Tidal-dominated sandy coast: the Lagarto Formation, early Cambrian, Sergipe

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Abstract The Estância Domain is the most external lithotectonic domain of the Sergipano Belt. Amongst the six domains that form the Sergipano Belt, it is the only one that underwent minor tectonic deformation and metamorphism. Four lithostratigraphic units are recognized in the Estância Domain, from the bottom to the top: Juetê, Acauã, Lagarto and Palmares formations. We studied in detail a portion of 120 m of the Lagarto Formation sedimentary succession and successively extended our observation on 1500 m of the unit. We recognized six lithofacies that allow identifying the depositional system as a sandy tidal flat, protected by the wave activity for barrier island and/or positioned in narrow sea, as an embayment area, with the main axis NW directed. High frequency (with a period around 100y) tidal cycles generated sedimentary sequences from 3 to 100 cm m thick that allow identifying the basin as high subsiding. Age data of the youngest detrital zircon claim that the sedimentary input was from the Sergipano belt orogenic front. The sedimentary basin of the Lagarto Formation is conclusively identified as high subsiding basin, receiving high detrital input from the orogenic front and located in a tidal-dominated narrow sea. Taking into account these considerations, we propose that the Lagarto Formation represent the sedimentation in a peripheral foreland basin.

Keywords: Lagarto Formation, Tidal cycles, Sergipano belt.

INTRODUCTION The Estância Domain is the most external lithotectonic domain of the Sergipano Belt (Davison & Santos 1989). The Estância Domain is, amongst the six domains that form the Sergipano Belt, the one which underwent minor tectonic deformation and metamorphism. The strata dip up to 35°, prevalently with dip direction between NE and NW, and the low metamorphic grade did not modify the mineralogical and fabric features, allowing the perfect preservation of the sedimentary structures and making possible the interpretation of the depositional mechanisms.

Four lithostratigraphic units are recognized in the Estância Domain (Saes & Vilas Boas 1989, Santos *et al*. 1998), from the bottom to the top: Juetê, Acauã, Lagarto and Palmares formations. The thickness of the sedimentary succession making up the Estância Domain is not well constrained. D'el-Rey Silva (1999) suggests a thickness of 1-3 km, while Saes & Vilas Boas (1983) estimate a total thickness of about 3500 m. According to our preliminary field studies the thickness could be greater than estimated until now, probably more than 5 km. The Estância Domain filling is generally interpreted as a continental and coastal depositional environment, which began with alluvial fan (Juetê Formation), passes to a shallow carbonatic shelf (Acauã Formation), then to a tidal-dominated terrigenous coastal environment (Lagarto Formation) and finally to a coastal alluvial fan (fan-deltas) interbedded and covered by tidal generated sandstone (Palmares Formation) (Silva Filho *et al*. 1978, D'el-Rey Silva 1999).

The geodynamic origin of the sedimentary basin represented by the Estância Domain is still controversial. Silva Filho *et al.* (1978) suggest an origin linked to a passive margin basin (Juetê, Acauã and Lagarto formations) followed by a molasse basin (Palmares Formation); D'el-Rey Silva (1999) sustains that the Estância, Vaza Barris and Macururé domains constitute the filling of an extensional basin prior to the collisional phase that formed the Sergipano Belt.

The Lagarto Formation is the object of this work. Our main objective is to define the depositional aspects of this unit and to insert it in a logical sedimentary and geodynamic context, according to the data elaboration, obtained by the depositional mechanism analyses and the sequential development of the studied succession.

THE LAGARTO FORMATION General features We analyzed four sections of the Lagarto Formation with centimetric detail, located in small quarries, near Lagarto city. They have a limited vertical exposition (up to 15 m), but an excellent lateral and 3D vision of the sedimentary features and of architectural organization. Moreover, we analyzed other small outcrops in the area around, covering a stratigraphic interval in the Lagarto Formation of about 1500 m.

The four studied outcrops show similar lithological features (Fig. 1, 2, 3); in general, they are characterized by tabular or lenticular shape, fine or very fine sandstone, from few centimetres to 1.8 m thick, or by medium-fine sandstone, from 1 m to 4 m thick. The very fine or fine sandstone is frequently interbedded with reddish brown or greenish gray clayey siltstone. The petrographic features of the sandstone vary as a function of the grain size: fine and very fine sandstone are constituted prevalently by quartz and mica, while medium-fine sandstone is characterized by abundant lithic fragments, over quartz and feldspars. In all the cases the grains are subangular to subrounded.

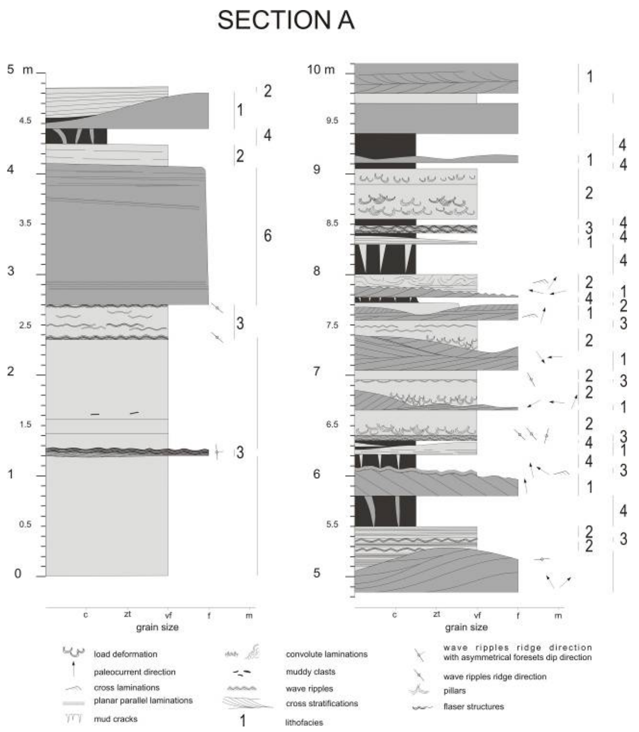

Figure. 1. Detailed section of the Lagarto Formation, near the locality Serrinha (outrocrop A). Numbers at the side of the section where the lithofacies is not labeled means that the outcrops does not allow an interpretation

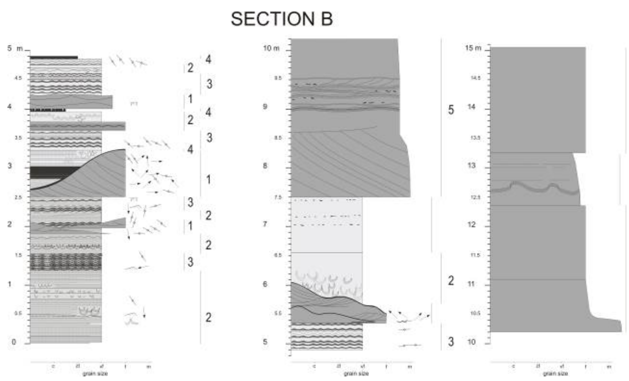

Figure 2. Detailed section of the Lagarto Formation, at locality Bueiro (outcrop B). Legend as in Figure 1

We measured and analyzed four sections, labeled from A to D. The alphabetic order of the four sections follows the stratigraphic order, being the section A the oldest. The four sections are distributed in a stratigraphic interval around 120 m thick: the section A is located in the lower part of the interval and the other three in the last 50 m.

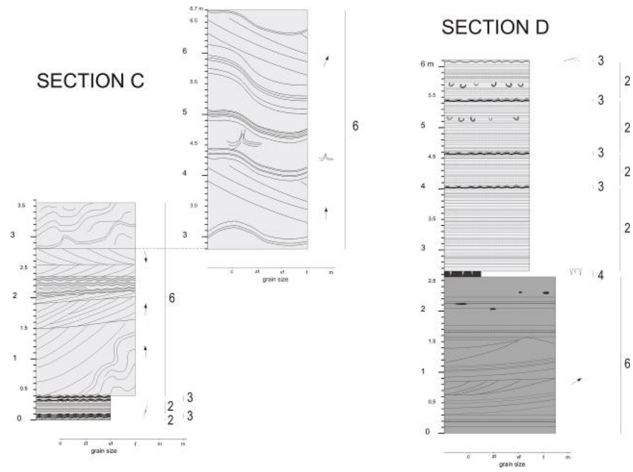

Figure 3. Detailed section of the outcrops C and D, at locality Bueiro. Legend as in Figure 1

Lithofacies descriptions In the four sections we recognized six lithofacies, labeled from 1 to 6.

Lithofacies 1 – fine sandstone planar-convex bedform trains. This lithofacies is constituted of well-sorted fine sandstone, forming planar-convex strata, 40-100 cm thick at the maximum, from 5 to 10 m long in the paleocurrent direction, and with a lateral spacing around 10-15 m (Fig. 4A). The bottom is sharp, but non erosive. This lithofacies is typical of the sections A and B (Fig. 1 and 2). The lithofacies 1 is organized in sets of tangential cross stratifications, from few to 50 cm thick, commonly showing reactivation surfaces. At times, the cross stratifications show sigmoidal shape, with lateral thickness variations of the foresets, that can be interpreted as tidal bundle structure (Yang & Nio 1985). Frequently, this lithofacies is formed by superimposed planar-convex bedforms, separated by few millimetres of clayey siltstone. The upper surface of this bedforms is modeled by wave ripples. The paleocurrent directions, pointed out by the foreset dipping, are in general unidirectional in a same bedform, but some foresets dipping diverge up to 150° from the main direction. Herringbone cross stratifications are also observed.

Lithofacies 2 – very fine sandstone with planar parallel laminations. Very sorted and very fine sandstone, showing faint planar parallel laminations, from 1 mm to 2 cm thick, characterizes this lithofacies (Fig. 4B). This lithofacies is diffused in all the studied sections. Silty sandstone laminae interrupt the vertical continuity of the planar parallel laminations. It is usual to observe that the planar parallel laminations are laterally deformed by post-depositional processes, forming convolute laminations, concentric load structures, bulb shaped, and sandy pillars. These lithofacies make up strata from a few centimetres to 50 cm thick, which have a lateral continuity limited to 10-15 m: commonly the planar parallel laminations onlap on the lithofacies 1.

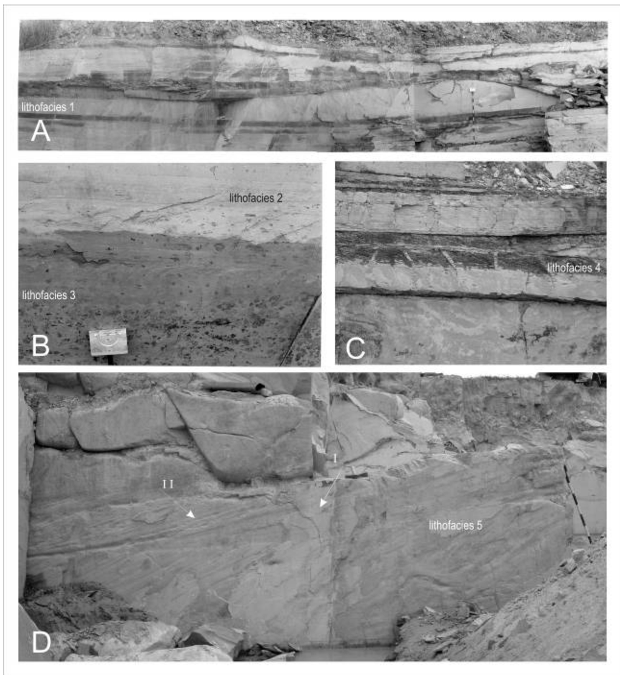

Fig. 4. Main lithofacies of the Lagarto Formation. A: lithofacies 1 is formed of planar-convex bedforms, representing sand waves (Hayes 1980), deposited in an intertidal sandy flat during the higher range tides. The Jacob's staff is 1.5 m. B: lithofacies 2 and 3 are frequently interbedded, testifying analogous depositional conditions. Lithofacies 2 is produced by weak tidal currents, while the lithofacies 3 by a weak wave reworking of the sandy bed during slacking water conditions. C: lithofacies 4 is a clayey siltstone frequently showing sandy filled mud cracks. It represents the moments of less depositional energy of the environment, with partial and temporarily emersion. D: lithofacies 5 is the coarser and thicker bed observed in Lagarto Formation. It is formed by large bedforms that probably migrated in a tidal channel in subtidal environment. The arrow I point out a reactivation surface on the cross stratifications; the arrow II small current ripples climbing on the foreset surface

Lithofacies 3 – very fine sandstone with wave ripples. The lithofacies 3 is made up of very fine sandstone organized in sets of wave ripples; it is diffused in all the sections. Both the ripple foresets are preserved in vertical superposition pointing out high sedimentation rate in oscillatory flows (Fig. 4B). On the bed surface the wave ripples show rectilinear and bifurcated crests; at times, the wave rippled surface is covered by a thin lamina of clayey siltstone with mud cracks. Flaser structures are also frequent. The thickness of this lithofacies varies from 2 cm to 30 cm.

Lithofacies 6 – medium-fine sandstone with planar or low angle dipping parallel laminations. *Lithofacies 4 – clayey siltstone*. The lithofacies 4 is constituted of reddish brown or greenish gray clayey siltstone (Fig. 4C). The thickness varies from a few millimetres to 30 cm. The clayey siltstone is massive. Its lateral continuity is limited to 10-20 m with frequent thickness variations. Mud cracks, filled of sandstone, are very frequent; they have a typical triangular shape in section, and commonly they are deformed by diagenetic strata compaction; different orders of mud cracks are observed on the bed surface. This lithofacies has tabular shape, but when it overlies the planar-convex bedform trains shows maximum thickness in the depression between a bedform and an other.

Lithofacies 5 – medium-fine sandstone with thick cross stratifications. The lithofacies 5 occurs in the section B and C (Fig. 2 and 4); it is formed by well sorted medium-fine sandstone characterized by medium scale cross stratifications from 20 to 110 cm (Fig. 4D). The thickness is more than 6 m and the lateral continuity longer than 30 m. The cross stratifications show tangential bottom, frequent reactivation surfaces (Fig. 4D), foresets dip in opposite direction with respect to the preferential direction and small current ripples climbing on the foreset surface (Fig. 4D). Postdepositional processes deformed the foresets, forming large scale convolute laminations and pillar structures. At times, sets of wave ripples are observed in this lithofacies.

Fine or medium-fine sandstone beds, 1 to 1.5 thick, with planar or low angle dipping laminations constitute the lithofacies 5. This lithofacies was observed only in the section A and D (Fig. 3). Isolated sets of trough cross bedding, up to 20 cm thick, occur in this lithofacies interbedded with the planar or low angle laminations.

The first four lithofacies are typical of all sections: they constituted most of the lithofacies of the sections A, B and C, and the first 40 cm of the section D. These lithofacies are often associated. The lithofacies 1 overlies indifferently the lithofacies 4 or 2 and less frequently the lithofacies 3. The lithofacies 1 is overlain commonly by the lithofacies 4 and 3. The lithofacies 2, 3 and 4 have shape adapted to the planar-convex form of the lithofacies 1. The lithofacies 5 and 6 are isolated, over- or underline the other four lithofacies, but do not appear to be interbedded with the last.

Paleocurrent data Data of the paleocurrents are extracted by three sedimentary structures: cross bedding, typical of the lithofacies 1 and 5; wave ripples crests from the lithofacies 3; cross laminations of asymmetrical wave ripples from the lithofacies 3. Each single bedform of the lithofacies 1 shows a preferential direction of the cross stratification foresets, nevertheless directions up to 120° from the preferential can be observed in the same bedform (Fig. 1 and 2). The global evaluation of the cross stratification data of the lithofacies 1 displays three main modes (Fig. 5A): two main modes, between N45 and N90, and one secondary towards N315; notices also a width distribution of the values around these main modes.

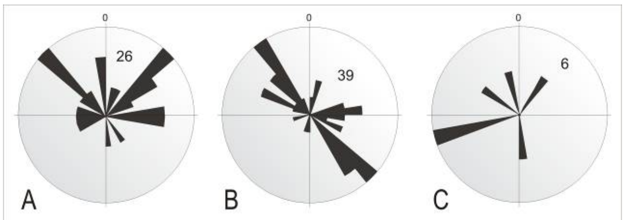

Figure 5. Rose diagrams of paleocurrent data from three sedimentary structures. The numbers correspond to numbers of measurements. A: Paleocurrent direction from cross stratifications in small-medium sand waves (lithofacies 1). Two close modes (N45 and N90) and a secondary mode (N315) are highlighted; the data dispersion is high although the paleocurrents are directed towards the north hemisphere. B: Axes of the wave ripples have a preferential orientation towards N320-140. These data can indicate an analogous alignment of the coastline. C: Paleocurrent data from cross laminations of asymmetrical wave ripples. These values are very dispersed

The cross stratifications observed in the lithofacies 5 (Fig.3) exhibit a principal paleocurrent direction towards north and a secondary towards south. The wave ripples crests display homogeneous data, pointing out a preferential crest axes directed N320-140 (Fig. 5B). It is interesting to observe that this value is perpendicular to main modes of the cross stratifications in lithofacies 1. Some wave ripples show asymmetrical pattern with preferential cross laminations. Few data have been possible to collect because of the unfavorable outcrop conditions; the values vary from N345 and N145, with a principal mode towards N250 (Fig. 5C).

INTERPRETATION OF THE DEPOSITIONAL MECHANISMS The lithofacies 1, 2, 3 and 4 are commonly associated, either in vertical or in horizontal sequences, suggesting they are part to the same portion of the depositional system. The four facies, in the listed order from the bottom to the top, make up a decrease of energy of the depositional processes, from fine sandstone to clayey siltstone sedimentation. The lithofacies 1 represents composite bedforms formed by the migration and superposition of 3D dunes, attributable to sand waves (Hayes, 1980). The direction of movement of the bedforms was variable, showing two preferential mode towards N45 and N90, a secondary towards N315; moreover, 3D dunes with high angle direction with respect to the main are frequent in a same sand wave bedform. The presence of flows with high angle direction with respect to the principal is testified also by the reactivation surfaces, produced by the erosional activity of the secondary flows. Constant variations of the flow energy are suggested by the tidal bundles formation. Hydraulic flows produced by tidal currents could be responsible for the building of these sand waves, justifying the cyclic energy and direction variability of the flows.

The very fine sandstone with faint planar parallel laminations of the lithofacies 2 could be attributed to sedimentation in plane bed phase in a very thin water lamina, probably produced by very weak tidal currents. It is often observed that these structures laterally are deformed by post-depositional events that produced convolute laminations, sandy pillars and concentric “bulb shape” load casts. Very fine sandstone has a low capacity to drain waters and the water pressure variations due to the water level oscillation, as in tidal environment, within or above the deposits can provoke the fluidification of the same.

Wave rippled very fine sandstone (lithofacies 3) are produced by oscillatory flows. Normally they display opposite foresets, nevertheless sometimes cross lamination with preferential foreset dipping (main mode N250) prevail, testifying a preferential direction of the water movement in oscillatory flow. This lithofacies points out to reworking of sediments on a very weak wave activity. Wave crests are parallel to the wave front, which in shallow water parallelize to the coast line. Thus, we can suppose that the main direction of the wave crest axis (N320-140) correspond to the main coastline direction.

The lithofacies 2 and 3 are frequently interbedded; both of them point out a phase of shallow water and very weak hydrodynamic energy conditions.

The clayey siltstone of the lithofacies 4 was deposited by settling from slack waters. The absence of laminae suggests that each bed was the consequence of a single depositional event. The lithofacies 4 is not continuous laterally, being thicker between a sand wave and the other, testifying that the settling of fine sediments occurred in small and often isolated puddles, during the low tide phase. Mud cracks are a clear sign of temporary and periodic emersion of the depositional area.

The lithofacies 5 and 6 are produced by greater energy processes of the depositional system, being characterized by medium-fine sandstone and larger sedimentary structures. The outcrop condition does not permit to discriminate the large bedforms that constituted the lithofacies 5, but probably they are associated to large 3D mesoforms (sand waves?). Depositional flows with variable energy and different migration are testified by cross stratifications with different foreset dimension and dipping (Fig. 3), reactivation surfaces (Fig. 4D) and wave ripples covering cross stratification foresets (Fig. 4D).

The poor outcrop quality of the lithofacies 6 in the sections A and D do not allow an adequate interpretation of the depositional processes; we suggest that the low angle or planar parallel lamination corresponds to plane bed laminae formed on a foreshore surface, and the small cross stratification in section D could represent a 3D dune of upper shoreface.

DEPOSITIONAL SYSTEM AND SEQUENCE DEVELOPMENT The data suggest that the sedimentary succession of the Lagarto Formation corresponds to coastal sediments controlled by tidal currents, and secondarily by wave motion.

Diagnostic criteria useful for the recognition of tidal depositional system can be identified in: tidal bundles, reactivation surfaces, bi- or polymodal paleocurrent distributions, herringbone structures, frequent vertical variations of the facies related to hydraulic variation (Nio & Yang 1991). The wave activity is testified by the lithofacies 2 and 6.

The narrow spatial relationship between the lithofacies 1, 2, 3, and 4 suggest they represent the same portion of the depositional system. The sedimentary structures point out shallow water or emerged sedimentary systems, which were characterized by frequent energy variations. Considering the tidal signatures, we can interpret the lithofacies association 1, 2, 3 and 4 as intertidal sand flat. Low wave action could be explained as consequence of high tidal range (meso or macrotidal influence), protected depositional area by barrier islands or embayment morphological conditions. The small wave ripples are produced in slacking water by frictional waves.

The lithofacies 5 and 6 are deposited in greater energy areas. The lithofacies 5 is produced by tidal activity, as variable energy and different migration depositional flows testify. It could be associated to great sand waves generated within a main tidal channel. Data are insufficient to interpret the depositional system of the lithofacies 6, which could belong to a little shoreface associated to a sandy spit.

We observed two different orders of sequential organization. The lower order is from 30 m to 2 m thick, it is constituted by the superposition of the lithofacies 1, 2, 3 and 4, generally in this order (Fig. 1 and 2). Not always this sequence is observed, at times, directly above the lithofacies 1, the lithofacies 4 is present. The sequence indicates a progressive decreasing of the tidal current influence. Taking into account that the described tidal bundles represent diary or monthly cyclic order, this tidal sequence should represent a greater time span, probably from one year to some decades (Allen 1993).

A sequential organization of upper order can be observed putting in vertical succession the sections from A to D. From the second half part of section B a change to greater energetic depositional conditions is observed (from an intertidal sandy flat to a subtidal channel). It is not clear if this vertical variation represents a general retrogradation of the depositional system or a more simple lateral variation of the depositional area, as a function of the tidal channel migration. In this stage of the study we opt for the last alternative, since the intertidal sandy flat crops out in all the measured section and the sandy spit shoreface is without a clear vertical distribution.

BASIN ANALYSIS CONSIDERATIONS The depositional area of the Lagarto Formation can be characterized as a sandy tidal flat, protected by the wave activity of barrier island and/or positioned in narrow sea, as a embayment area (Fig. 6). The Lagarto Formation is deposited above the carbonatic Acauã Formation or directly above the bedrock, represented by the São Francisco craton, which was emerged and without sedimentation processes.

The coastline could have had an alignment along the present NW direction (Fig. 6). The São Francisco Craton, located towards SW, should have constituted an emerged and stable area. The Sergipano collisional belt, probably also an emerged area, should have located far away from the studied area (towards the present NE**)** and separated by a depositional marine basin. Age data of the youngest detrital zircon (from very fine sandstone of lithofacies 2 and 3) is ~570 Ma (Oliveira *et al*. 2005), points out to a provenance from the Sergipano Belt, that is from NE. Present tidal flats, unconnected with deltas or estuaries, receive most of the detrital input from the ocean (Davis & Fitzgerald 2004); thus, we can deduce that the ocean was located towards NE, as the sandy input come from NE

The lower order sequence could represent a temporal span not greater than 100y, as it testifies cyclic variations of the tidal range greater than the neap-spring cycle. Each lower order cycle is 30-100 cm thick, suggesting a very high sedimentation rate. As the depositional features does not vary significantly, at least for 1500 m, we can extend these considerations to all portion of the Lagarto Formation. Thus, we conclude that this unit was characterized by high creation of space accommodation which keeps up with a high sedimentary input.

The sedimentary basin, where the Lagarto Formation deposited, is identified as a high subsiding basin, receiving high detrital input from the orogenic front, located in a tidal-dominated narrow sea (Fig. 6). Taking into account these considerations about the sedimentation rate, the paleomorphology of the basin and the contemporaneous presence of an orogenic front towards NE, we propose that the Lagarto Formation represent the sedimentation in a peripheral foreland basin (Miall 1995).

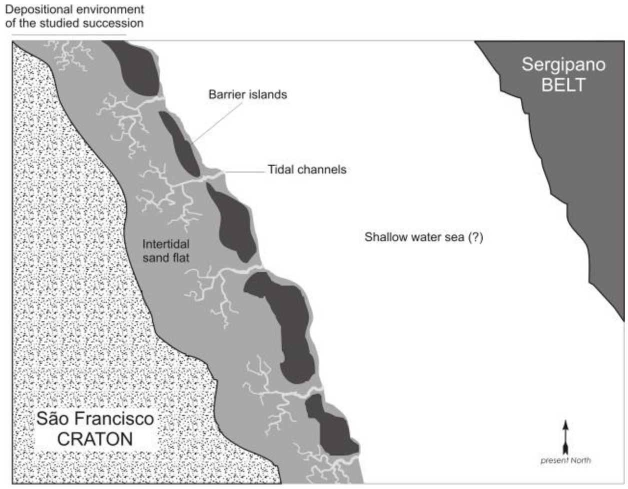

Figure 6. Schematic paleogeographic and paleodepositional reconstruction of the Lagarto Formation. The facies analysis suggests that the Lagarto Formation deposited in an intertidal flat protected by barrier islands and probably in a embayed sea. High values of sedimentation rate keep up with high space accommodation formation, thus the Lagarto Formation record, at least for 1500 m of sedimentary succession, the same depositional environment

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