paleosol maturity defined on the basis of structure and salt morphology increases from grade 1 to grade 4: (1) burrowed or rooted horizons with no evidence of salt minerals; (2) horizons containing columnar structure indicating Na-salts with or without halite casts; (3) horizons containing stage I snowballs of gypsum or barite; and (4) horizons containing stage II nodules of gypsum, barite, or carbonate. Paleosol maturity varies geographically and stratigraphically in the Carroza Formation, with grade 1 paleosols occurring most commonly in channel deposits, grade 2 paleosols in channel, crevasse-splay and distal floodplain facies, grade 3 paleosols most common in crevasse spays, and uncommon grade 4 paleosols only near the salt wall and at the base of the section near the contact with the underlying Viento Formation where it is upturned near the salt wall.

Paleosols are most commonly compound, in that they are separated by C horizons, or composite in having vertically overlapping successive profiles, depending upon the lithofacies in which they formed (Kraus, 1999). Compound paleosols are most abundant, and are commonly present in the tops of Carroza channel deposits. Composite paleosols are commonly present in thick crevasse-splay or distal floodplain deposits (Fig. 9). Cumulative profiles consisting of overthickened horizons that result from slow sedimentation rates are not as common as compound or composite paleosols in the Carroza Formation but are present in distal floodplain deposits.

Differentiating individual paleosol profiles in the deposits of this highly arid to semiarid, saline environment is difficult. In some cases, A horizons can be used to distinguish between multiple stacked paleosols; however, because of the paucity of preserved organic material, A horizons are usually identifiable only on the basis of root traces and burrows. Water movement in extremely arid environments can be either downward, due to heavy rain events or periods of cool temperatures, or upward as a result of capillary fringe evaporation. Therefore, salt/natic horizons can occur both above and below gypsic horizons (Fig. 9; Buck et al., 2006). As a result, some individual profiles identified in this study may in fact be composite as a result of unrecognized overprinting.

The distribution and variety of salt mineral accumulation in Carroza paleosols indicate a local source for the salt and soil development in an arid climate. Because paleosol maturity and abundance increase with proximity to the salt wall, we interpret the diapiric evaporite as the primary source for gypsum, barite, and halite in the Carroza paleosols. That the diapiric evapo-rite, exposed at the modern surface as gypsum, contained sufficient sodium to form salic/natic paleosols is confirmed by a PEMEX (Petroleos Mexicanos) well that encountered over 3000 m of halite in the Minas Viejas Formation in an anticline directly southeast of the La Popa basin (Lawton et al., 2001). The exposed gypsum in the diapir thus represents a Holocene cap-rock residue from which the halite has been leached. A topographically elevated salt wall is demonstrated by diapir-derived metagneous grains in local conglomerate near the salt wall (Waidmann, 2004).

DISCUSSION

The geographic and stratigraphic distribution of paleosols and depositional facies within the Carroza Formation has important implications for paleoclimatic and salt tectonic studies, both regional and worldwide. The depositional system of the Carroza red beds is unique in that it records a strongly seasonal arid climate with continental deposition in a salt-withdrawal basin. Flashy ephemeral discharge is indicated by abundant parting lineation formed by supercritical flow in generally shallow channels, typical of wadi settings or distal sandy braided-fluvial systems (McKee et al., 1967; Glennie, 1970; Miall, 1977, 1996). Complete and long-term drying of the channel system is indicated by ubiquitous desiccation features and occupation of channel sands by burrowing insects. Stacking of channel bodies in the hinge of the broad Laramide syncline, channel flow subparallel to the fold and growth geometries near the salt wall demonstrate that sedimentation was syntectonic and was accompanied by high diapir rise rates, which created attendant thinning and truncation of strata near the diapir. Rapid diapiric rise likely resulted in continuous long-term exposure of the diapir—further indicated by conglomerate with diapir-derived detritus—and high flux of halite to the surface environment, implied by halite, gypsum, and barite in the paleosols.

The absence of obvious eolian deposits in the Carroza minibasin, although somewhat perplexing, is common in many Holocene arid landscapes. Unrecognized, thin eolian sand-sheets may be present, but the overwhelming abundance of salic/natic horizons may have obliterated eolian structures required for their identification. Alternatively, eolian deposits were simply not present or there was complete deflation of sandy bedforms, their former presence indicated only by sandstone fill of desiccation cracks, may have removed much evidence for eolian sediment dispersal.

The assemblage of evaporite paleosols in the Carroza was previously unknown in
pre-Neogene strata. In Holocene landscapes, such soils must have a source of salt minerals in order to form. Potential sources of salt minerals include in situ weathering of parent material (Mermut and Arshad, 1987; Carter and Inskipp, 1988), fluvial or eolian input of such minerals (Taimeh, 1992a; Buck and Van Hoesen, 2002), or less commonly, weathering of sulfide minerals, volcanic gases, chemical reactions in the atmosphere, or an atmospheric source from seawater (Podwojewski and Arnold, 1994; Rech et al., 2003; Michalski et al., 2004; Oyarzun and Oyarzun, 2007). The Carroza Formation contains no evaporite or sulfate deposits that might have served as a source for salts in the paleosols, nor are there such strata in nearby source areas. Other sources including volcanic gases, atmospheric chemical reactions or an atmospheric source from seawater are considered unlikely because: (1) There were no nearby volcanic sources to provide reduced sulfate gases; (2) chemical reactions in the atmosphere are known to produce salts in abundance only in the hyperarid and extremely old, stable surfaces of the Atacama Desert (e.g., Michalski et al., 2004; Oyarzun and Oyarzun, 2007); and (3) detrital gypsum in Carroza conglomerate and sandstone, and the more highly developed salt morphology in paleosols near the salt wall suggest that sea spray, although a possible source, was not a primary source of salts in Carroza paleosols. The abundance of salic/natric, gypsic, and baritic horizons and the observed increase in their maturity near the salt wall are best explained by derivation of salt from a continuously exposed salt wall. Therefore, evaporitic paleosols such as those in the Carroza Formation can preserve an important record of coeval salt tectonics (e.g., Lawton and Buck, 2006).

Mature paleosols (i.e., grade 4) occur near the salt wall and are inferred to indicate the presence of tectonically elevated surfaces that possessed a variety of factors that promoted soil development, including reduced sedimentation rates and proximity to exposed evaporite of the salt wall, which resulted in high influx of saline minerals. The degree of soil maturity in saline soils is based on the amount of accumulated salt, which indicates duration of surface exposure and pedogenesis (Reheis, 1987; Amit et al., 1993, Buck and Van Hoesen, 2002; Howell, 2009). A factor that may complicate interpretations of soil maturity is the rate of eolian or fluvial salt input, which can vary strongly with climate and proximity of the salt source (Buck et al., 2004). Variable precipitation resulting from climatic cyclicity can leach salts from the soil, effectively erasing previous soil development, or suppress the rate of salt input by affecting the source of the salts. For example, studies of Holocene diapirc systems in the Persian Gulf region suggest that a thick residuum with dense vegetation develops in more humid climates and covers the diapirc salt, inhibiting transport of salt or even saline waters into adjacent basins (Bruthans et al., 2000, 2008, 2009). In contrast, increased aridity results in more extensive salt diapir exposure in response to increased vegetation cover and only thin development or complete absence of a weathered diapirc mantle, or residuum (Bruthans et al., 2000, 2008, 2009). Such diapirs are easily eroded and thus provide abundant salt minerals into adjacent basins via eolian or fluvial transport, or in saline groundwaters. Thus, the degree of soil development based solely on accumulated salt morphology is not necessarily a valid indicator of sedimentation rate. Overall low paleosol maturity and the abundance of compound paleosols (e.g., Kraus, 1999; Kraus and Aslan, 1999) in the Carroza Formation suggest high sedimentation rates concomitant with diapirism, but more highly developed paleosols near the diapirc salt wall indicate either increased rates of input of evaporite minerals there and/or greater periods of time for soil formation along topographically elevated sites near the diapir where sedimentation rates were comparatively lower.

Carroza paleosols are also key indicators of Paleogene paleoclimate. The presence of calcic or petrocalcic horizons in paleosols is commonly interpreted to indicate arid or semiarid paleoclimates (Buck and Mack, 1995; Retallack, 2001). But in a gypsum-dominated system such as that of the Carroza Formation, carbonate soil development is prevented by the common-ion effect, which decreases the solubility of calcite, making it unavailable for precipitation (Reheis, 1997; McFadden et al., 1991; Buck and Van Hoesen, 2002). In addition, soils with abundant soluble salts and those in extremely arid and hyperarid climates commonly lack vegetation, resulting in lower bicarbonate availability, which further inhibits calcite formation (Rech et al., 2003; Amit et al., 2006). Therefore, recognition of evaporite-bearing paleosols is critical for paleoclimate interpretations, especially if carbonate paleosols are not present. Paleosols containing soluble salt accumulations have previously been under-recognized in the rock record (for exceptions, see Lawton and Buck, 2006; Rech et al., 2006). Important indicators of arid or hyperarid evaporite pedogenesis include stage 1 snowballs, diagnostic features of pedogenic gypsum or other sulfates, and columnar structure, formed only in the presence of Na+.

The stratigraphic distribution of paleosols indicates a significant shift in climate during the deposition of the Carroza Formation. The consistent and stratigraphically persistent presence of diapir-derived detritus, primarily mafic igneous clasts, in Paleogene strata indicates that the salt wall was exposed continuously during deposition of the Adjuntas, Viento, and Carroza formations. However, climate can greatly impact the degree to which evaporite minerals are transported into surrounding basins. Increased effective precipitation in Iran forms a thicker cover of weathered residuum on salt diapirs that limits dissolution and transport of soluble minerals into adjacent areas (Bruthans et al., 2000, 2008, 2009). Conversely, increased aridity limits vegetation, decreases residuum cover, and enhances transport of evaporite minerals into surrounding areas. We infer that the absence of evaporite paleosols in the Adjuntas, Viento, and lowermost Carroza formations reflects a more humid, yet still semiarid climate, in which residuum cover on the diapir limited evaporite mineral input into surrounding soils, and root respiration encouraged calcic paleosol development. Evaporitic paleosol types abruptly supplant the calcic paleosols ~20 m above the interfering contact between the Carroza and Viento formations and continue in abundance as the exclusive paleosols to the top of the Carroza Formation (Fig. 5). This stratigraphic shift in paleosol type near the onset of Carroza deposition records an abrupt increase in aridity that was likely induced by eastward retreat of the Paleogene shoreline and consequent reduction of maritime humidity. Attendant reduction of vegetation and thinning of residuum above the diapirc salt in turn led to significant increases in the input of saline dust and water into the Carroza minibasin. This combination of increased sulfate salts (i.e., common ion effect) and decreased vegetation inhibited calcic soil development. Vegetation and attendant calcic soil development could have been further suppressed by high exchangeable sodium derived from halite eroded from the diapir. In Holocene soils, few plants can tolerate soils that have high exchangeable sodium percentages because clay dispersion causes poor drainage (Reid et al., 1993; Brady and Weil, 2002).

Although suitable environments were available for development of evaporitic paleosols in the Adjuntas, Viento, and lowermost Carroza formations, evaporite soils are nevertheless absent from that stratigraphic interval. The progradation of facies from marine to increasingly continental deposits at the end of Viento deposition could have resulted from Laramide shortening and concomitant sediment influx, eustatic decline or reduced rates of subsidence; however, the presence of calcic rather than evaporitic paleosols in local red bed facies of the Viento Formation indicates that changing depositional environments alone did not cause the observed transition in paleosol type. A greater maritime
influence during deposition of the Viento and lower Carroza formations likely resulted in higher humidity and effective precipitation than prevailed during deposition of most of the Carroza Formation. Increased water availability could have resulted in thick residuum on the salt diapir, thereby inhibiting evaporite mineral transport into time-equivalent soils, increasing vegetation and driving calcic soil formation. Thus, we infer that the shift to evaporite paleosols in the lower Carroza marks a significant climatic shift to increased aridity.

To gauge the magnitude of this climate shift, we compared Carroza paleosols to Holocene evaporite paleosols. Modern salic horizons occur either in arid or hyperarid climates (<80 mm/yr) in which evaporation exceeds precipitation and results in upward wicking of soil water and precipitation of saline minerals near the surface; alternatively, seasonal downward movement of soil waters transports saline minerals to subsurface horizons (e.g., Abtahi, 1977; Amit et al., 2006; Howell, 2009) (Fig. 9). Salic horizons can also occur in semiarid climates (<450 mm/yr) in which high or perched saline water tables are present and evaporation wicks the saline water upward (e.g., Abtahi, 1977; Gumuzzio and Casas, 1988; Taimeh, 1992b; Reid et al., 1993; Buck et al., 2006). Carroza evaporite paleosols that contain both subsurface and surficial salic horizons (Fig. 9) most likely formed under climatic regimes spanning the range of hyperarid to semiarid.

Distinguishing high water tables in Holocene arid, saline landscapes can be problematic since many normal indicators of reducing conditions do not form in these environments (Boettinger, 1997; Buck et al., 2006). Similarly, Carroza evaporic paleosols rarely show unequivocal evidence of high or perched saline water tables. Textural contrasts in floodplain soils, the high degree of seasonality indicated by fluvial architecture and sedimentary structures, and clay dispersion caused by high Na+ contents (Abtahi, 1977; Brady and Weil, 2002) could have also induced temporarily high or perched saline water tables in Carroza paleoenvironments. Additionally, the preservation of both detrital and pedogenic gypsum indicates that, as a whole, the Carroza Formation has been an aquiclude since the Late Pleistocene. Holocene surficial paleosols that contain both subsurface and surficial salic horizons (Fig. 9) most likely formed under climatic regimes spanning the range of hyperarid to semiarid.

CONCLUSIONS

The Carroza Formation in the La Popa Basin consists of red sandstone and shale deposits in a salt-withdrawal minibasin occupied by an ephemeral braided-fluvial system that consisted of straight channels with intermittent supercritical flow. Flood events resulted in deposition of crevasse-splay sands across floodplains dominated by mud and silt. Channel stacking and thickness were enhanced in the hinge of a Laramide syncline, and channel orientation was roughly parallel to the minibasin axis with flow to the east. All deposits thinned toward the uplifted flank of the minibasin adjacent to a diapiric salt wall.

Exposed salt in the diapir provided a source of halite, gypsum, and barite that were incorporated in a remarkable assemblage of evaporitic paleosols previously unknown in pre-Paleogene strata. Paleosols include salic/natric, gypsic, and baric horizons. These paleosols contain important indicators of arid evaporite pedogenesis including stage I snowballs, diagnostic features of pedogenic gypsum and other sulfates, and columnar structure, formed only in the presence of Na+. Evaporitic soils increase in maturity toward the salt wall and hence record comparatively enhanced development on the diapiric salt wall. Calcic paleosols are restricted to the base of the Carroza Formation and red mudstone intervals within subjacent strata and record elevated maritime humidity and water availability that prevailed when the Paleogenne marine shoreline lay not far to the east. Increased aridity and supply of abundant sulfate from the diapir subsequently suppressed development of calcic soils through the common-ion effect and decreased bicarbonate availability.

The geographic and stratigraphic distribution of paleosols in the Carroza Formation records a strongly seasonal, dominantly arid or even hyperarid climatic regime, with possible transient excursions to wetter, semiarid conditions.
Evaporitic paleosols in continental strata of the Carroza Formation, La Popa Basin, Mexico: Record of Paleogene climate and salt tectonics

By analogy with studies of modern diapirs in Iran, aridity resulted in exposed salt or development of only a thin protective weathering residuum on the salt wall, permitting rapid diapir erosion and transport of abundant evaporite minerals into all depositional settings of the minibasin by eolian and fluvial processes. Local gleysed soil conditions, evidence for high water tables, and leaf fossils of plants requiring peren- gleyed soil conditions, evidence for high water tables, the latter supplied by intermittent over- topping of fluvial channels, were an important component of the depositional system.

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