Temporal evolution of a Playa Lake: the sedimentary record of Quiricó and Três Barras Formation (Sanfranciscana Basin, south-eastern Brazil)

Evolução temporal de um *Playa Lake*: o registro sedimentar das formações Quiricó e Três Barras (Bacia Sanfranciscana, sudeste do Brasil)

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ABSTRACT: Playa lakes are depositional environments developed in endorheic continental basins in which the hydric balance is normally negative. The sedimentary record of the formations Quiricó and Três Barras (Sanfranciscana Basin) suggest the transition from a playa lake to aeolian dune field. Detailed sedimentological analyses of 28.3 m thick sedimentary succession allowed distinguishing four stages of local depositional evolution. In the first stage the sedimentary environment was dominated by an inner saline mudflat, a flat area with high relief efflorescent salt crusts, which suggest a shallow groundwater table. The second stage consists in the record of expansion of a temporally perennial shallow lake, indicative of a wetter period. The record of the third stage consists in an outer saline mudflat, characterized by thin efflorescent salt crusts, which indicates the relatively deeper groundwater table, and a drier period. The fourth stage resembles an extremely dry environment, the playa lake disappeared and the aeolian dune field was constructed. The analysis suggest the progradation of an aeolian dune field over the playa lake environment, indicating a transitional period controlled by decrease of the water influx through the groundwater table, which produced a progressive increase in the availability of sand to aeolian dunes field construction.

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INTRODUCTION

Playa lakes may be defined as end members of closed drainage systems, located in lowland areas of continental basins (Briere 2000, Teller and Last 1990, Tunbridge 1984). These environments are developed under influence of semi-arid or arid climates and are strongly influenced by environmental moisture content, which varies according to the balance between water influx and outflux, induced respectively by surface and/or subsurface water flows and evaporative processes (Benison & Goldstein 2001, Bobst et al. 2001, Smoot 1983). Considering that the playa lakes are depositional environments composed of genetically linked subenvironments, Hardie et al. (1978) defined that in the shallow and wide sedimentary basins, setting in arid sub-tropical high pressure belts, the environments are composed of a salt pan surrounded by a saline mudflat, which, in turn, is bordered by aeolian dune field and ephemeral fluvial streams.

Although this depositional setting is common and easy to recognize in several present-day playa lake environments (Bobst et al. 2001, Hardie et al. 1978, Lokier 2012, Smoot & Castens-Seidell 1994), their sedimentary records are not so easy to identify, especially when the evaporite minerals are not preserved. Indeed, the saline mudflats are characterized by the wide diversity of efflorescent salt crusts, which may be partially or completely filled by clastic sediments (Smoot & Castens-Seidell 1994), producing a variety of sedimentary records (Goodall et al. 2000, Smoot & Castens-Seidell 1994).

In this article, we examined the transition from a playa lake to an aeolian dune field. The idea is to discuss the factors of control that were responsible for the paleoenvironmental transformation in this part of the Sanfranciscana Basin. This study may contribute to the recognition and interpretation of other ancient playa lakes.

Geological setting

The studied area occurs in the city of Presidente Olegário, in Minas Gerais State, southeast of Brazil. The sedimentary succession is part of the formations Quiricó and Três Barras, and it is composed of poorly cemented coarse-grained sandstone to mudstone; rare beds show calcite pseudomorphs after gypsum. These two units constitute part of the Sanfranciscana Basin, which is interpreted as a sag type basin (Campo & Dardenne 1997). The Sanfranciscana Basin is divided in two sub-basins (Abaeté & Urucuia sub-basins) (Fig. 1A). The tectonic evolution of this basin is related to the uplift of the Alto Paranaíba where isostatic adjustment creates the accommodation space on the Abaeté sub-basin (Hasui & Haralyi 1991). The Alto Paranaíba Uplift also constitutes the main source of clastic sediment to the Abaeté sub-basin (Sgarbi et al. 2001).

The analysed sedimentary succession is part of the Abaeté sub-basin (Fig. 1A), in which the sedimentary filling (~300 m thick) is constituted by deposits of Areado and Mata da Corda Groups; an angular unconformity separates the bottom of Areado Group from the Proterozoic Bambuí Group (Fig. 1B) (Fragoso et al. 2011, Sgarbi et al. 2001). The Areado Group is divided in three formations: from the bottom to the top, Abaeté, Quiricó and Três Barras Formation (Fig. 1C) (Campos and Dardenne 1997, Fragoso et al. 2011, Sgarbi et al. 2001). The Abaeté Formation occurs locally and it is composed of conglomerates, *breccias* and sandstones and it is interpreted as alluvial fan deposits. The Quiricó Formation is constituted of mudstones and subordinately sandstones, which are formed in playa lake systems (Sgarbi et al. 2001). The Três Barras Formation is formed of well-sorted sandstones deposited in an aeolian environment. This sedimentary succession is overlain by an Upper Cretaceous mafic/ultramafic volcano-clastic succession (Mata da Corda Group) (Fig. 2A).

Methods

The study area is illustrative of the change from playa lake to aeolian dune field paleoenvironment. A sedimentary section, 28.3 m thick, was measured and analyzed in detail (Fig. 2B). The sedimentary deposits were subdivided in facies associations, which are considered a group of facies genetically related (Walker 2006). The description of facies associations demanded the observation of lithology, sedimentary texture and structure (Reading & Levell 1996). Geometry of the beds and their bounding surfaces were described during the field activity. The deposits subdivided as facies association were interpreted comparing them with examples of the present-day depositional environments and using analogous from ancient and well-studied sedimentary succession.

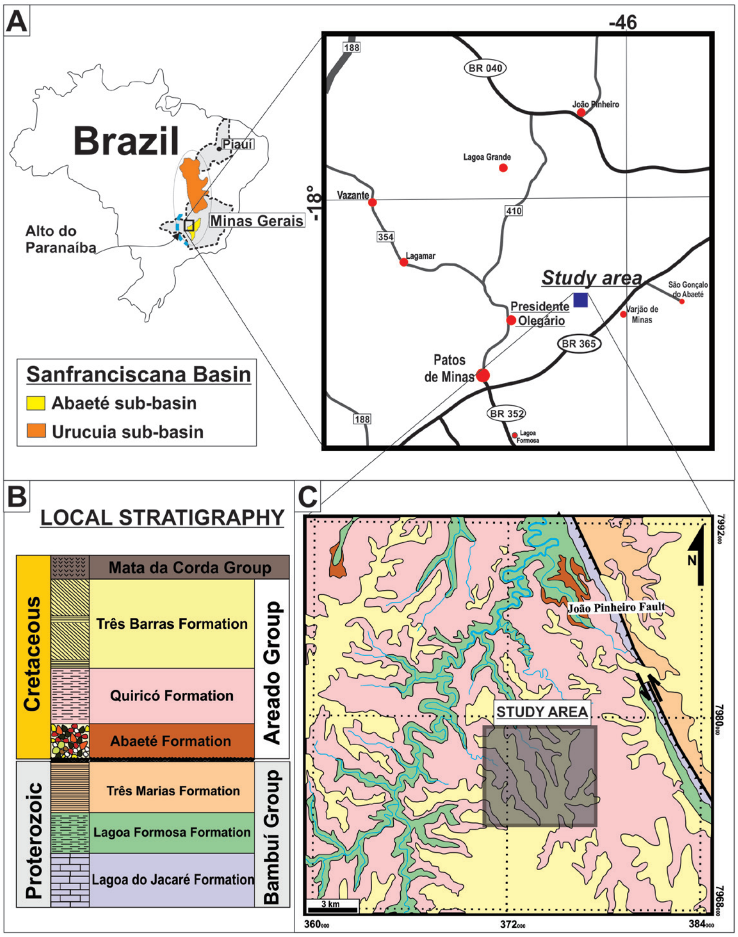

Figure 1. Geological setting and location of the study area. A) In the left side, look at the extension of Sanfranciscana Basin, which is divided in two sub-basin (Abaeté and Urucuia), and in the right side the geographical location of the study area. Stratigraphy of the study area and C) the geological map, that the study area is belong. Modified after Campos and Dardenne (1997), Sgarbi et al. (2001) and Fragoso et al. (2013)

Results: the facies associations

Six facies associations compose the studied stratigraphic interval (Fig. 2B). They are named as shallow lake, inner saline mudflat, outer saline mudflat, flooding deposits, small channel and aeolian dunes facies associations.

Shallow lake facies association

This facies association consists of claystone laminae alternated with muddy sandstone laminae (Fig. 3). The claystone laminae are red or yellowish-grey, 1 to 6 mm thick. The contacts in the base of the laminae are normal graded and are composed of fine-grained sand to clay, are pale-yellow, 3-8 mm thick (Fig. 3A). Ripple bedforms are common (Fig. 3B) and they form beds, 3-22 mm thick; in cross-section they show cross-laminations; in plan-view, they show rectilinear, flatted and bifurcate crests, normally covered by thin film of claystone (Fig. 3B). Sometimes interference ripples are observed in plain view. This facies association constitutes intervals up to 2.5 m thick, and are laterally extend more than 40 m. The bottom boundary is sharp, not erosive, planar to slightly undulating; they are interbedded with inner saline mudflat facies associations.

Interpretation

The general characteristics described in this facies association suggest deposition in shallow-lake with periods of stagnant conditions alternated with water flows. The subaqueous flows are probably associated with flood events, which introduced sediment to the lake system by underflows and decrease of flow velocity; depositing sand to clay by the mechanism of down flow (Abdul-Aziz et al. 2003, Armenteros et al. 1995, Paik and Kim 2006). Sandstone lenses observed in cross-section were formed by oscillatory movement, as well as the symmetrical to weakly asymmetrical ripples bedforms observed in plain-view. The cross-laminations were produced by combination of oscillatory and unidirectional flows. The clay films suggest period of stagnant water. The relative large extension combined with the small thickness of this facies association indicates large water bodies with long periods of stagnancy. The absence of evaporite deposits or pseudomorphs of evaporite minerals may suggest freshwater chemistry.

Inner saline mudflat facies association

This facies association is constituted of red or yellowish green, sandy mudstone beds with small sandstone lenses (Fig 4). These deposits consist of tabular beds, 0.20-3.4 m thick and laterally extended to more than 100 m. The sandy mudstones are poorly sorted deposits composed mostly of clay to fine-grained sand and in some beds medium-grained sand; the sand grains are

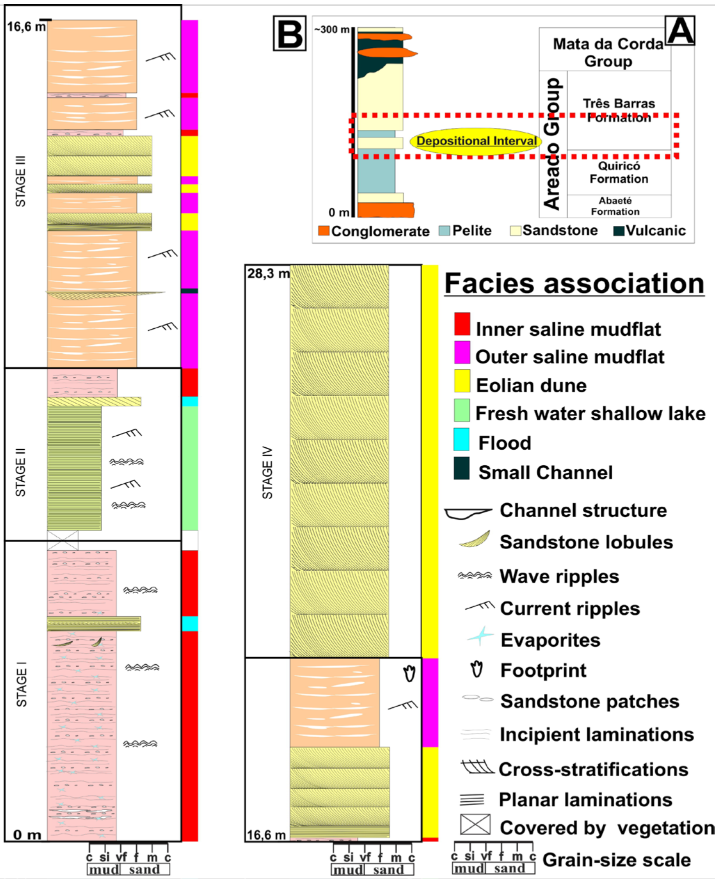

Figure 2. The sedimentary succession analysed and the four depositional stages described in this study. A) Regional correlation of the depositional interval analised in this study, which correspond to the transition of the Quiricó to Três Barras Formation, modified after Fragoso (2011). B) The drying upward sequence, which is representative stratigraphic section of the progradation of aeolian dune field on the playa lake palaeoenvironment

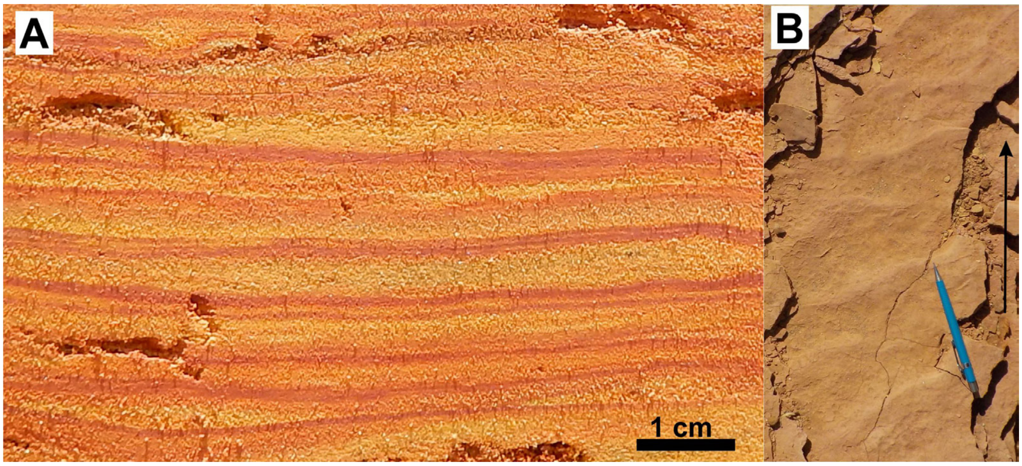

Figure 3. Shallow lake facies association. A) Planar-parallel laminae of interbedded muddy sandstone (yellow) and claystone (red). The laminae are slightly undulated. B) Sandstone layer with asymmetrical ripples in plain view showing rectilinear and bifurcate crests covered by clay. The arrow (right side) indicates the flow direction

angular to sub-rounded. Sedimentary structures are rarely observed in these beds; planar- or cross-laminations, and some rippled structures (Fig. 4A) are weakly preserved. Lenses composed of sandstones or claystones are common. The sandstone lenses are white or yellowish red and are composed of very fine- to medium-grained sand. The shapes of lenses are slightly spherical or elliptical. Spherical shape is 4-30 mm in diameter and elongated shape is 2-3.5 cm thick and 90-190 mm wide. In addition, plane to concave-up, 4 to 13 cm thick and 5-20 cm wide, medium-grained sandstone lenses with planar- and/or cross-laminations, were observed embedded in some beds (Fig. 4B). Although rare, ripple bedforms are preserved in some beds. Common feature observed in structureless sandy mudstone deposits are the intrasediment calcite pseudomorphs after gypsum (Fig. 4C). The crystals are preserved in two different ways: as displacive lenticular crystals of 2-4 cm high (Fig. 4C and D) or aggregates of millimeter scale (less than 2 mm). This facies association is dominant in the lower part of the sedimentary succession (Fig. 2B) and this occurs interstratified with shallow lake and outer saline mudflat facies association.

Interpretation

The poorly sorted and almost structureless deposits reflect a peculiar process of deposition, in which silt- to fine-grained sand was transported by wind and trapped by capillary adhesion on the high relief efflorescent salt crusts in the inner parts of the saline mudflat (Goodall et al. 2000, Smoot and Castens-Seidell 1994). The process of trapping creates a film of sediments on the crusts, which isolated it and inhibit the insolation, and by consequence, making the underlying saline crust be dissolved by the contact with the capillarity fringe (i.e., without evaporation the subsurface water may be unsaturated). New saline crusts grew above the film of sediment and the process continues until the next period of insolation loss (Smoot & Castens-Seidell 1994). The repetition of these processes produces a structureless sandy mudstone. Efflorescent salt crusts are rarely preserved in the sedimentary record by itself (Smoot & Castens-Seidell 1994, Lokier 2012). The small spherical or elongated lenses, were produced by deposition of sand on the irregular tops of high relieve efflorescent salt crusts. In the inner saline mudflats, efflorescent crusts are thick, with steep and narrow depressions. The distance to source-area is likely the main reason of the scant presence of sand deposits on the efflorescent salt crusts. The sandstone lenses with preserved planar- and cross-laminations embedded in sandy mudstone beds consists in the filling of hollows, which were produced by differential dissolution of the efflorescent salt crusts surface after flooding periods. The hollows were filled by sand sediments transported by ephemeral water flows (Goodall et al. 2000). Lenticular calcite pseudomorphs after gypsum and crystals aggregates were formed after deposition (Benison and Goldstein 2001, Eugster & Hardie 1975). Smoot & Castens-Seidell (1994) argument that displacive evaporites associated with deposits of poorly sorted and structureless sandy mudstone correspond to an important feature to recognition of deposits from inner saline mudflats.

Outer saline mudflat facies association

This facies association consists of red or purple muddy sandstones with white sandstone lenses, which is widespread (Fig. 5A). The muddy sandstones are poorly sorted and composed of clay to medium-grained sands. The sand grains are sub-rounded to well-rounded. The white lenses are well-sorted, fine- to medium-grained sandstones. They show different types, which may be divided into three different groups. (1) The most common type consists of small lenses (2-4 cm thick) that display cuspate and jagged edges with muddy sandstones (Fig. 5B), which occur as aggregates and shows a large variety of forms, similar to mottling aspect (Fig. 5A). (2) Another type is constituted of bowl-shaped lens and upturned edges (Fig. 5B and C), which are composed of well- to very well-rounded and well-sorted sandstones. The bowl-shaped lenses variates in dimensions and may be 1-3 cm thick and 6-46 cm wide, although the most are less than 10 cm wide and 2 cm thick. (3) The third type is composed of ripple lenses in vaguely layered and deformed aspect; sometimes they have hump-shaped crests (Fig. 5D). Other structures occur in this facies association; tepee-like structures are observed in sandstone beds. The crests are 0.4-0.5 m distant and 3-4 cm high (Fig. 5E). This facies association has sharp, but non-erosive contact with inner saline mudflat at the base of the succession. In the upper portion of the succession this facies association is alternated with aeolian dune facies association.

Interpretation

The muddy sandstones were formed by sediment trapping due to capillary adhesion on thin efflorescent salt crusts, followed by salt dissolution after loss of insolation and evaporation, and consecutive re-growth of efflorescent salt crusts. Thin efflorescent salt crusts are typical from outer parts of saline mudflats (Goodall et al. 2000). The small sandstone lenses with cuspate and jagged edges reflect the morphological features of thin efflorescent salt crusts that sometimes are characterized by irregularities with depressions and humps, which were nicknamed "popcorn surface" by Smoot and Castens-Seidell (1994). These surfaces, due to the proximity with the edges of saline mudflat, have their depressions completely filled by sand grains. Similarly, the bowl-shaped lenses reflect the shape of the polygons structures that are bordered by salt ridges, other common morphology from outer saline mud flat (Bobst et al. 2001, Goodall et al. 2000, Lokier et al. 2012). Some lenses show upturned edges, which suggest that the depression keeps growing in the same time that are filled by sand grains (Smoot & Castens-Seidell 1994). Probably, the greater volume of sandstones in this facies association results of the proximity with fluvial and aeolian systems. Rippled structures with hump-shaped crests correspond to ripples deformed by the growth of efflorescent salt crusts on the poorly sorted sandy mud (Goodall et al. 2000). The tepee-like structures are deformations, which reflect the development of large polygons on the depositional surface, typical from outer edges of saline mudflats (Smoot & Castens-Seidell 1994). The common interbedding with aeolian dunes facies association and the upward decrease of thickness of this facies association suggest the proximity and progressive progradation of the aeolian dune field.

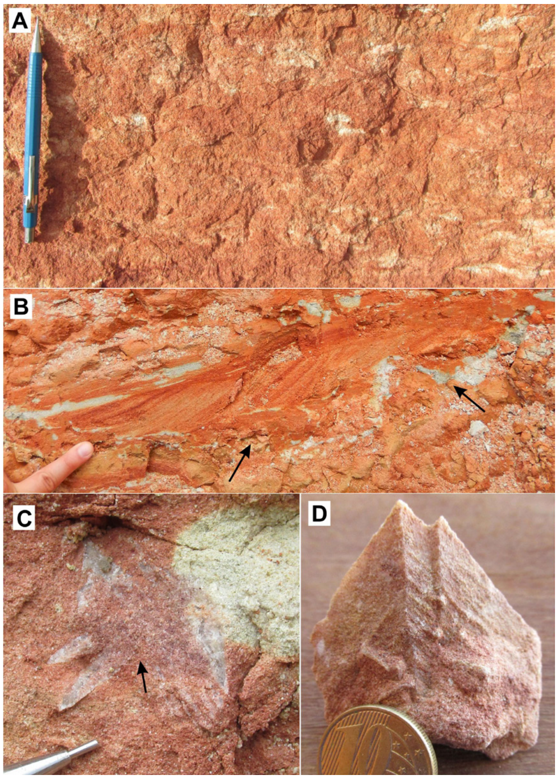

Figure 4. Inner saline mudflat deposits. A) Observe in this image the structureless feature of the inner saline mudflat facies association. Small lenses (white) in sandy mudstone bed (red). Observe the slightly preserved ripple bedform in the lower and right corner. B) The image shows sandstone lens with cross or low-angle laminations embedded in sandy mudstone, "lobate projections" from Goodall et al. (2000). C) Calcite pseudomorph after desert-rose gypsum (black arrow). D) Crystal of calcite pseudomorphs after gypsum

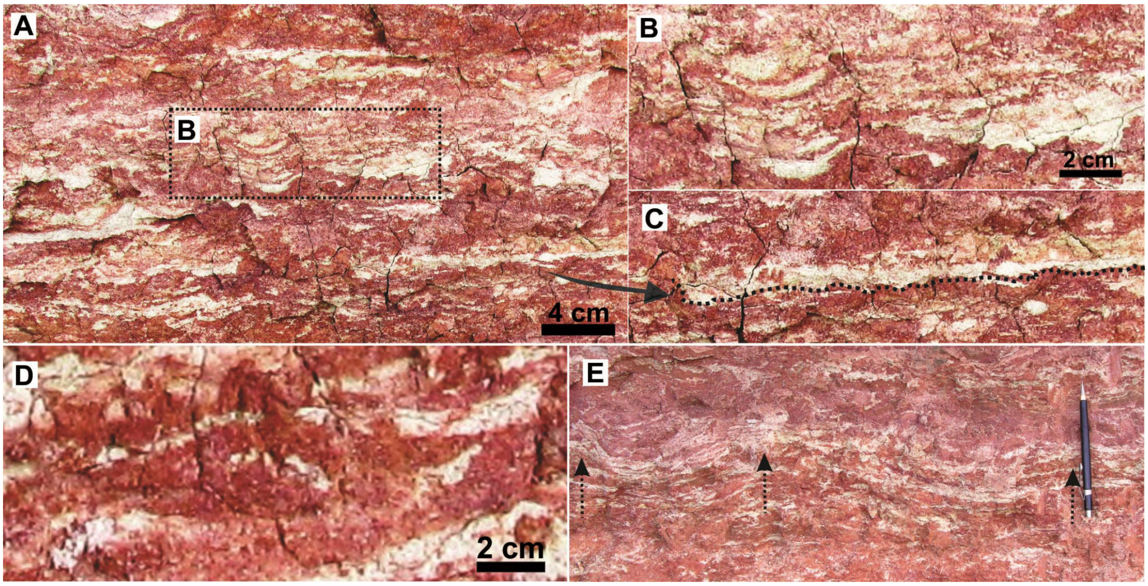

Figura 5. Outer saline mudflat deposits. A) Muddy sandstone (red to violet) with widespread sandstone lenses (white). B) Observe the bowl-shaped sandstone lenses with upturned edges (left side) and the lenses with jagged edges (right side). C) Detail to thin sandstone lens with jagged boundaries, feature imitative of "popcorn surface". D) Deformed ripple are also observed in some lenses. E) Observe the tepee-like structures. The arrows indicate the crests. (pencil: 140 mm)

Flooding deposit facies associations

This facies association is constituted of tabular beds with horizontal and erosive planar to slightly concave-up bottom, and planar top. The bed thickness varies from 11 to 30 cm and they are laterally continuous up to 20 m. Cross-stratifications (Fig. 6A) and planar laminations (Fig. 6B) are the main sedimentary structures that compose these beds. The cross-stratifications occur in single sets and are composed of fine- to medium-grained, angular to sub-rounded and moderately sorted sandstones. The foresets are planar in the basal contact and 17° dip (Fig. 6A). The beds with planar laminations are composed by very fine to fine-grained, angular to sub-rounded, well-sorted sandstones. The laminations are 1-3 mm thick, and characterised by the differences of grain-size and colour variations (Fig. 6B). Red to brown mudstone clasts, 15 mm large, are observed in the some beds. This facies association occasionally occur interbedded with inner saline mudflat and outer saline mudflat facies associations; its lower boundary is sharp and erosive, the top is sharp.

Interpretation

The features described in this facies association indicate deposition in flood event, where turbulent flows were responsible to generation of erosive scouring observed in the bottom contacts. The absence of channelized shape of the beds and the large lateral extension of the beds indicate unconfined or poorly confined flows. The cross-stratifications are interpreted as depositional record of bi-dimensional subaqueous dunes. Planar laminations suggest deposition in upper regime flow (Alexander et al. 2001, Bridge 2006, Fielding 2006).

Small-channels facies associations

This facies association consist of lenticular beds of sandstones, up to 2.5 m thick and 1.5 m wide in section perpendicular to the cross-stratification (Fig. 6C). The bottom is erosive and concave-up and the top is planar. Well-sorted, fine- to medium--grained sandstones filled this channelized form. Internally, various sets of low angle cross-stratifications were observed. This facies association is rare; it occurs embedded within outer saline mudflat facies association.

Interpretation

Concave-up with erosive bottom and planar top suggest ribbon-shaped channelized flows. Grain--size features and sedimentary structures indicate that these channels were filled by subaqueous and small dunes (Ramos et al. 1986). Isolated small channels are common to present-day saline mudflats, as described by Smoot and Castens--Seidell (1994) in the Saline Valley from California.

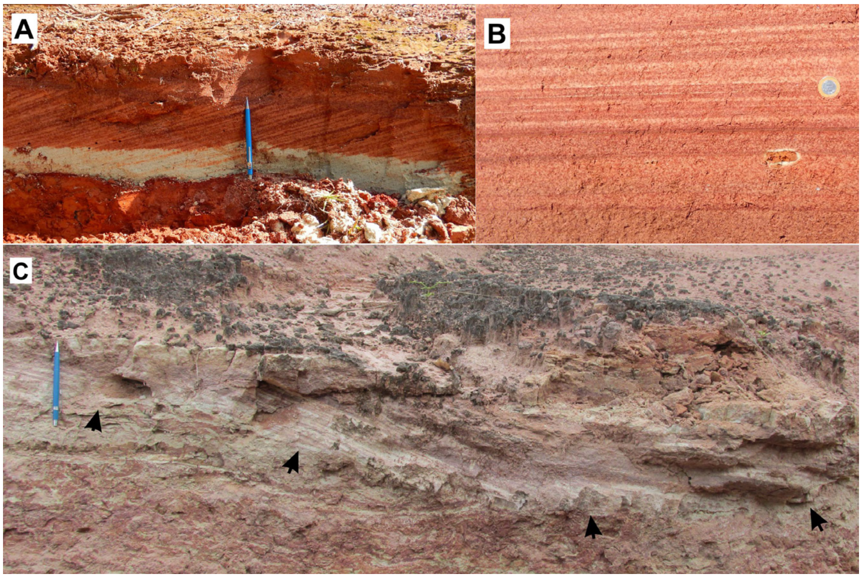

Figura 6. Subaqueous deposits. A) Sandstone bed with cross-stratification in angular basal contact. (Pencil: 14 cm). B) Sandstones bed with planar lamination. Observe the small mudstone clast. (Coin: 2 cm). Each lamination exhibits a lateral continuity of 0.1 to 0.6 m. (Pencil: 0.14 m). C) Channel structure isolated in sandy mudstone bed of outer saline mudflat facies association. The structure shows erosive concave-up base (arrows) and top planar filled of low angle cross-bedded sandstone

Aeolian dune facies association

This facies association consists of red to pale-yellow, very fine- to medium-grained sandstone, with well-sorting or bimodal sorting. Sets of planar cross-bedding (9-15° dip) may overlap one another in angular or tangential contact. Sometimes, sets of tangential cross-bedding overlap planar and parallel to low angle cross-lamination (Fig. 7). The sets are 0.1-1.2 m thick and its lateral extension may be more than 15 m. The cross-stratifications are composed of foresets of very fine-grained sandstone alternated with wedge-shaped medium-grained sandstone (i.e. bimodal sorting). In section perpendicular to the dip direction, the foresets are large trough sets with cross-bedding, 5-9 m wide and 0.6-1.2 m high, and <7° dip; in this case the boundaries are tangential. The contact with planar and parallel to low angle cross-laminations, which are 0.8-1 cm thick and more than 15 m large, are gently inclined (<6°). This facies association may occur intercalated with outer saline mudflats, and in this case they may occur intercalated with deformed laminations.

Interpretation

This facies association is interpreted as aeolian dune deposits. The very fine sandstone layers are interpreted as grain-fall strata whilst the medium-grained with wedge-shape as grain-flow strata (Hunter 1977). The alternation of grain-flow and sometimes grain-fall strata correspond to a typical product of migration of aeolian dunes (Kocurek and Dott 1981, Hunter 1977, Mountney 2006). The sandstones with trough cross-bedding correspond to sedimentary record of sinuous crested aeolian dunes. The planar and parallel to low angle cross-laminations correspond to subcritical climbing translatent strata produced by climbing wind ripple migration (Hunter 1977). The sets composed of sandstone with cross-bedding in gently inclined and tangential contact with planar and parallel to cross-laminated beds are interpreted as plinth dune deposits (Pye and Tsoar 2008). The cross-bedded sets intercalated with deformed ripples indicate alternation of periods of efflorescent crust formation (rise of groundwater table) and aeolian dunes. The association of this facies association with outer saline mudflat indicate decrease of local moisture.

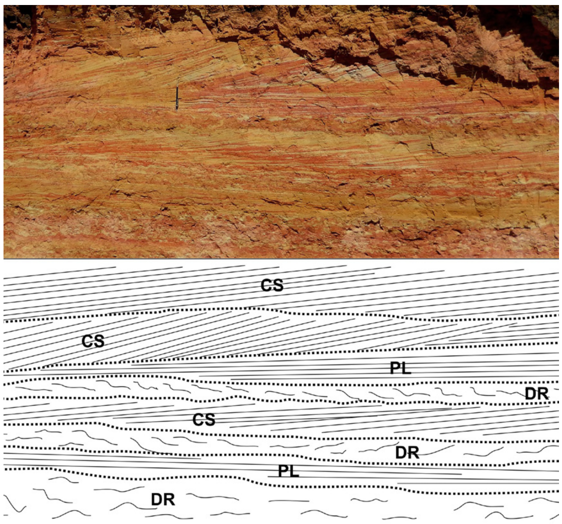

Figura 7. Sandstone beds with cross-strata (CR) separated by erosive surfaces (dotted line), sometimes intercalated with deformed ripples (DR) or planar laminations (PL). Deformed lamination are related with efflorescent salt crusts

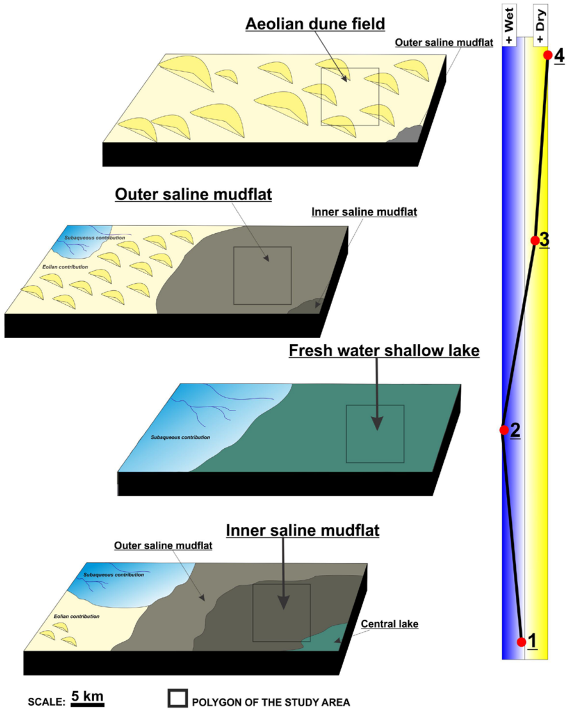

Figura 8. This picture represents a sequential development during the transition from Quiricó to Três Barras Formation, where occurred the progradation of the aeolian dune field on the playa lake. Observe the four stages of deposition and the relationship between subenvironments controlled by the water balance (wet to dry). From the lower to upper part, the environment is dominated by: (1) the inner saline mudflat, (2) shallow lake, (3) outer saline mudflat and (4) eolian dune field

Description of the sedimentary sequence

The analyzed sedimentary succession in the study area is stratigraphically positioned in the transition interval between Quiricó and Três Barras Formation and results from the superposition of aeolian dune field deposits over playa lake deposits (Fig. 2). The interval analyzed is divided in four stages that are characterized by peculiar facies associations (Fig. 8).

Stage I (21.3% of succession by thickness) - The first stage is mostly composed of inner saline mudflat facies association, which represent 95% of the stage. Within this stage, flooding deposits (5%) overlap inner saline mudflat facies association, in erosive and slightly planar bottom contact. The transition from stage I to stage II occurs when inner saline mudflat passes to shallow lake facies association, where the contact is abrupt, but not erosive.

Stage II (12.2% of succession by thickness) - This second stage is mainly constituted of shallow lake facies association, which represent 76.6% of the stage. The deposits of shallow lake consist of a 2 m thick tabular body that is observed for more than 1 km. An erosive and slightly horizontal surface separates this facies association of a thin bed of flooding deposits (5.5%). This facies association is overlapped by inner saline mudflat deposits, in sharp and non-erosive boundary. The limit of this stage consists in a non-erosive, irregular to slightly horizontal surface which separates the inner saline mudflat facies association of the outer saline mudflat facies association.

Stage III (38.7% of succession by thickness) - This third stage is mainly composed of outer saline mudflat facies association, which constitutes 65.9% of the stage. The contact that separates this stage of the lower (stage II) is slightly horizontal. In this stage, aeolian deposits (29.7%) are interbedded with outer saline mudflat facies association (Fig. 7); the aeolian deposits increase their thickness upward in the succession. The contacts are sharp, planar and erosive in the base of aeolian deposits. At the top of this stage, inner saline mudflat facies association (2.7%) is interbedded with outer saline mudflat. Locally, small channel facies association (1.7%) occur into outer saline mudflat facies association. This stage ends when the outer saline mudflat facies association is substituted by aeolian dune field facies association.

Stage IV (27.8% of succession by thickness) – This stage is totally composed of aeolian dune facies association. The boundary corresponds to an erosive and horizontal surface that may be observed for kilometers (Fig. 9). This stage is composed by aeolian dunes cross-strata without interdune deposits, at least locally.

Depositional environment

The sedimentation in the Sanfranciscana Basin took place under influence of arid climate (Sgarbi et al. 2001), in which minor variations in water balance can induced severe changes in the depositional environment. Temporal changes were demonstrated by the analysis of the local sedimentary succession, which were observed in the transition of a playa lake environment (*sensu* Eugster & Hardie 1975) to an aeolian dune field (Fig. 8). At least in the study area, this interval may be divided and interpreted as stages, which probably underwent climate changes that resulted in variations in the water balance, with associated decreasing in the salinity of the playa lake, and rising in the clastic availability to aeolian reworking.

Figure 9. Observe the boundary surface (dotted line) in the contact of deposits of the stage III and stage IV

The deposits analyzed in the first stage reveal that initially, at least in the study area, the sedimentation occurred within an inner saline mudflat. During this stage, the main control parameter was the height of the water table; the surface flows were rare and did not exerted great influence in the system. The main evidence in favor of the influence that groundwater flows were relevant consists in the fact that the inner saline mudflat subenvironment was characterized by the presence of thick efflorescent salt crusts (Goodall et al. 2000, Lokier 2012, Smoot & Castens-Seidell 1994). The relative thickness of the efflorescent salt crusts resulted of enrichment of the brine solutes from the edge to the center of the playa lake which combined with high evaporation rates, produced the ideal conditions to saturation of solutes and efflorescence of evaporite minerals. Other evidence of influence of the groundwater movement to the deposition consists in the presence of displacive or aggregate minerals, as calcite pseudomorphs after gypsum, preserved within structureless sandy mudstones (Benison and Goldstein 2001, Eugster and Hardie 1975, Rosen 1994). The rare presence and small thickness of flooding deposits demonstrate that the inner saline mudflat subenvironment was rarely crossed by sheet floods, attesting the episodic nature of subaqueous flows in the surface. The second stage is mainly constituted of shallow lake facies association, thus recording an increase of moisture produced by the increase of water input. Differently from what is observed in the first stage, in this case there was more surface runoff due to probable increase of the number of water springs, resulting in greater water supply, as evidenced by presence of ripples cross-laminations and planar laminations and non-observation of evidences related to the surface exposure. Another difference consists of the non-observation of evaporite minerals, which indicates an environment with water too fresh for the development of brines, which would be necessary for the precipitation of evaporite (Rosen 1994). This wet period finished when the playa lake changed into an inner saline mudflat again.

The onset of the third stage occurred in the contact of inner saline mudflat and outer saline mudflat facies association, which was geographically close to aeolian dune field and ephemeral fluvial systems. Because of this, the outer saline mudflat was susceptible to a bigger sediment input from the neighbor subenvironments. Outer saline mudflat has low relief efflorescent salt crusts, which allows distinguishing it from inner saline mudflat (Goodall et al. 2000, Lokier 2012, Smoot & Castens-Seidell 1994). The low relief of the saline crusts reveal groundwater table relatively deep and poor solute concentration (Smoot & Castens-Seidell 1994). The stage III constitutes evidence that the groundwater table rarely was deeper, given that, only few and thin beds of inner saline mudflat facies association were recognized. The upward increasing of the thickness of aeolian deposits, which are interbedded with outer saline mudflat, suggests progressive deepening of groundwater table and consequent increase of sand availability (Kocurek and Havhlom 1993). The subenvironment rarely was disturbed by surface runoff, since only small channels entered in the system.

The fourth stage recorded the definitive establishment of an aeolian dune field over the playa lake (Fig. 8). The progradation of aeolian dune field on the playa lake was possible because the water input decreased and created the necessary condition to aeolian construction. The increase of availability of sand was the main parameter responsible to aeolian dune construction (Kocurek & Havholm 1993). The preserved deposit of the stage IV corresponds to aeolian dunes facies association where interdunes are absent, which may be resulted from the probable combination of the extremely dry surface and a limited storage of sand materials.

Conclusions

The deposits of Quiricó and Três Barras Formation were sedimented during the Early Cretaceous in the Sanfranciscana Basin, where occurred the transition from a playa lake to aeolian dune field. The process of progradation of an aeolian dune field over a playa lake was the result of the progressive decrease of water influx, as demonstrated by the analyses of the 28.3 m thick sedimentary succession. The deposits analysed were divided in four stages, according to the dominant facies association.

The stages of paleoenvironmental evolution record possible climate changes. (1) In the first stage the inner saline mudflat, characterized by high relief efflorescent salt crust, was the dominant subenvironment, where the groundwater table was shallow and the brine concentration greater. (2) The second stage records a temporal increase in the water influx and consequent expansion of the shallow lake. (3) The third stage was dominated by an outer saline mudflat subenvironment characterised by thin efflorescent salt crusts, which indicate relatively deeper groundwater table and poor solute concentration. This subenvironment was sensitive to minor variations in water balance and more it a more susceptible subenvironment to the incursions of the aeolian dunes. (4) The fourth stage recorded a period in which the groundwater table stopped to feed the playa lake, leading to the disappearance of the playa lake and follow construction of aeolian dune field.

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RESUMO: Os *playa lakes* são ambientes deposicionais que se desenvolvem em bacias endorréicas continentais e de balanço hídrico negativo. O registro sedimentar das formações Quiricó e Três Barras (Bacia Sanfranciscana) sugerem uma transição de um ambiente de *playa lake* para um campo de dunas eólicas. Análises sedimentológicas detalhadas realizadas em uma sucessão sedimentar de 28,3 m de espessura levou ao reconhecimento de quatro estágios de evolução deposicional local. No primeiro estágio o ambiente sedimentar consistiu na parte interna de uma planície lamosa salina, uma área plana com crostas eflorescentes salinas de alta espessura, o que sugere que o lençol freático esteve alto. O segundo estágio consiste no registro de expansão de um lago raso perene, o que indica um período mais húmido. O registro do terceiro estágio indica que o ambiente era característico de uma área externa de uma planície lamosa salina, caracterizados por crostas eflorescentes salinas finas, o que indica um lençol freático relativamente profundo, e um clima mais seco. O quarto estágio indica um ambiente extremamente seco, onde o *playa lake* já não existia e somente um campo de dunas eólicas era construído. As análises sugerem a progradação de um campo de dunas eólicas sobre um *playa lake*, indicando um período de transição controlado pela diminuição da entrada de água através do lençol freático, o que produziu um aumento progressivo na disponibilidade de areia para a construção de um campo de dunas eólicas.

Palavras-Chave: *Playa lake*, planície lamosa salina, crostas eflorescentes salinas, campo de dunas eólicas, Bacia Sanfranciscana.