Linking lacustrine cycles with syn-sedimentary tectonic episodes: an example from the Codó Formation (late Aptian), northeastern Brazil

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Abstract – The Codó Formation exposed in the eastern Grajaú Basin, northeastern Brazil, consists mostly of black shales, limestones and evaporites arranged into several shallowing-upward cycles formed by progradation of lake deposits. Three ranks of cycles are distinguished. The lower-rank cycles correspond to millimetric interbeddings of: bituminous black shales with evaporites, calcimudstones or peloidal wackestone–packstone; grey/green shale with calcimudstone, peloidal wackestone–packstone or ostracodal wackestone/grainstone; and ostracodal wackestone/grainstone and/or calcimudstones with cryptomicrobial mats and ooidal/pisoidal packstones. The intermediate-rank cycles average 1.7 m in thickness and are formed by complete and incomplete cycles. Complete cycles show a transition from central to intermediate and then to marginal facies associations and include two types: C1 cycle with central lake deposits consisting of evaporites and black shales; and C2 cycle with central lake deposits formed by grey/green shale. Complete cycles were produced by the upward gradation from central to marginal environments of the lake or saline pan–sabkha system. Incomplete cycles are those where at least one facies association is lacking, having been formed by successions either with central and intermediate facies associations (I1) or intermediate and marginal facies associations (I2). The higher-rank cycles are, on average, 5.2 m thick and consist of four depositional units that display shallowing-upward successions formed by complete and incomplete intermediate-rank cycles that vary their distribution upward in the section, and are bounded by sharp surfaces. While the lower-rank cycles display characteristics that reveal their seasonal signature, detailed sedimentological characterization and understanding of stratal stacking patterns related to the intermediate- and higher-rank cycles support a genesis linked to syn-sedimentary tectonic activity. This is particularly suggested by the high facies variability, limited lateral extension, and frequent and random thickness changes of the intermediate-rank cycles. Additionally, the four higher-rank cycles recognized in the Codó Formation match with stratigraphic zones having different styles of soft-sediment deformation structures attributed to seismic activities. Therefore, the several episodes of lake shallowing recorded in the Codó Formation are linked to seismic pulses that alternated with sediment deposition. This process would have created significant changes in the lake water level and resulted in sharply bounded successions with upward gradation from deeper to relatively shallower facies associations.

Keywords: lake system, cyclic sedimentation, evaporites, syn-sedimentary tectonics, late Aptian, Brazil.

1. Introduction

Shallowing-upward cycles are one of the most common characteristics of lacustrine successions, and many authors have related them to orbital forcing (e.g. Olsen, 1986; Glenn & Kelts, 1991; Olsen & Kent, 1996, 1999; Juhász *et al.* 1997; Vugt *et al.* 1998; Steenbrink *et al.* 2000; Hofman, Tourani & Gaupp, 2000; Aziz *et al.* 2000). Developments in the understanding of facies relationships and thickness consistency have also allowed lacustrine cycles to be related to tectonic pulses. However, only a few studies have clearly demonstrated the linkage between shallowing-upward cycles and tectonic activity (e.g. Martel & Gibling, 1991; Anadon *et al.* 1991).

The Codó Formation (late Aptian) exposed in several quarries along the eastern Grajaú Basin, northeastern Brazil (Fig. 1) is a lacustrine to saline pan/sabkha complex characterized by different ranks of shallowing-upward cycles. This unit, particularly well exposed in the Codó and Grajaú areas, consists chiefly of bituminous shales, evaporites and limestones, forming a succession up to 25 m thick. Internally, the Codó Formation displays several depositional cycles formed by episodes of upward shallowing. Although smaller-scale cycles are probably attributed to seasonal

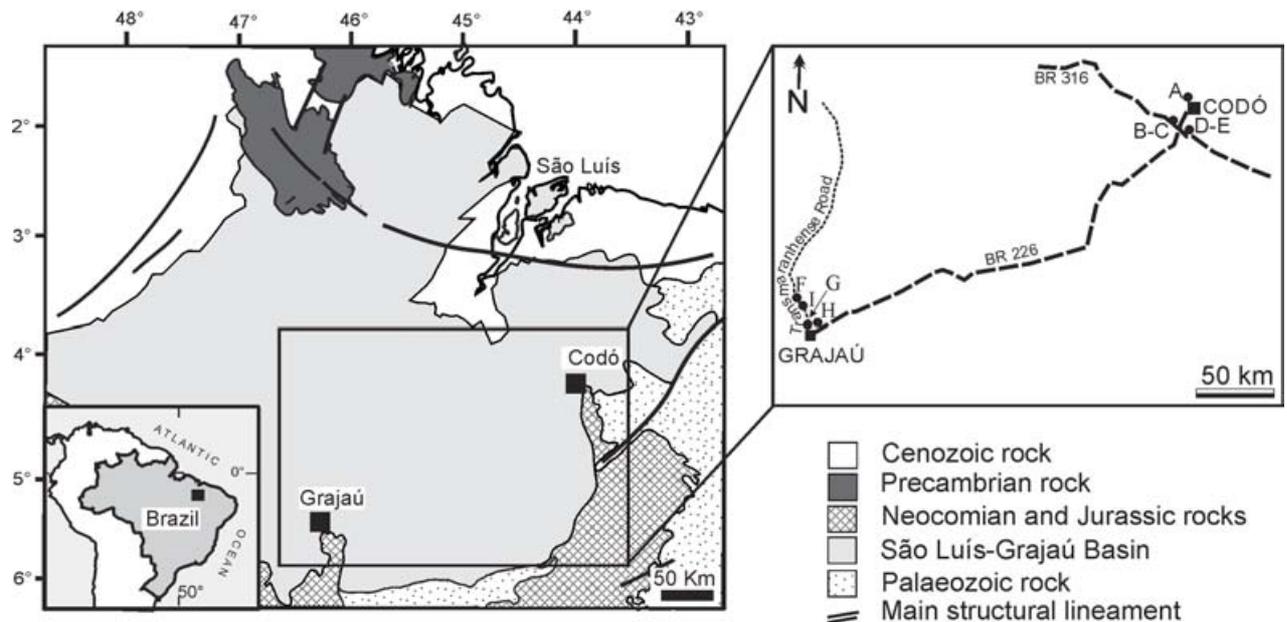† Author for correspondence: rossetti@dsr.inpe.br

Figure 1. Location map of the study area in the eastern and southern São Luís-Grajaú Basin, northern Brazil, with inset showing location within Brazil. The map on the right indicates the studied localities where the Codó Formation is well exposed in limestone and evaporite quarries. A – Santo Amaro; B–C – Itapicuru Evaporite Quarry; D–E – Itapicuru D-6 Limestone Quarry; F – Transmaranhense Road, km 22; G – Olho D'água Quarry; H – Chorado Quarry; I – Transmaranhense Road, km 16.

fluctuations, intermediate- and higher-rank cycles show features that do not appear to reflect climate influence. In this work we present a detailed sedimentological and stratigraphic analysis of the shallowing-upward cycles recognized in the Codó Formation, in order to demonstrate that their genesis is, at least in part, related to syn-sedimentary tectonic pulses.

2. Geological setting

The splitting apart of the African and South American continents led to the establishment of several rift basins along the equatorial Brazilian margin. The São Luís and Grajaú basins are expressions of this tectonic phase, occupying together more than 150 000 km^2. These basins are interpreted to represent a unique structural feature formed by the combination of pure shear stress and strike-slip deformation associated with an intracontinental rift (Góes & Rossetti, 2001). Fault displacement that (Fig. 2a, b) initiated during Aptian times resulted in the development of a shallow basin where the Codó Formation was deposited. During the main rifting in Albian times, fault offsets reached up to 400 m, culminating with the amplification of the rift system. Vertical to sub-vertical, normal and reverse faults cut through the entire sedimentary package, with some continuing downward into the crystalline and Palaeozoic basement. Three main fault trends can be distinguished (Fig. 2a): NE–SW, NW–SE and, less commonly, E–W (Rezende & Pamplona, 1970; R. P. Azevedo, unpub. Ph.D. thesis, Royal School of Mines Imperial College, London, 1991; C. A. P. Ferreira Jr,

unpub. M.Sc. thesis, Universidade Federal do Pará, Brazil, 1991). The latter is closely associated with the E–W-oriented Sobradinho Fault, which represents the continuity of the Romanche Transcurrent Zone (Pindell, 1985). E–W-oriented thrust faults with offsets of a few metres are present in outcrops located in the southern and eastern margins of the basin (Góes & Rossetti, 2001).

The Codó Formation records the late Aptian deposition of the São Luís-Grajaú Basin. Gamma-ray log correlation in this basin shows that the sedimentary record consists, from bottom to top, of three major, probably second-order (5–10 Ma: cf. Mitchum & Van Wagoner, 1991) depositional sequences bounded by regional discontinuity surfaces, interpreted as sequence boundaries (Rossetti, 2001; Fig. 3). The two lowermost sequences (S1 and S2) are Aptian to middle Albian in age, and show an internal tripartite organization into lowstand, transgressive and highstand systems tracts (Rossetti, 2001), as expected in a complete depositional sequence. The lowstand systems tracts of sequences S1 and S2 are composed of continental (fluvial, deltaic, eolian and lacustrine) deposits in the southern margin of the Grajaú Basin, which interfinger with shallow marine/estuarine deposits to the north in the São Luís Basin. In both sequences, the transgressive systems tracts are characterized by muddy lithologies with marine fossils that sharply cover the underlying sandier deposits, resulting in wedges that pinch out southward. Discontinuity surfaces marked by sharp lithological contrasts define the base and top of these successions and are interpreted as transgressive and maximum
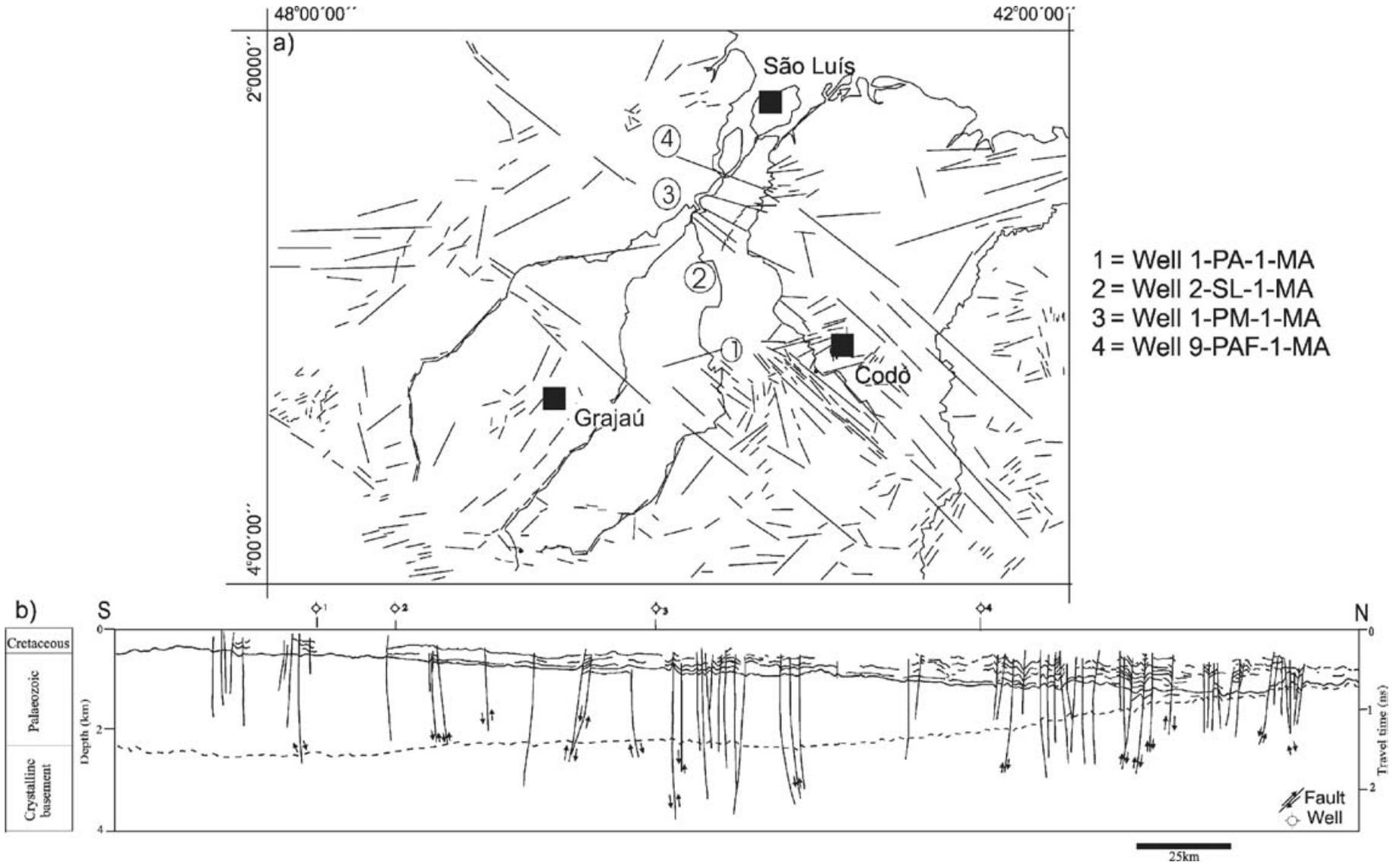
Figure 2. (a) Map displaying the structural lineaments of the São Luís-Grajaú Basin. Note the main NW–SE- and NE–SW-oriented fault traces, and the subordinate E–W lineaments, the latter representing the record of the strike-slip phase of the basin. (b) A geological section interpreted from a seismic line and the well logs indicated in (a), with the plot of the main fault traces. Note that these are vertical to nearly vertical and represent reactivations of faults derived from the crystalline and Palaeozoic basement. The faults cut through the entire basin, particularly disrupting the Cretaceous successions, attesting to rift development.

TECTONIC STAGE	AGE	DEPOSITIONAL SEQUENCE	STRATIGRAPHIC UNIT	
Drift	Plio-Pleistocene		Post-Barreiras sediments	
	Miocene		Barreiras Formation (II)	
			Barreiras Formation (I) ⌇	
	Early Tertiary?		⌇ Pirabas Formation	
	Late Cretaceous	Sequence S3	Itapecuru Group	Cujupe Formation
	Late Albian/ Cenomanian			Alcântara Formation
Rift	Late and middle Albian	Sequence S2		Undifferentiated unit
Pre-rift	Early Albian/ late Aptian	Sequence S1	Codó Formation ⌇	
			⌇ Grajaú Formation	

Figure 3. Stratigraphy of the São Luís-Grajaú Basin.

marine flooding surfaces, respectively (Rossetti, 2001). The highstand systems tracts are characterized by deposits displaying aggradational stratal patterns that grade upward into intervals with an overall prograding character, formed when the relative sea level started to decline at the end of the highstand stage. In contrast to sequences S1 and S2, sequence S3 does not show a tripartite internal organization but consists of several sharply bounded, fining- and then coarsening-upward successions. The two uppermost successions are partly exposed and record estuarine systems formed during the Late Cretaceous (Rossetti, 2001).

The Codó Formation correlates with the lowstand deposits of sequence S1 described above (Fig. 3). It is interesting to note that, in the southern margin of the basin, the Codó Formation contains a horizon marked by soft-sediment deformation sandwiched within entirely undisturbed deposits, which is attributed to syn-sedimentary seismic activity. Four zones of deformation have been recognized (Rossetti & Góes, 2000); these are briefly summarized here (Fig. 4) due to their close relationship with the shallowing-upward cycles discussed in this paper. They include: (1) zone Z1, with cracks filled by fine-grained calcite crystals, small-scale faults, fissures and stylolites inclined at a high angle to bedding; (2) zone Z2, represented by complex convolute folds associated with thrust faults, pseudonodules and mound-and-sag structures, the latter requiring alternating periods of deposition and sediment deformation; (3) zone Z3, which is associated with intraformational boulders up to 2.5 m long and consists of normal faults and fissures that are vertical to near vertical, present ragged morphologies with small, delicate edges, and taper both downward and upward after a few centimetres; and (4) zone Z4, characterized
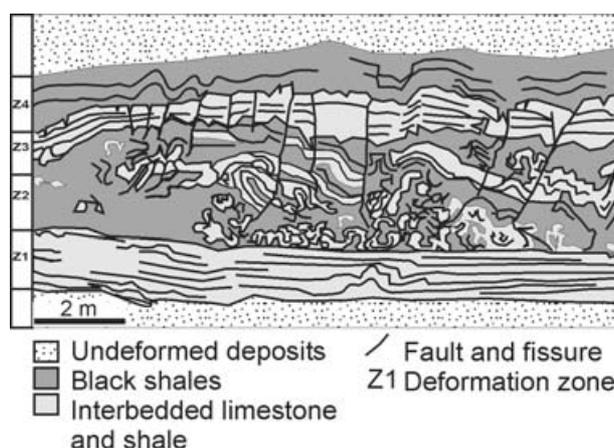

Figure 4. Exposure of the Codó Formation in a limestone quarry, near the town of Codó, eastern São Luís-Grajaú Basin, with indication of the syn-sedimentary soft sediment deformation zones formed by seismic activity as described the text.

by shales with irregular convolute folds. This vertical succession of deformation events was attributed to syn-sedimentary shear stresses associated with the early rifting that gave rise to the São Luís-Grajaú Basin. These syn-sedimentary seismic pulses seem to have had a strong influence on the evolution of the Codó lake and saline pan/sabkha complex and on the origin of its shallowing-upward cycles, as proposed in this paper.

3. Depositional environment

A detailed facies analysis of the Codó Formation was presented elsewhere (Paz & Rossetti, 2001; Rossetti, Paz & Góes, 2004). However, given its importance in
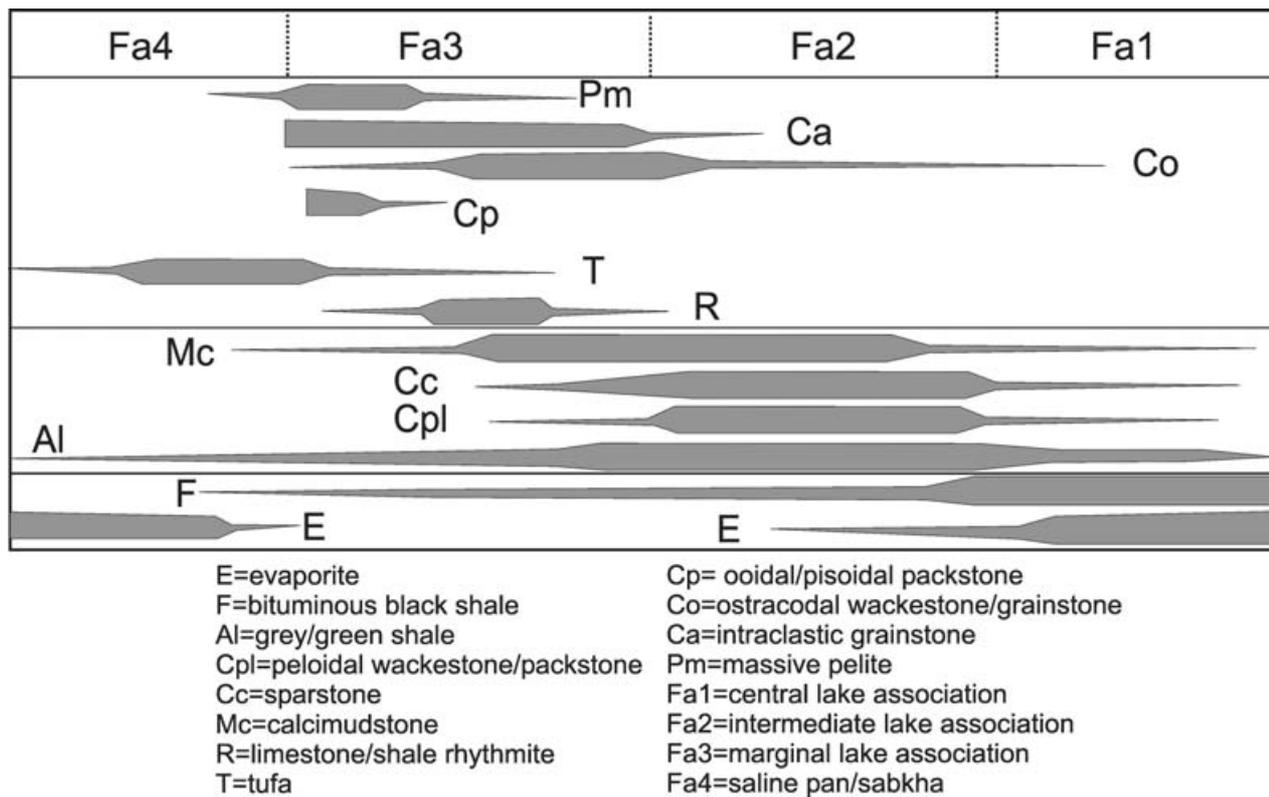
Figure 5. A summary of sedimentary facies described in the Codó Formation, with their distribution arranged according to facies associations Fa1 to Fa4, attributed to central, intermediate and marginal lake, as well as saline pan/sabkha environments, respectively.

providing a general overview of the depositional setting and defining the shallowing-upward cycles discussed here, the main descriptions and interpretations will be summarized in this section, together with some new information that helps to support the proposed palaeo-environmental model. The Codó Formation can be described in terms of four facies associations in the study areas (Fig. 5), which are attributed to central lake, intermediate lake, marginal lake and saline pan/ sabkha depositional environments. Ostracods, including two genera, *Harbinia* and *Candona*, are abundant throughout these deposits, occurring either dispersed or as thin (up to 10 cm thick) beds of shell middens. Disarticulated and articulated shells, including both young and adult individuals, are present, as are fresh-water *Charophytes* algae.

3.a. Central lake facies association (Fa1)

The central lake deposits (Fig. 6a, b) occur at the base of the shallowing-upward cycles, and consist mostly of bituminous black shale and evaporite (mostly gypsum). The bituminous black shale is the most frequent facies in this association, occurring as packages up to 3 m thick. It consists of bituminous shales (Fig. 6b) with total organic content up to 30 %, which contain plant remains, pyrite crystals that are as large as 0.5 cm, and lenses of native sulphur. Silt includes grains of quartz and feldspar, while clays are composed mostly of detrital (irregular, laminated flakes) smectite and, secondarily, kaolinite and illite. Bioturbation does not occur in this facies association.

The evaporite facies reaches up to 5 m in thickness and includes massive/macronodular (Fig. 6a) and, subordinately, laminated gypsum. Packages of gypsum up to 1 m thick showing well-developed horizontal lamination are locally present. The massive gypsum forms unstructured bodies intergraded with macro-nodular gypsum, the latter consisting of centimetre-sized gypsum nodules with or without a muddy matrix. The gypsum nodules display an almond-like form, defined by a web of undulating, horizontal to oblique fractures filled by bladed crystals up to 0.5 cm thick and with sutured contacts that grow perpendicularly to the fracture walls. Rosettes of dark gypsum up to 5 cm in diameter are common in this facies. The massive/ macrogranular gypsum is in sharp contact with the laminated gypsum, locally forming diapirs several metres long. The latter comprises laterally continuous, horizontally laminated, alternating dark/light beds that vary from a few millimetres up to 10 cm thick. The dark beds are formed by either crystals or micronodules of gypsum less than 0.5 cm long distributed within a matrix of black shale, while the light beds consist of upward-oriented chevron gypsum crystals.
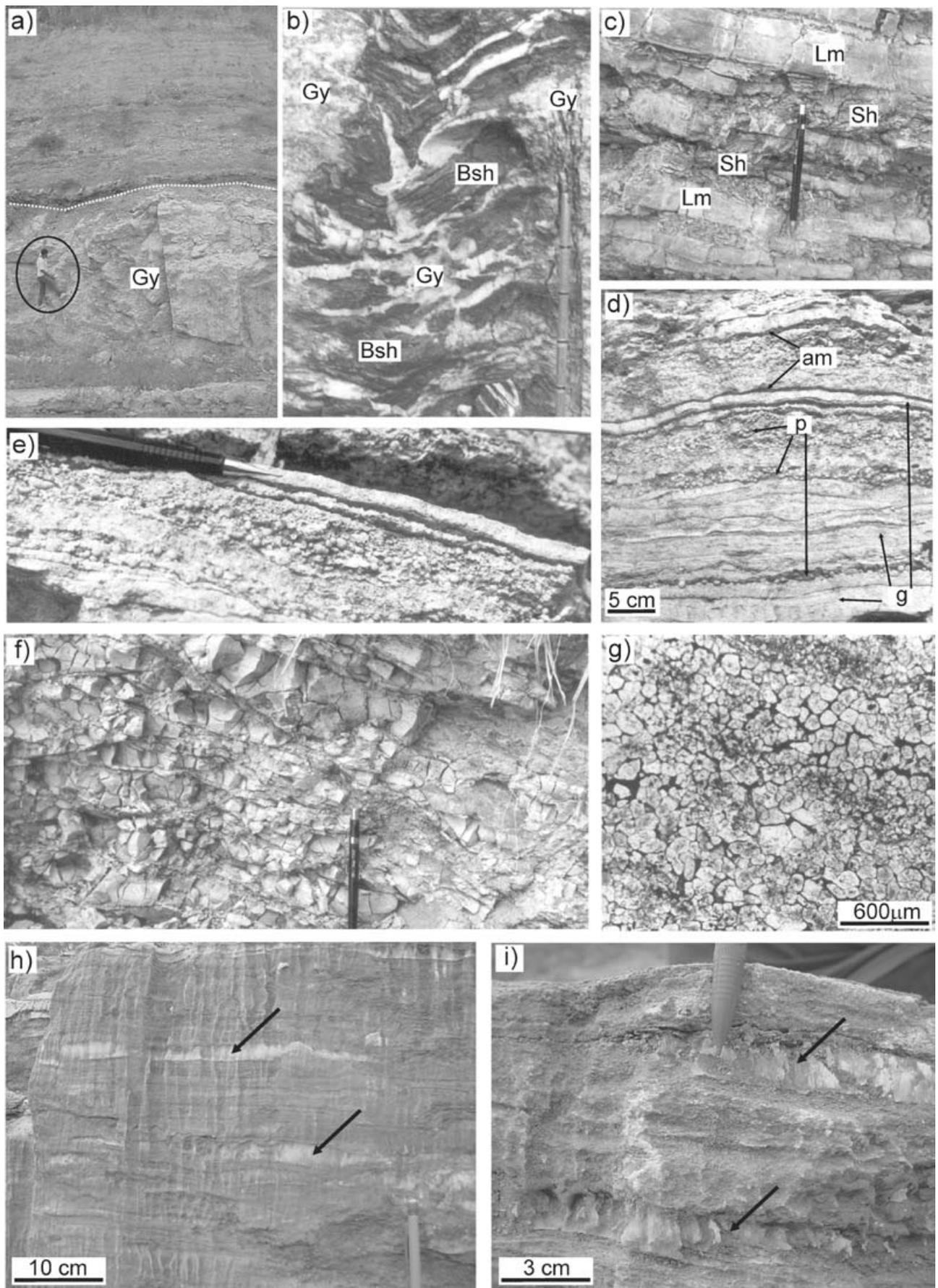
Figure 6. For caption see facing page.

3.b. Transitional lake facies association (Fa2)

The transitional facies association (Fig. 6c) consists of interbedded grey/green shale and limestones. Bioturbation is locally present, as are symmetrical ripple marks at the top of some limestone beds. The grey/green shale is the dominant facies in this association and is particularly well developed in the Grajaú area, where it reaches up to 4 m thick. The total organic content of this facies is much lower than in the black shale, reaching up to only 1 %. Films of gypsum or calcite as acicular or fibrous, vertically aligned crystals, are locally present on bedding planes.

The limestones can be described in terms of three facies: calcimudstone, peloidal wackestone–packstone and sparstone. The calcimudstone is the dominant limestone facies in this association. It consists of microcrystalline calcite, locally silicified to chalcedony, which occurs as laterally continuous, either laminated or massive beds up to 15 cm thick. Grains of quartz and mica (mostly muscovite) occur dispersed or parallel to bedding planes. The peloidal wackestone–packstone facies forms beds up to 20 cm thick, characterized by well-sorted, rounded to sub-rounded, spherical to oblate peloids within a micrite matrix. Disarticulated ostracod shells and microspherules are frequently present, reaching up to 15 % of the allochemical grains. This facies is commonly parallel laminated and, less commonly, massive. Films of microbial mats might be present, paralleling bedding planes. The sparstone facies (cf. Wright, 1992) consists exclusively of calcite crystals ranging in size from 250 to 500 μm and displaying sutured contacts, arranged as a blocky mosaic.

3.c. Marginal lake facies association (Fa3)

The marginal lake facies association (Fig. 6d–g) occurs at the top of the shallowing-upward cycles and comprises a variety of intergrading lithofacies, including pelite, intraclastic grainstone, ostracodal wackestone to grainstone, ooidal/pisoidal packstone, rhythmite (Fig. 6d, e), tufa and sandstone. Wave-ripple marks are commonly observed within this facies association, and gypsum occurs locally as discontinuous laminae. Bioturbation is generally absent, although a few undetermined tiny traces were locally observed.

The pelite facies is indurated, massive, and displays a blocky fabric (Fig. 6f). Its colour varies upward from olive-green to brownish-red. The intraclastic grainstone (Fig. 6g) consists of well-sorted and well-rounded, fine- to coarse-grained calcite grains. This facies forms structureless and, less commonly, tabular and sigmoidal cross-stratified beds that are up to 20 cm thick. Millimetre- to centimetre-long lensoid cavities (fenestrae), locally filled by mosaics of sparite, are typical of this facies, as are microkarstic structures, and vadose meniscate calcite cement. Ostracodal wackestone to grainstone occurs as beds or concretions up to 15 cm thick, the latter typically displaying articulated shells with a mixture of young and adult individuals. Ooidal/pisoidal packstone consists of coalescing, well-rounded or elongated ooids and pisoids (diameter < 5 mm) displaying internal botryoidal or fibrous radial fabric. This facies forms layers up to 5 cm thick, which are laterally continuous for the entire extension of the exposures (at least hundreds of metres). Rounded to slightly elongated fenestrae are abundant in this facies. The tufa facies is a highly porous limestone with sparry calcite filaments arranged into a dendritic web. Rounded calcite grains less than 200 μm in diameter occur encrusting the branches. Rhythmite occurs as packages 10–20 cm thick of thinly (millimetre-scale) laminated, ostracodal wackestone–grainstone, shale, and less commonly, siltstone beds. Fish remains are frequent in this facies. Cryptomicrobial mats are abundant in association with ooidal/pisoidal packstone and rhythmites, being recognized in the field as black, corrugated films parallel to bedding planes.

The sandstone facies is structureless and occurs only locally as lenses up to 0.5 m thick, being represented by moderately sorted, well-rounded, fine quartz grains.

3.d. Saline pan/sabkha facies association (Fa4)

This facies association is up to 6 m thick, and is mostly present in the Grajaú area, where it occurs between lacustrine deposits. This is an evaporite-dominated association composed of laminated gypsum, gypsarenite, and secondarily tufa, grey/green shale, and calcimudstone. The three last facies will not be described here, as they have the same characteristics described in previous facies associations. Tufa is found

Figure 6. Sedimentary facies representative of the Codó Formation in the study area. (a, b) Central lake deposits, with massive macronodular evaporites 'Gy' and bituminous black shales 'Bsh' within evaporites. The hatched line in (a) indicates the top of the evaporite beds. The deposits overlying this surface consists of limestone and grey/green shale interbeddings, attributed to transitional lake settings. Person for scale is 1.6 m tall; rod subdivision in (b) is 10 cm. (c) Transitional lake deposits, consisting of limestone 'Lm' and grey/green shale 'Sh' interbeddings. Pen is 15 cm long. (d–g) Marginal lake deposits, illustrating: rhythmites of ooidal/peloidal packstone 'p' and ostracodal wackestone–grainstone 'g' with cryptomicrobial mats 'am' in (d); a detail of the ooidal/peloidal packstone in (e); fractured massive pelite in (f); and photomicrography of intraclastic grainstone in (g). Pen for scale in (e) and (f) is 15 cm long. (h, i) Saline pan/sabkha deposits, showing the laminated gypsum (arrows indicate laminae of gypsum formed by vertical aligned crystals replaced by satin spar gypsum). Note in (h) the cycles formed by darker/lighter couplets, which consist of microgranular gypsum/vertical aligned gypsum, respectively, attributed to seasonal fluctuations.

much more in this facies association than in the marginal lake deposits, occurring as beds up to 5 cm thick that disappear laterally within a few metres. A typical feature of this facies association is the preservation of primary horizontal lamination.

The laminated gypsum (Fig. 6h, i) consists of horizontal beds typically formed by alternating darker and lighter couplets that become progressively thicker upward, varying from a few millimetres to 30 cm. The darker beds consist of either crystals or micronodules of gypsum, in general less than 5 mm long, which occur within a matrix of dark mud. The lighter gypsum consists of upward-oriented crystals displaying aligned twin planes and superimposed well-defined faces in a zig-zag arrangement, perpendicular to the crystal long axis (chevron gypsum); this gypsum intergrades with acicular and fibrous (satin spar) gypsum.

The gypsarenite is interbedded with the laminated gypsum, and forms layers a few centimetres thick of moderate to poorly sorted, rounded to sub-rounded gypsum grains varying from very coarse to pebbly in size. Calcite cement is common. This facies increases in frequency upward in this association. Shallow (< 2 mm deep) potholes averaging 3 cm in diameter and with ragged concave-up shapes completely filled up by layers of growth-aligned gypsum crystals, are present at the top of some gypsarenite beds. A film of yellow to light brownish calciferous clay is settled out on the bottom of these structures.

3.e. Interpretation

Although displaying similar lithologies, a comparison of the sedimentary features and facies architecture between the Grajaú and Codó areas reveals some basic differences in their depositional systems. Hence, the Codó area displays deposits formed in comparatively more stable, well-stratified lakes with significant periods of anoxia and closure, when evaporites were formed almost exclusively in deeper, central areas. Facies analysis, added to the abundance of continental ostracods and *Charophyte* algae, as well as the absence of any marine fauna, led us to attribute these deposits to a dominantly lacustrine system. The abundance of shales in the central lake deposits shows a low-energy depositional setting. Pyrite, bitumen, well-preserved fossils (ostracods and fishes) and the almost complete lack of bioturbation support anoxic conditions. Under such circumstances, the preservation of large amounts of organic matter is favoured, being derived from organisms living in upper, more oxygenated water layers (Trewin, 1986; Martill, 1988).

The transitional lake facies association is characterized by its position between central and marginal lake facies associations. The abundance of fine-grained deposits, recorded by calcimudstones and grey/green shales, is consistent with a low-energy environment with dominance of mud deposition below

wave base (e.g. Specht & Brenner, 1979; Shinn *et al.* 1989). In this sense, this association resembles central lake deposits, but the lighter colour (suggesting less preservation of organic matter and absence of bitumen), local bioturbated horizons, symmetrical ripple marks, and disarticulated ostracod shells, all support a shallower environment relative to the central lake association, with more oxygenated waters and wave action.

The marginal lake facies association was recognized by its position at the top of the shallowing-upward cycles and by the abundance of sedimentary features attributed to subaerial and/or meteoric exposure, such as palaeosol (recorded by the massive pelite), micro-karstic surface, fenestrae and meteoric cement. The presence of coalescing pisoids of variable sizes and elongated shapes that are associated with microbial mats suggests stagnant, shallow-water conditions and/or even subaerially exposed environments (e.g. Risacher & Eugster, 1979; Chafetz & Butler, 1980; Schreiber, Smith & Schreiber, 1981; Tucker & Wright, 1990). Under such conditions, microbes lead to *in situ* formation of pisoids (cf. Ferguson, Bubela & Davies, 1978), an interpretation favoured in the study area due to the close association of pisoids and microbial mats. Fenestrae support formation close to the vadose zone. The concretions of ostracodal wackestone–packstone associated with these deposits might have resulted from microbial influence (Raiswell, 1976) combined with anisotropic permeability, since the concretions occur within more permeable limestone/shale rhythmite that overlies less permeable shales. The local occurrence of sandstone facies in this association is probably related to episodic influx of sands through small deltas during rain episodes.

In contrast to the Codó area, much more ephemeral conditions apparently prevailed in the Grajaú area, which presents better-oxygenated water pans with evaporite precipitation only in their margins and along the surrounding mudflats, forming a saline pan/sabkha complex. This depositional setting displays widespread pans and evaporitic flats, the first being restricted to more depressed areas of the system. The depositional setting recorded in the Grajaú area might have been crucial in controlling the distribution of the evaporite deposits. A saline pan/sabkha facies association is indicated by evaporite precipitation in a very shallow subaqueous environment that was interrupted by periodic exposure. The thin beds of grey/green shales and calcimudstones are thought to be the record of deeper waters, probably representing central saline pans. Shallower areas of the pans and surrounding flats were dominated by evaporite deposition. The dominance of gypsum with well-preserved horizontal lamination reflects original bedding on flatter-lying environments surrounding the saline pans. The chevron crystals of the lighter beds indicate relics of primary gypsum deposition on the floor

of brine pools. Precipitation of similar features in many modern and ancient environments occurs when water depths are less than about 2 m (e.g. Logan, 1987; Handford, 1991; Smoot & Lowenstein, 1991; Hovorka *et al.* 1993). Shallow waters favour a high degree of supersaturation, as well as less dense and unstable brines, which are conditions required to promote the upward growth of crystals. The darker beds in the couplets record displacive intrasediment growth of crystals beneath the brine from supersaturated pore fluids in the capillary and/or upper phreatic zone, thus indicating periods of descending ground waters and eventual exposure (e.g. Kerr & Thomson, 1963; Warren, 1999). These deposits formed slightly post-depositionally, but still under a strong influence of the depositional setting as precipitation took place within only a few millimetres of the depositional surface. The alternating dark and light gypsum couplets are attributed to pulsating episodes of the water table. The growth-aligned crystals grew upwards at the sediment–brine interface during times when saturated brines were flushed into the basin. The formation of such evaporite layers requires a subaqueous environment with stable phases to allow the aggradation of the upper euhedral surface of the crystals (Warren, 1999). As the water level falls, precipitation of this type of crystal is precluded. During these episodes, evaporite precipitation in the study area occurred only within the sediment.

The gypsarenite records periods when evaporite crystals were reworked. Because these deposits are mostly associated with the laminated gypsum, it is possible that their formation is due to reworking of growth-aligned crystals as the water level slightly decreased, but that the process still occurred sub-aqueously. The increased occurrence of this facies upward in the evaporite section attests to progressive shallowing, an interpretation that is supported by the presence of numerous potholes attributed to partial evaporite dissolution due to subaerial exposure. As the evaporite basin was dissected, the deposits were at least temporarily kept above the water level and dissolution took place, forming small depressions. Water accumulated in these depressions, bringing suspended sediments that settled to form the clay films. A later submergence of the dissolved planes led to the infill of the potholes by thin layers of growth-aligned crystals.

4. Shallowing-upward cycles and depositional units

4.a. Description

Three ranks of shallowing-upward cycles are distinguished in the Codó Formation. The lowest-rank cycles display regular thickness ranging from 5 to 10 cm, and consist of facies that vary according to their position in the lake setting. Hence, the central lake deposits show interbedding either of bituminous black shales and evaporites, or bituminous black shales with streaks of calcimudstone and bituminous black shales with native sulphur. The intermediate lake deposits display bituminous black shale interbedded with peloidal wackestone–packstone or grey/green shale interbedded either with calcimudstone or peloidal wackestone–packstone. The marginal lake deposits show either grey/green shale and ostracodal wackestone/grainstone, as well as alternations of ostracodal wackestone/grainstone and/or calcimudstones with cryptomicrobial mats and ooidal/pisoidal packstones. The lower-rank cycles in the saline pan/sabkha deposits consist of alternating dark and lighter gypsum, consisting of microgranular gypsum grown within shales and vertically aligned gypsum crystals, respectively. These are locally arranged into packages containing 3 to 7 couplets; a succession of 4/7/5/6/6/7/6 couplets was counted in one place.

The intermediate-rank cycles vary from 0.3 m up to 5.6 m thick (averaging 1.7 m thick), and contain the lower-rank cycles. They can be either complete or incomplete according to the relative proportion of facies associations representing the several lacustrine and saline pan/sabkha sub-environments (Fig. 7). Hence, complete cycles display facies associations that record the upward gradation from central to marginal environments of the lake or saline pan–sabkha system, indicating the complete preservation of one shallowing episode. Three different types of complete cycle were recognized (Fig. 8): complete cycle type 1 (C1), where central lacustrine deposits are entirely formed by evaporites and bituminous black shales; complete cycle type 2 (C2), where central lake deposits consist of black and/or grey/green shales and limestones; and complete cycle type 3 (C3), where grey/green shale and calcimudstone record central saline pan environments, while evaporites (laminated gypsum, gipsarenite) and tufa record shallower saline pan and surrounding evaporitic flats. Incomplete cycles are defined by shallowing-upward successions where at least one facies association is lacking. There are also three types of incomplete cycle (Fig. 8): incomplete cycle type 1 (I1), where central and intermediate lake associations dominate; incomplete cycle type 2 (I2), composed mostly of intermediate and marginal lake facies associations; and incomplete cycle type 3 (I3), consisting of only shallower saline pan and evaporitic flat deposits.

The higher-rank cycles define four laterally continuous depositional units, referred as 1 to 4 from bottom to top (Figs 7, 9a, c). Unit 1 is only partly exposed at the base of the sections and forms an interval that reaches up to 3.6 m thick (averaging 2.7 m thick) composed of thin I1 cycles. Its top is marked either by a horizon of breccia containing clasts of grey/green shale up to 5 cm long, or by lenses of medium- to coarse-grained sandstones; these lithologies occur along a sharp surface with erosional relief up to 4 m. Unit 2 (Fig. 7)
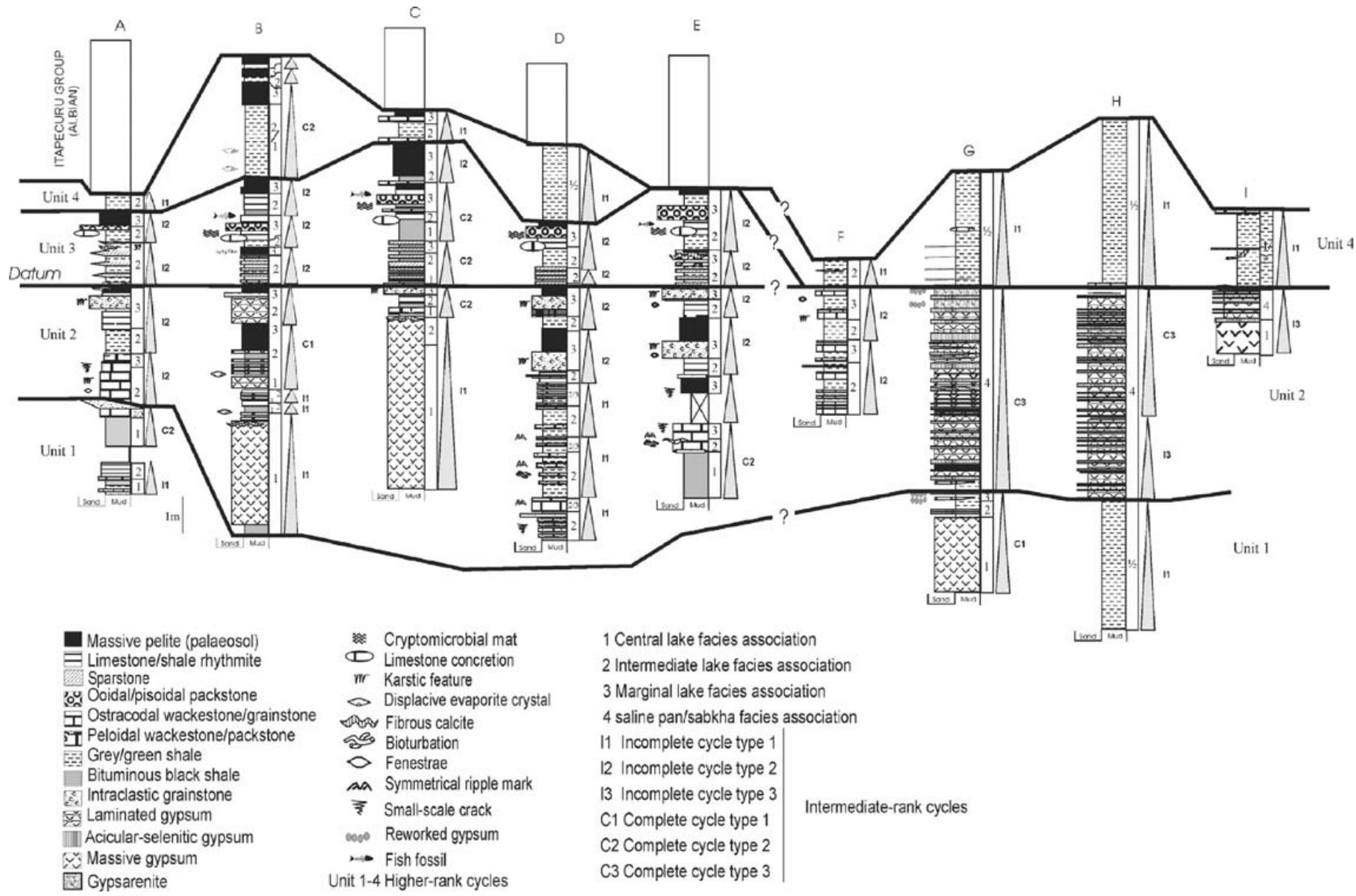
Figure 7. Lithostratigraphic profiles representative of the Codó Formation exposed in the study area, with the main facies characteristics and the two ranks of shallowing-upward cycles described in the text. (See Figure 1 for location of the profiles A–I). *Datum* = discontinuous surface with evidence for maximum subaerial exposure within the Codó Formation.
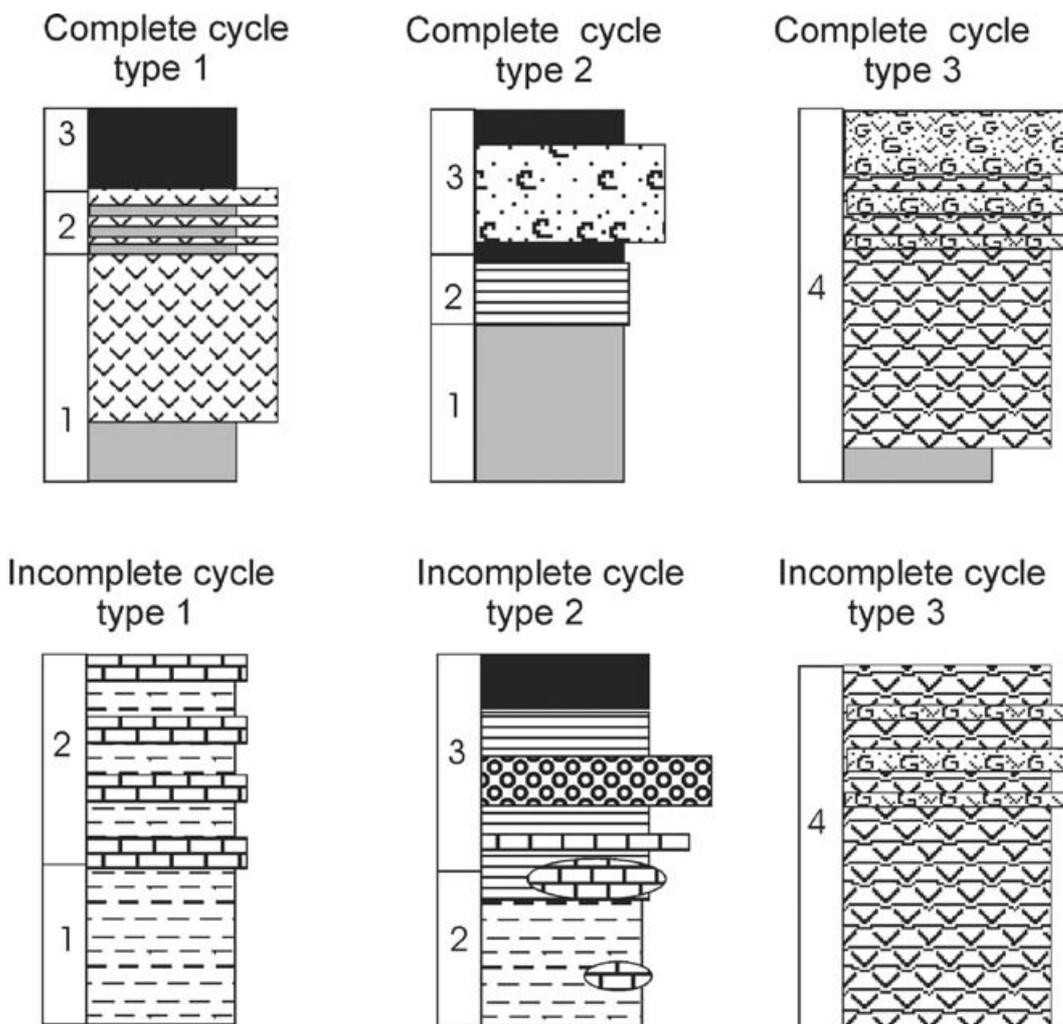
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Figure 8. Diagrams illustrating the four types of lower-rank, shallowing-upward cycles of the Codó Formation. Thickness of individual cycles range from 0.3–5.6 m. See Figure 7 for legend.

reaches up to 8 m thick (averaging 5.2 m) and contains all types of cycles. Although in number there is a prevalence of incomplete cycles, this unit displays the highest volume of complete cycles found in the whole of the Codó Formation exposed in the study area. Up to five successive shallowing-upward cycles were observed in this unit, with C1 cycles being the thickest and dominant ones. These occur mainly in profiles B and C of the Codó area and profiles G and H of the Grajaú area (Fig. 7). It is noteworthy that the marginal facies of the shallowing-upward cycles located closer to the top of unit 2 are characterized by the abundance of gypsarenite, intraclastic grainstone with fenestrae, karstic features and nodular chert (silcrete). The top of unit 2 is marked by a sharp bounding surface that is either planar or displays an erosional relief up to 1 m at the outcrop scale.

Unit 3 (Figs 7, 9b–c), confined to the eastern portion of the study area, is up to 3.8 m thick (averaging 2.6 m thick) and is comprised mostly (nearly 80 %) of I2 cycles, with the remaining 20 % being represented

by C2 cycles. A remarkable and unique feature of this unit is the presence of ooids/pisoids and concretions of ostracodal wackestone–grainstone, which constitute important stratigraphic markers throughout the study area. The latter occur invariably at the transition from intermediate to marginal lacustrine deposits, while the ooids/pisoids are present in marginal lake deposits located close to the top of unit 3. The concretions bearing articulated ostracod shells include a mixture of juvenile and adult individuals. These lithologies are interbedded with rhythmites bearing abundant articulated and disarticulated fish bones, and which also contain a high volume of former microbial mats. Unit 3 is also bounded at the top by a sharp surface with erosional relief up to 2.5 m.

The uppermost part of unit 4 (Fig. 7) is up to 4.6 m thick (averaging 2.2 m thick) and typically starts at the base with grey/green shales containing only thin (< 1 mm thick) laminae of gypsum and/or fibrous calcite, both formed by vertically aligned crystals. Upward, the shales are interbedded with few and thin
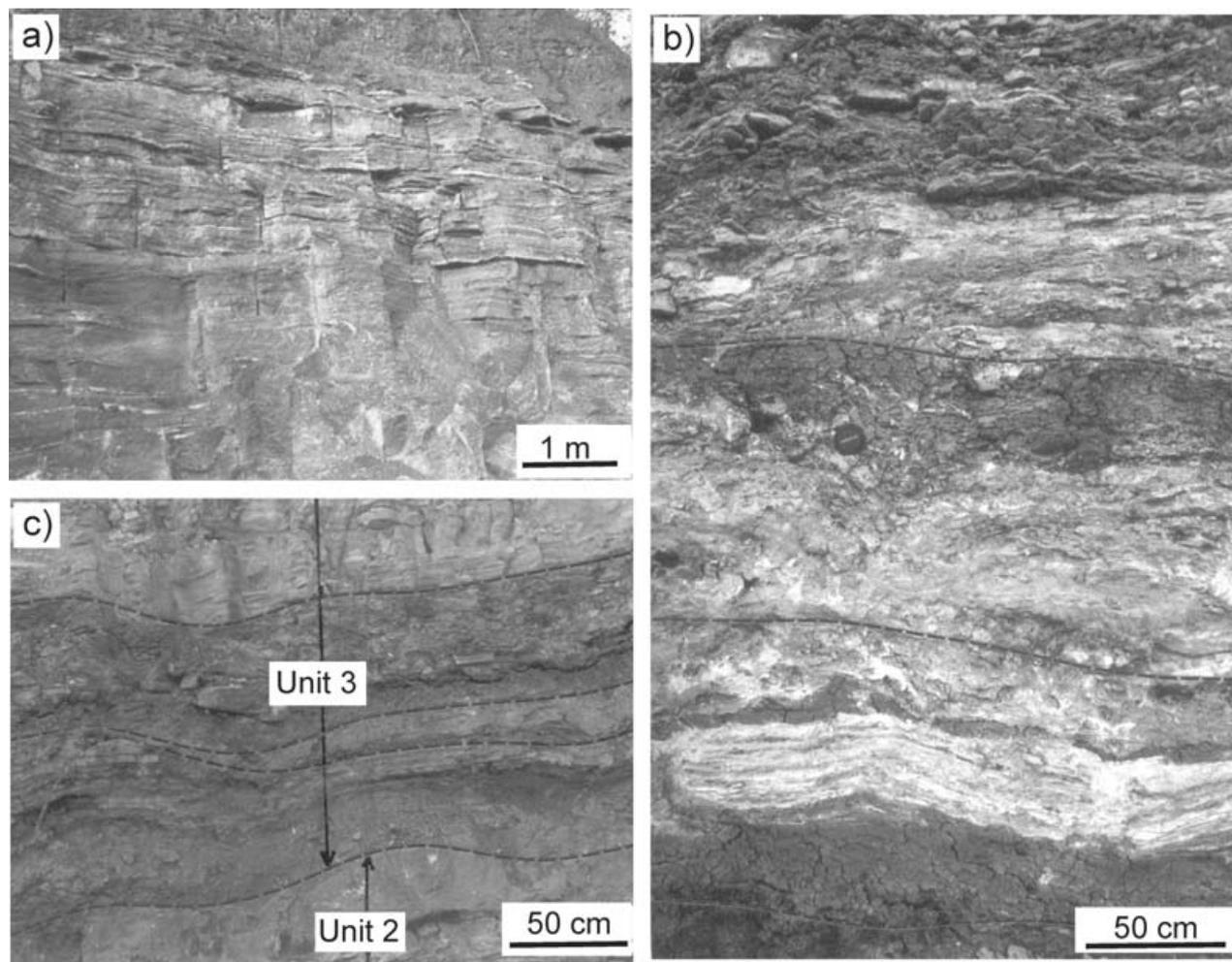
Figure 9. Types of shallowing-upward units present in the Codó Formation, illustrating: (a) Unit 2, represented by one complete cycle type 1 with evaporites and shales. (b) Unit 3, presented by two incomplete cycles type 1 (bottom and middle) and one complete cycle type 2 (uppermost). (c) The uppermost portion of unit 2 and the base of unit 3, with the later showing three incomplete cycles type 1 (lower three) and an upper incomplete cycle type 2 (uppermost).

(millimetres to a few centimetres) layers of calcimud-stones. I1 cycles are dominant in this interval, but no black shales are present. Secondarily, this unit also shows I2 cycles. Unit 4 is truncated by a discontinuity surface showing erosional relief up to 5 m, marked by a red-coloured palaeosol horizon overlain by Albian sandstones and argillites of the Itapecuru Group (Fig. 7).

4.b. Interpretation

The lower-rank cycles recognized in the Codó Formation record minor changes in depositional conditions, attesting to alternations between mud settling and chemical precipitation of evaporites or limestones. This characteristic, added to the regular thickness variation, is consistent with seasonal fluctuations, with mud deposition and chemical precipitation taking place during less and more arid phases, respectively.

The intermediate-rank, shallowing-upward cycles reflect periods of progradation of the lake shoreline resulting from superposition of marginal lake deposits upon intermediate and/or central lake deposits. The higher-rank cycles record several episodes of upward-shallowing due to lake desiccation, bounded by subsequent floodings. In this sense, they are good continental analogues for parasequences described in marginal marine settings (Vandervoort, 1997). The maximum shallowing was reached at the top of each unit, and it is marked by better-developed marginal lacustrine facies associations, indicated by the features recording wave reworking and subaerial exposure such as palaeosol, karstic features, fenestrae and chert (silcrete) nodules.

Units 1 and 2 reflect the prevalence of anoxic conditions and a water column with sufficient depth to favour stratification. The abundance of C1 cycles in unit 2, rich in bitumen and evaporites, is the most representative record of this phase, and is attributed to a phase when the lake had the maximum relative depth; this is consistent with the fact that in this unit cycles are thicker than in the other units.

Unit 3 records a time with the greatest development of marginal lake deposits, suggesting prevalence of shallower water conditions due to lake desiccation. The abundance of ostracodal wackestone–grainstone displaying a mixture of juvenile and adult articulated ostracod shells, as well as both articulated and disarticulated fish bones, attests to episodes of mass mortality. This event was probably associated with the reduction in the lake area due to shallowing, which is suggested by the fact that only marginal lake deposits display evidence for ostracod and fish mortality. Fish mass mortality recorded in lacustrine settings of the Achanarras Middle Old Red Sandstone of Middle Devonian age from the Orcadian Basin in Scotland has also been interpreted in a similar way (Trewin, 1986). The factors that led to this abrupt drought in the study area will be discussed below.

Unit 4 records a return to dominantly deeper water conditions, but without significant evaporite precipitation and no black shale formation, as indicated by the prevalence of I1 cycles, characterized only by grey/green shales. This unit was deposited during a time when the lake was oxygenated throughout the water column and no water-column stratification was present. The thickness of the shallowing-upward cycles suggests that the lake depth was again as deep as in unit 2. However, a better understanding of the conditions leading to the formation of unit 4 is not possible due to the strong erosion associated with the development of the late Aptian/Albian unconformity (Fig. 7).

5. Origin of the shallowing-upward cycles

Analysis of the vertical stratal stacking patterns represented by the shallowing-upward cycles recognized in the Codó Formation is the key to understanding their nature. These cycles were formed as the lake or saline pan/sabkha base level episodically decreased through time. In this depositional system, drops in base level, with resulting facies progradation, were caused chiefly by one of, or the interaction of, the following factors: increase in sediment supply either from a fluvial drainage or a marine inflow, progressively increased aridity, or increase in subsidence due to syn-sedimentary tectonics.

In the particular case of the Codó Formation, the influence of sediment supply might be considered negligible, since siliciclastic sands supplied into the lake system were reduced, as indicated by their scarcity even in marginal deposits. Deciphering whether climate or subsidence linked with syn-sedimentary seismic activity was the main cause for progradation is not so straightforward, particularly because both factors might have combined to produce shallowing-upward units (e.g. Anadon *et al.* 1991).

Climate has been used to explain many shallowing-upward lacustrine deposits recorded in ancient and modern environments (e.g. Smoot & Olsen, 1994; Olsen & Kent, 1996; Hofman, Tourani & Gaupp, 2000; Aziz *et al.* 2000; Steenbrink *et al.* 2000). The small, lower-rank cycles, particularly recognized in the saline pan/sabkha deposits of the Codó Formation, record minor changes in depositional conditions, indicating alternations between mud accumulation and chemical precipitation of either evaporites or limestones. This characteristic, added to the rhythmic and regular thickness variation, is consistent with seasonal fluctuations, with alternating mud deposition and chemical precipitation taking place during less and more arid phases, respectively. This is particularly suggested by the succession of evaporite couplets, which are attributed to pulsating episodes of water table change. Although locally observed, packages displaying regularly distributed bundles varying in number from 4 to 6 probably result from seasonal base level changes.

While seasonal fluctuations may explain the lower-rank cycles recognized in the Codó Formation, the origin of the intermediate- and higher-rank cycles are probably related to syn-sedimentary tectonics. A climatic cause seems to be unlikely in these instances because, if so, one would expect increased precipitation of evaporite minerals during phases of maximum shallowing, when the lake and saline pan level was minimal (Carroll & Bohacs, 1999). This did not happen in the Codó Formation, neither in the intermediate cycles, nor in the overall higher-rank cycles that form the depositional prograding units described herein.

The intermediate- and higher-rank cycles recognized in the Codó Formation show characteristics that are better explained by a tectonic signature. A line of evidence might be claimed to suggest tectonic episodes as the main cause for the intermediate-rank cycles: (1) the high variability of facies within individual cycles; (2) the limited lateral distribution, usually on the order of less than a few tens of metres; and (3) the frequent and random change in cycle thickness in the upward direction, ranging from few centimetres up to several metres. These characteristics match better with those typically recorded from tectonically influenced, shallowing-upward cycles (Martel & Gibling, 1991; Benvenuti, 2003), as climatically related cycles are expected to have more regular thicknesses and more monotonous facies distribution throughout large areas (Hofmann, Tourani & Gaupp, 2000; Harvey, 2003).

The higher-rank cycles of the Codó Formation exposed in both the Codó and Grajaú areas are particularly suggestive of formation under the influence of syn-sedimentary tectonics. The four higher-rank cycles reflect lower frequency episodes of lake shallowing. The two lowermost units record progressive episodes of lake shallowing in deep-water, anoxic conditions, when lake stratification prevailed. Following this phase, progradation of lake shoreline proceeded under shallower water conditions, as recorded by unit 3. The
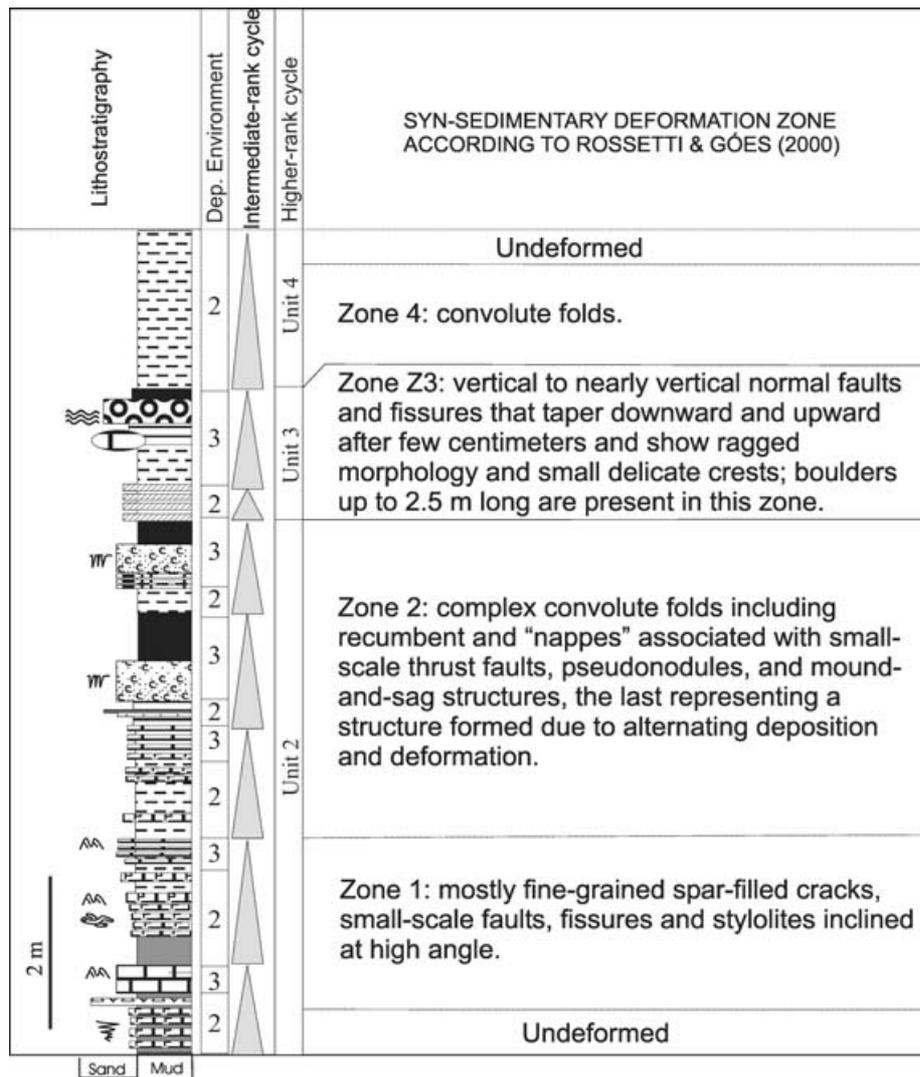
Figure 10. A representative lithostratigraphic profile of the Codó Formation showing the good match between higher-rank shallowing-upward cycles, represented by depositional units 1 to 4, and the syn-sedimentary deformational zones described by Rossetti & Góes (2000) (see Fig. 7 for legend).

fossil assemblage preserved in this unit indicates mass mortality, which in this instance might have been caused by a subtle reduction in the lake area. Stagnant waters favoured a widespread distribution of microbial mats. A renewed episode of significant lake deepening took place during deposition of unit 4, which at this time occurred under dominantly oxidizing conditions.

A tectonic influence is also proposed for the origin of the higher-rank cycles recorded by depositional units 1 to 4. This is suggested because these units have good correspondence with stratigraphic intervals representing different styles of deformation zones that characterize the Codó Formation in the Codó area. As summarized previously (see Section 2), these deformation zones (Fig. 4) were attributed to alternating periods of sediment accumulation and shear stress associated with syn-sedimentary seismic activity linked to the rifting of the São Luís-Grajaú

Basin during the late Aptian (Rossetti & Góes, 2000). Hence, depositional units 1 and 2 are stratigraphically correlatable with deformational zones Z1 and Z2 (Fig. 10), respectively. In other words, during the two first episodes of shallowing recorded in the study area, sedimentation in the lake system was strongly affected first by extensional and then by compressional forces, as shown by the upward gradation from small scale cracks and normal faults to complex convolute folds associated with thrust faults and vertical to sub-vertical stylolites. Deformation would have initially increased the accommodation space, promoting the development of a thicker higher-rank shallowing-upward cycle (unit 1) with increased deeper water facies, as recorded by a higher volume of C1 and I1 cycles. As the sedimentary succession evolved, the area might have experienced some compression, with consequent local uplift giving rise to the development of shallower-water facies at the top of depositional unit 2.

Uplift or more stable tectonic conditions would have produced even shallower-water environments in the Grajaú area, represented by the saline pan/sabkha deposits that form complete and incomplete cycles of types C3 and I3, respectively. After this time, a relative stability seems to have prevailed, with the lake basin becoming progressively shallower due to low accommodation rate and resulting in deposition of unit 3, which is characterized by the abundance of I2 cycles. A period of extension led to development of several normal faults and slumpings at the top of unit 3, which corresponds to deformation zone Z3. As a result of this extension, new accommodation space was created and the lake system became relatively deeper, favouring deposition of unit 4, characterized by thicker C2 and I1 cycles. However, anoxic conditions no longer existed during this time, as revealed by the scarcity of organic matter in the shales of this unit. Tectonic activity seems to have continued, resulting in convolution of these deposits and producing deformation zone Z4.

The seismic interpretation of the shallowing-upward cycles provided here is in agreement with the structural framework of the São Luís-Grajaú Basin. As noted previously, the main rift stage of this basin took place during Albian times, but reactivation of ancient fault systems started earlier in the Aptian, with the establishment of a shallow but widespread basin where the Codó Formation was deposited. The presence of deposits with evidence of soft sediment deformation in this unit is taken as an indication of syn-sedimentary tectonic activity (Rossetti & Góes, 2000). At the basin margins, where the study areas are located, the displacement of faults with small offsets would have favoured the development of subsiding areas, promoting the establishment of lake systems. The prevalence of fine-grained and chemical deposits in the depositional setting is not inconsistent with this model. Tectonically influenced settings are usually considered to be recorded by a dominance of coarse-grained siliciclastic deposits. However, modern examples have shown that coarse-grained deposits will not occur immediately following episodes of tectonic activity. Instead, it has been suggested that the first response to tectonic activity in several settings from marine to lacustrine is represented by fine-grained deposition, as a depositional setting usually takes a time to re-equilibrate and respond to tectonic activity (Blair & Bilodeau, 1988). In areas dominated by mild tectonic activity with fine-grained and chemical sedimentation, as occur in the Codó Formation, higher rates of accommodation give rise to deposition of evaporites and preservation of shales with high organic content in central lake areas (Carroll & Bohacs, 1999). On the other hand, periods of quiescence favour deposition of shallower-water limestones and evaporites as the accommodation space is reduced. It is possible that the increased sediment reworking, recorded by the

occurrence of gypsarenites and intraclastic grainstones in marginal deposits of depositional unit 2, might also be related to this tectonic phase. The presence of breccia and coarse-grained sandstones only at the top of unit 1 is probably an indication of a progressive decrease in the intensity of the tectonic process through time.

6. Conclusions

Although more often attributed to climate fluctuations, many shallowing-upward lacustrine cycles might result from pulsating tectonism taking place contemporaneously with sediment deposition. The Codó Formation exposed in the eastern Grajaú Basin seems to be an unequivocal example of an ancient lacustrine system displaying two ranks of shallowing-upward cycles reflecting prograding episodes driven by syn-sedimentary seismic activity. Despite the seasonal signature recognized in the lower-rank cycles, a tectonic cause is proposed for the intermediate- and higher-rank cycles described in this unit. In the particular case of the intermediate-rank cycles, a tectonic origin is revealed on the basis of: (1) high facies variability; (2) limited lateral extension; and (3) frequent and random thickness change. The higher-rank cycles were also formed as a result of tectonic episodes that alternated with sediment deposition, a conclusion supported by their matching with stratigraphic zones characterized by different styles of soft sediment deformation that are attributed to contemporaneous seismic activity. Based on the observations made in the study area, one can state that extension affecting lake deposits, with subsequent creation of accommodation space, promotes the development of prograding successions internally formed by thicker (deeper) water cycles. Bed shortening by compression and/or stability reduces the water depth and leads to the development of thinner and shallower-water cycles. Therefore, different styles or/and intensities of seismic pulses alternating with sediment deposition might cause substantial changes in lake level, promoting deeper and shallower water phases, and ultimately resulting in cyclic deposition. Deciphering the genesis of such prograding episodes in ancient lacustrine successions is a task that requires detailed facies analysis and precise mapping of the stratal stacking patterns, as well as their association with tectonically driven structures.

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