



## Stratigraphic Relations of the Ipubi Formation: Siliciclastic-Evaporitic Succession of the Araripe Basin

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### ABSTRACT

The Ipubi Formation represents the Aptian-Albian siliciclastic-evaporitic succession of Araripe Basin, NE Brazil. This succession comprises siliciclastic rocks (bituminous shales and claystones) and evaporites (gypsum and secondary anhydrite) and represents part of the lacustrine-shallow marine post-rift phase I. This study used sequence stratigraphy concepts to define the relations between changes in the relative lake level and the formation of Ipubi deposits. Results show that the organic-rich shales of the Ipubi Formation formed during a transgressive pulse that covered large areas of the proximal domains. These deposits overlie a regional unconformity that marks the end of the deposition of the underlying Crato Formation. A High Stand stage that followed the transgression influenced the formation of evaporitic deposits. Climate conditions played a major role in influencing the triggering and stopping of evaporite deposition. Thus, a new relative lake level fall event caused the exposure of the Ipubi Formation deposits, and created another regional subaerial unconformity accompanied by widespread karstification of evaporite beds. A posterior transgression caused the deposition of siliciclastic rocks of the Romualdo Formation over the Ipubi Formation strata, and also promoted a new event of karstification of the Ipubi upper evaporite beds.

**Key words:** Araripe Basin, evaporite succession, interior basins, Ipubi Formation, sequence stratigraphy.

### INTRODUCTION

Evaporites represent sedimentary rocks that normally form in saline aqueous bodies under arid conditions with high evaporation rates. Such

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conditions, as well as a lack of terrigenous input, allow evaporites to form in saturated brines (Collinson and Thompson 1982, Cavalcante and Ramos 2010, Warren 2006, 2010, Mohriak et al. 2008, Ortí et al. 2017). Tectonic processes are also important in forming and sustaining evaporitic systems due to the formation of restrictive conditions in lakes and epeiric seas. Topographic barriers can

restrict water circulation in gulfs, shallow seas and lakes, and mountain chains can limit atmospheric circulation, which carries humidity (Warren 2006). In a large number of both marginal and interior sedimentary basins, evaporite deposits present complex deformation processes associated with salt tectonics (Hudec and Jackson 2007). Evaporites present very low permeability and plastic response to deformation, which makes their seal capacity more competent than of brittle rocks, and that allows these rocks to be used for the excavation of storage facilities for the disposal of toxic and radioactive waste (Munson et al. 1991). In the same way, evaporites also represent an important part in many petroleum systems, because they form good seal rocks and strongly influence migration and accumulation of hydrocarbons (Mohriak et al. 2008, Bengaly 2003, Medeiros 1999, Szatmari and Milani 2016, Warren 2017). Abundant deposition of evaporites occurred in many marginal basins in Brazil during the Upper Aptian period (Hashimoto et al. 1987, Uesugui 1987, Mohriak et al. 2008, Szatmari and Milani 2016).

To avoid misconception regarding the names, or the stratigraphic status, of the sedimentary units belonging to the post-rift phase I of the Araripe Basin, a few comments are necessary. The stratigraphic division of this succession (Barbalha, Crato, Ipubi and Romualdo formations) remained a matter of debate for decades. Along the time, some authors proposed that these sequences represented members of a formation (Assine 1994, 2007), or proposed different names for some units (Martill 2007). However, the proposition made by Neumann and Cabrera (1999) prevailed as the more consistent (Kellner et al. 2013, Assine et al. 2014). Thus, our investigation is based on the stratigraphic division proposed by these authors.

The Ipubi Formation represents a siliciclastic-evaporitic succession of the Araripe Basin, which is the largest interior basin in northeastern Brazil. This formation is composed of bituminous shales,

claystone and limestone beds and discontinuous evaporite layers that can reach from few meters to tens of meters thick and mainly comprise gypsum, followed by anhydrite (Silva 1986, 1988, Assine 1992, Assine et al. 2014). Silva (1988) suggested that these evaporite beds can reach thicknesses of 20-30 m, and were formed in systems of salinas and sabkhas, and that they were preceded by black shales and algal limestones. The few studies developed on the Ipubi Formation found difficult to define the relations between evaporite layers and other lithologies that compose the formation due to the lateral discontinuity of the evaporite bodies (Silva 1988, Assine 1992, 2007, Assine et al. 2014). Evaporite beds are found in proximal regions of the Araripe Basin, with good outcrops in the southwestern and northern borders, which attracted the mining industry. There is no record of evaporite deposits in distal domain of the basin, over the main depocenters (Assine 1992, 2007, Rios-Netto et al. 2012), where the thickness of sedimentary succession can reach up to 1500-1700 m (De Castro and Castelo Branco 1999). Due to the large extension of the Araripe Lake in post-rift phase, it is difficult to define regional stratigraphic relations across proximal and distal domains. Based on chemical evidence, some authors have suggested that marine incursions occurred during the evaporite deposition (Silva 2017). However, the Romualdo Formation, which overlies the Ipubi Formation, is the only unit that exhibits clear evidence of marine influence represented by the fossils of marine organisms (Assine et al. 2014). Ipubi Formation exhibits important lateral variations, in a relative thin succession, that are related to the physiography of the basin and the involved depositional systems. This makes it difficult to establish a general stratigraphic model for the entire basin (Fabín 2013), that covers an area of approximately 7.200 km<sup>2</sup> (Assine et al. 2014).

A new characterization of the stratigraphic relations of the siliciclastic-evaporitic Ipubi Formation is presented in this study, based on new stratigraphic and sedimentological information. The investigation focused the characteristics of the stratigraphic boundaries of the succession with the overlying Romualdo Formation, and the underlying Crato Formation (Assine 1992, Neumann 1999, Neumann et al. 2003, Assine et al. 2014). The research analyzed outcrops and exposures of quarries on the southwestern and northern borders of the basin, near the cities of Araripina and Nova Olinda (Fig. 1), respectively. The record of a new stratigraphic well drilled near the city of Crato on the northern border (Fig. 1) is also described. The research applied the sequence stratigraphy concepts to define the relationships between the major oscillations of the relative lake level and the development of the siliciclastic-evaporitic succession of the Ipubi Formation. The investigation adopted the concept of depositional sequences (Mitchum 1977, Vail 1987, Catuneanu 2002) meaning a pulse of deposition influenced by the relative lake level, that is separated from the adjacent depositional sequences by regional unconformities, created by major regressive events. The proposed relative lake level curve comprises two regressive-transgressive cycles that controlled the deposition in the proximal areas during the studied interval. The formation of two regional unconformities that mark the base and top boundaries of Ipubi Formation is discussed.

#### GEOLOGICAL SETTINGS

The origin of the Araripe Basin is linked to tectonic processes that occurred in the Borborema Province (NE Brazil) including Tithonian pre-rift and the Berriasian-Hauterivian rift phases (Assine 1992, Matos 1992, 1999). The basin is located in the Transversal Zone Domain (TZD), a central tectonic domain of the Borborema Province (Almeida et al.

1977, Van Schmus et al. 1997, 2008, Brito Neves et al. 2000, Santos et al. 2010, Neves et al. 2012, Araujo et al. 2013) (Fig. 1). The TZD is bounded to the north by the Patos Shear Zone, which strongly influenced the basin, and to the south by the Pernambuco Shear Zone. The basement of the Araripe Basin comprises the Piancó-Alto Brígida Terrain (Fig. 1), that represents a Neo-Proterozoic fold belt mainly composed of low-grade metasedimentary rocks with plutonic intrusions formed during the Brasiliano orogenic event (Almeida et al. 1977, Van Schmus et al. 1997, 2008, Brito Neves et al. 2000, Santos et al. 2010, Neves et al. 2012, Araujo et al. 2013).

Geophysical studies based on gravimetric and magnetometric data revealed that the structural framework of the basin comprises two main depocenters, or sub-basins: the western and eastern depocenters correspond to the Feitoria and Cariri Sub-basins, respectively (Rand and Manso 1984, Miranda and Assine 1986). These depocenters are separated by the central Dom Leme Horst (Assine 1992) (Fig. 1). De Castro and Castelo Branco (1999) confirmed the existence of the two main depocenters and the central high, and estimated a maximum depth about 1,600 m.

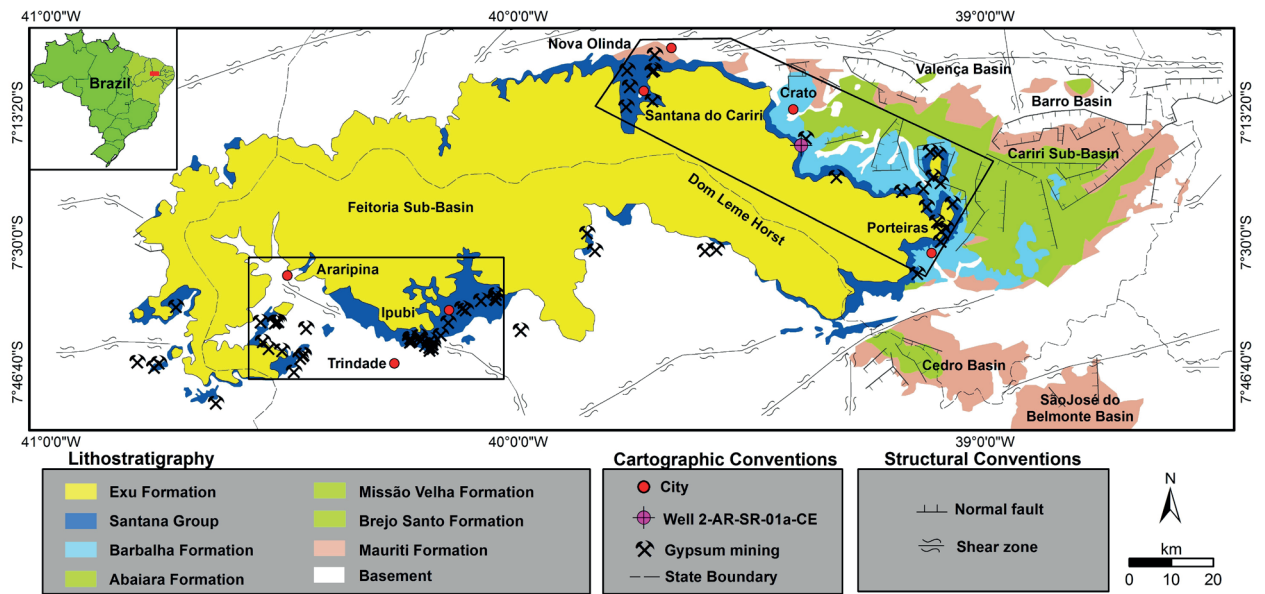
The tectono-sedimentary evolution of the basin encompasses four stages, with five tectono-stratigraphic phases (Assine 1992, 2007, Neumann 1999, Neumann and Cabrera 1999, Assine et al. 2014):

- a) Syncline phase (Silurian-Devonian) that is characterized by tectonic quiescence in the Borborema Province. It is represented by the deposits of the Cariri Formation, that include medium to coarse-grained quartz sandstones, locally conglomeratic, deposited in large braided fluvial systems (Assine 1992, 1994, 2007, Assine et al. 2014);
- b) Pre-rift phase (Jurassic-Tithonian) that is characterized by the mechanical subsidence due to lithosphere thinning that preceded

- the rift. It is represented by the Brejo Santo Formation, that comprises red shales and claystones, and the Missão Velha Formation, constituted by medium to coarse-grained quartz-feldspathic sandstones, locally conglomeratic, that contains entire trunks and fragments of silicified wood (*Dadoxylon benderi*) conifer (Assine 1992, 1994, 2007);
- c) Rift phase (Cretaceous-Berriasian-Hauterivian) that is characterized by increasing mechanical subsidence that created a system of grabens and half grabens. It is represented by the Abaiara Formation, that includes shales, siltstones, sandstones and conglomerates (Assine 1992, 1994, 2007);
- d) Post-Rift I phase (Aptian-Albian) that is characterized by thermal subsidence. The Santana Group was formed during this stage and comprises four stratigraphic units: the Barbalha Formation, that represents a fluvio-lacustrine phase and is composed of red and gray shales, siltstones and claystones (Assine 2007); the Crato Formation that is composed of six intervals of laminated limestones (C1 to C6), interbedded with calciferous siltstones and marls (Neumann 1999, Neumann and Cabrera 1999, Neumann et al. 2003), and is very rich in fossils of vertebrate and invertebrate organisms (Martill 1988, 2007, Kellner and Campos 1999); the Ipubi Formation, that is mainly composed of organic-rich, black-greenish bituminous shales, claystones and algal limestones that are interbedded with gypsum-anhydrite beds (Silva 1988, Fabin 2013, Assine et al. 2014, Silva 2017); and the Romualdo Formation, that represents a calciferous siliciclastic succession composed of fine to medium-grained sandstones, argillaceous siltstones, calciferous shales, and limestones (Assine 1992, Neumann et al. 2003, Assine et al. 2014), very rich in fossils (Beurlen 1963, Kellner and Campos 1999, Carvalho and Santos 2005, Fara et al. 2005, Martill 2007, Saraiva 2008, Vila Nova et al. 2011). This formation recorded the marine ingression that involved the Araripe Basin (Maisey 1991, Martill 1993, Kellner 2002), and other interior basins and created a large seaway throughout the Borborema Province during the Albian (Valença et al. 2003, Parméra et al. in press).
- e) Post-rift II phase (Albian-Cenomanian) that is characterized by a major sag phase, and is formed by two stratigraphic units: the Araripina Formation, that occurs in the western region of the basin and is composed by rhythmites and heterolithic layers of reddish, purplish and yellowish fine-grained sandstone and mudstone (Assine 2007); and the Exu Formation, that comprises medium-to-coarse grained sandstones, fine grained clayey sandstones and local conglomeratic beds (Beurlen 1962, Assine 2007).

#### MATERIALS AND METHODS

A detailed investigation was carried out on the Ipubi Formation and its lower and upper boundaries in two study areas (Fig. 1). These analyses provided detailed descriptions of the Ipubi sedimentary facies and its stratigraphic framework. The investigation involved the creation of photopanels from the main exposures available in quarries, samples collecting, study of samples through cuttings and macrophotography, and petrographic analysis. Data collected in the field were integrated with satellite images and a digital elevation terrain model created with SRTM (Shuttle Radar Topography Mission) data (90 m spatial resolution). Topographic and geological models helped the correlation of interpreted stratigraphic surfaces. The interpretation of the new borehole lithostratigraphic record is also compared with previous stratigraphic models that are based in outcrops and the boreholes of the Santana Project



**Figure 1** - Geological map (Assine 2007) and digital elevation model of the Araripe Basin. The two black rectangles mark the study areas: one in the southwestern border (Arapipina region) and another in the northern border (Nova Olinda region).

(Brazilian Geological Survey-CPRM) (Assine 1992, 2007, Rios-Netto et al. 2012, Assine et al. 2014). The present study also used information obtained with a new stratigraphic borehole, 2-AR-SR-01a-CE (continuous coring), drilled in the Sítio Romualdo locality, near the city of Crato (Fig. 1), on the northern border of the basin. This drilling was funded by the research cooperation project agreement developed between UFPE and Petróleo Brasileiro S.A. (PETROBRAS) (Projeto Três Furos no Andar Alagoas). This new borehole crossed all three units analyzed in this study (Crato, Ipubi and Romualdo Formations) (Cabral 2017).

**RESULTS**

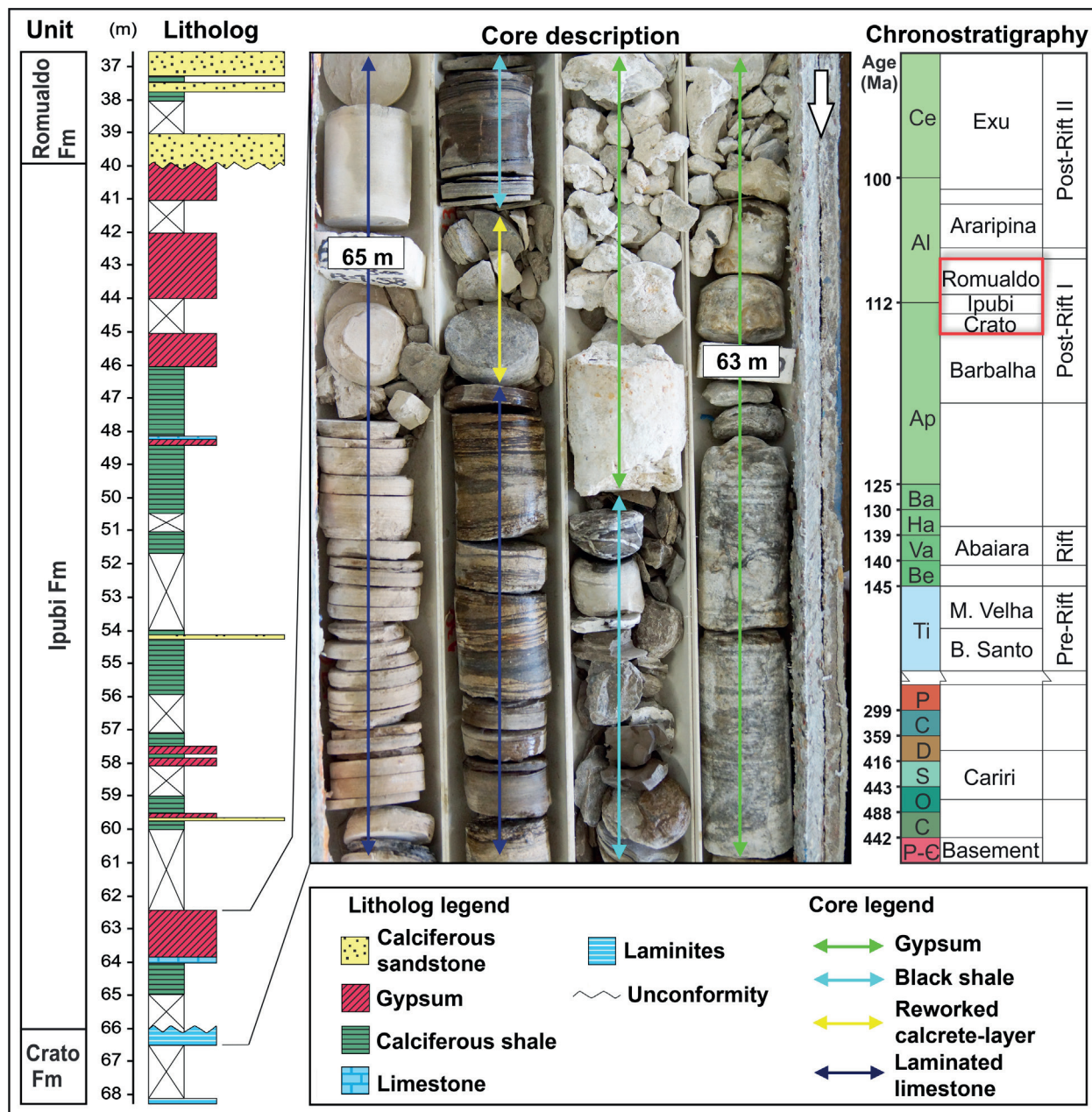
**SEQUENCE BOUNDARIES OBSERVED IN THE DRILL HOLE 2-AR-SR-01a-CE**

The analysis of the 2-AR-SR-01a-CE well cores (Fig. 1) showed no evidence of interfingering of the main lithologies of the three units (Crato, Ipubi and Romualdo) (Fig. 2). The division proposed here is similar to previous studies, based on the analyses of other stratigraphic wells drilled across the basin (Rios-Netto et al. 2012). The top of Crato

Formation is characterized by the formation of a calcrete formed under subaerial conditions with small clasts of limestones and local silicification. Figure 2 shows the interpretation of the well core (litholog), with the division of the main units according to the recent proposition for the basin stratigraphy (Assine et al. 2014).

**STRATIGRAPHIC AND SEDIMENTOLOGICAL ASPECTS OF THE IPUBI FORMATION AND ITS SEQUENCE BOUNDARY WITH THE UNDERLYING CRATO FORMATION**

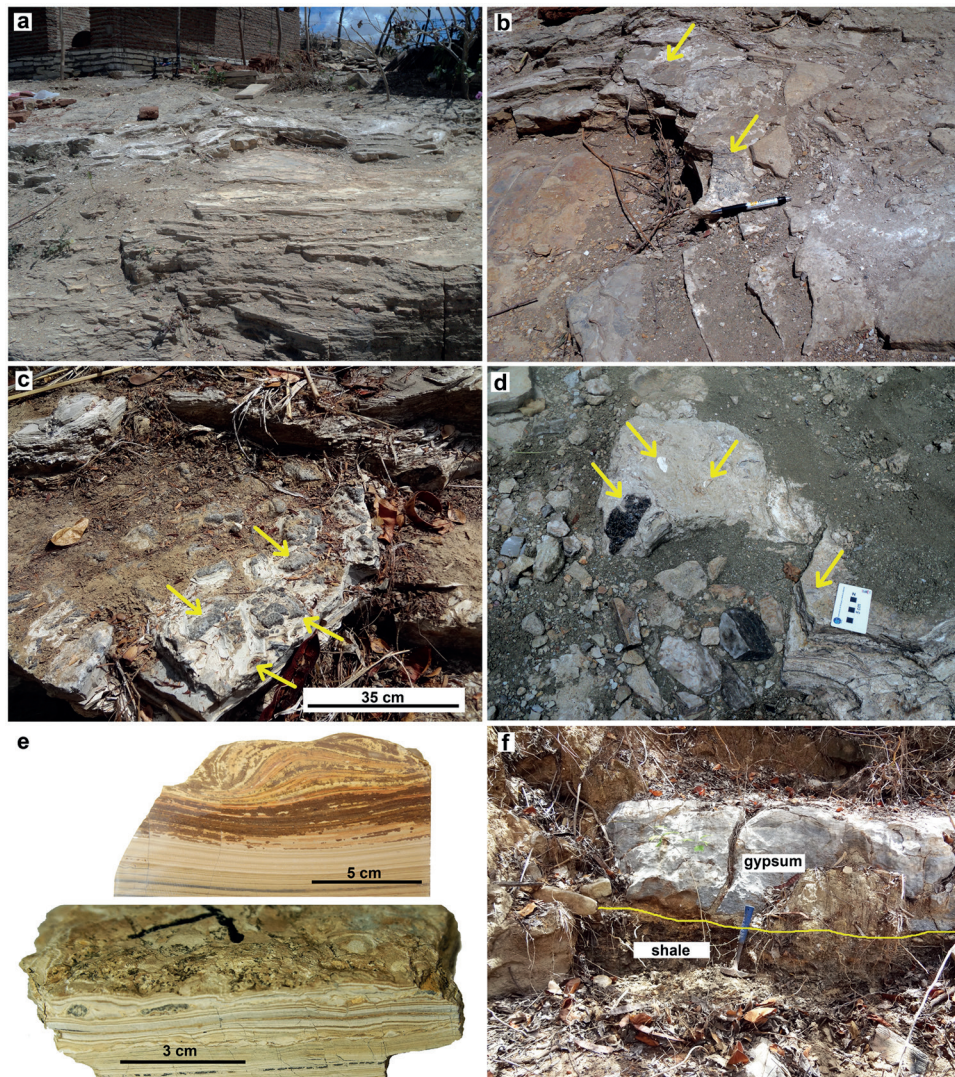
In the northern border of the Araripe Basin (Fig. 1), evaporite deposits of the Ipubi Formation overlies deposits of Crato and Barbalha formations (post-rift phase) and older deposits from the pre-rift and rift phases (Assine 1992, Neuman 1999, Assine et al. 2014). In the southwestern border, in the Arapipina region (Fig. 1), record from the groundwater wells shows that the siliciclastic-evaporitic sequence rests directly on the basement, suggesting an onlap relationship. In quarries located near the Rancharia village (Arapipina), black shales (Fig. 3e), that form the base of siliciclastic-evaporitic succession has been deposited directly above the basement.



**Figure 2** - Litholog of the 2-AR-SR-01a-CE elaborated from core description and detailed view of the cores across the contact between the Crato and Ipubi formations. An interval of cemented calcrete, with local silicification, occurs at the top of the Crato Formation and records evidence of subaerial reworking, as can also be observed in outcrops. Stratigraphic column based in Assine (2007) and Assine et al. (2014).

Between the Porteiras and Santana do Cariri localities on the northern border (Fig. 1), the top of the Crato Formation, represented by laminated limestone beds (C6), records evidence of subaerial exposure, which is mainly represented by a calcrete containing reworked oxidized fragments

of limestone and siliciclastic grains. The upper part of the laminites also present local silicification (Neumann 1999) (Fig. 3). Abundant wavy laminations in the top of the C6 layer possibly represents occurrence of microbial structures (Fig. 3e). Recent works have indeed discussed



**Figure 3** - Details of the C6 laminated limestone that marks the top of the Crato Formation in the Porteiras, Nova Olinda and Satana do Cariri regions. **a**) and **b**) Exposure of the C6 layer, exhibiting evidence of subaerial erosion and reworking represented by a calcrete containing oxidized and angulated fragments of limestone (yellow arrows), in Nova Olinda region; **c**) Exposure of the C6 layer showing evidence of subaerial erosion and reworking, near Porteiras, Mina Branca site, represented by a thin layer of calcrete that contains reworked and oxidized clasts of limestone (yellow arrows); **d**) Exposure of the C6 layer near Santana do Cariri, with a calcrete layer that contains clasts of limestone and quartz grains (yellow arrows); **e**) detail of samples from the upper part of the C6 interval, collected in Nova Olinda region, with wavy laminations that possibly represents algalic structures; **f**) Detail of a shale bed and a gypsum bed (Ipubi Formation) deposited directly above the C6 layer in nova Olinda Region.

the microbial influence in the formation of these laminites (Catto et al. 2016).

The succession deposited over the unconformity that marks the top of Crato Formation in the northern border is composed of black shale, clayey siltstone and greenish claystone beds. Black

shales are calciferous, bituminous and fossil-rich (fish remains, plant fragments, ostracods), and its TOC content reaches up to 25% of TOC (Souza Neto et al. 2013), and are mainly composed of expansive clay minerals, such as illite and smectite, and they record important contents of barium (up

to 2%). Evidences suggest that these basal deposits of the Ipubi Formation formed under anoxic conditions (Souza Neto et al. 2013, Nascimento Jr et al. 2016, Silva 2017).

Data collected in quarries in the southeastern border, integrated with available record of boreholes, indicate that the basal interval of the Ipubi Formation comprises calciferous black shales and thin beds of calciferous siltstone claystone and limestone (Fig. 4). In this border region, the siliciclastic interval ranges in thickness from 2 to 15 m. The upper portion of the siliciclastic interval present interbedding thin gypsum lenses and bedding-parallel fibrous gypsum veins possibly formed by overpressure hydraulic fracturing during burial processes (Meng et al. 2017). The total thickness of the Ipubi Formation, including

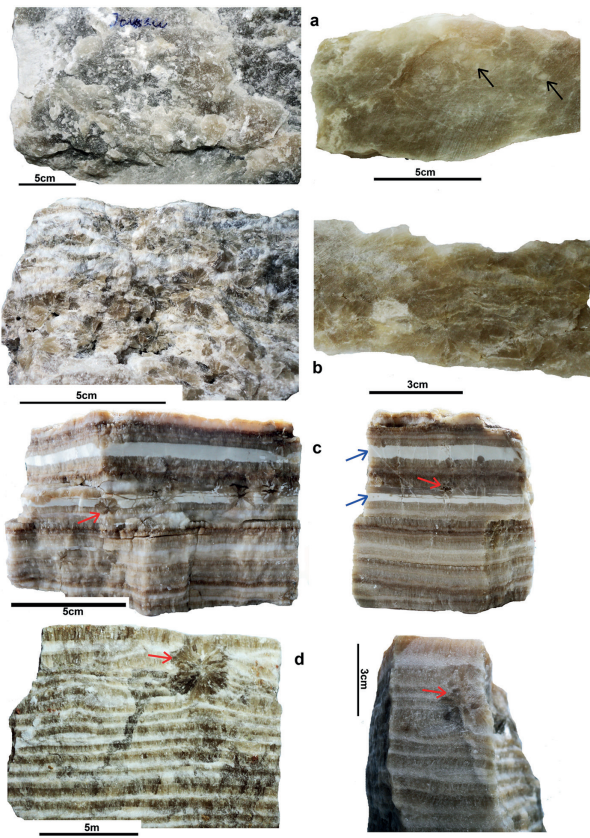
the shale interval and the evaporite beds, can reach 30 to 40 m. However, its average thickness, which is observed in many quarries, is approximately 15 m. Figure 4a shows the contact between the basal black shale and the gypsum at the Rocha Nobre Quarry in the southwestern border. However, the transition between the basal siliciclastic interval and the evaporite beds can be also gradual with the interbedding of gypsum and thin limestone lenses.

Evaporite beds comprise three main facies: 1 - banded gypsum, with millimetric bands of fine-grained, brown, gray and white gypsum crystals (Figs. 5, 6 and 7); 2 - microcrystalline/micronodular, light brown to light gray, homogenous gypsum; 3 - laminated gypsum, which is formed by millimetric laminae of prismatic, gray, white, yellow or brown gypsum crystals. Anhydrite occurs in the



**Figure 4** - Detail of the black shale that compose the base of the Ipubi Formation in outcrops and quarries in the Araripina (Fig. 1). **a)** Detail of the contact between the massive shale (below) and the gypsum (above), Rocha Nobre Quarry, Ipubi; **b)** pavement of bituminous shale, Campevi mine, Araripina; **c)** detail of plant fragments and ichnofossils in the black shale.

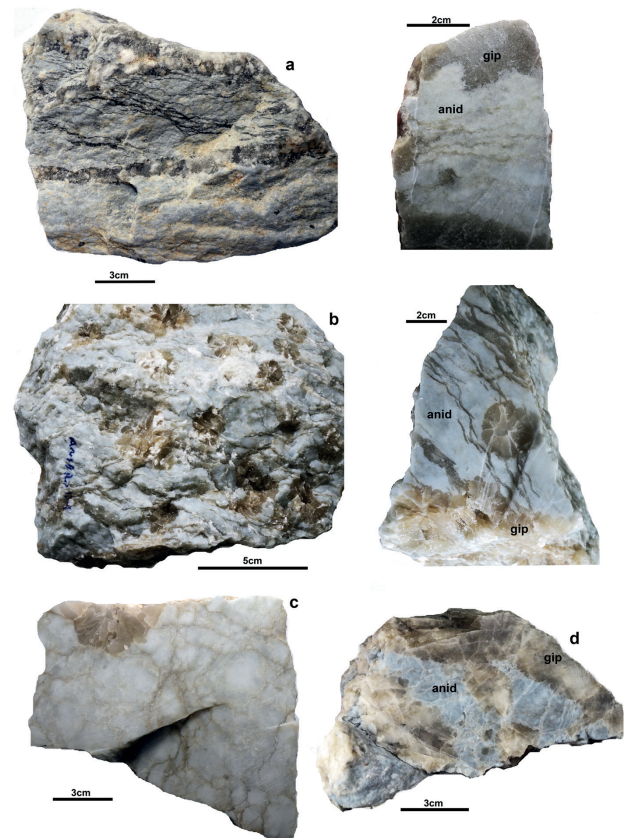




**Figure 5** - Samples of evaporites from the Ipubi Formation. **a)** Sample of massive, microcrystalline gypsum. The cutting surface shows small white nodules of recrystallized gypsum (black arrows); **b)** sample of recrystallized gypsum (rosettes); **c)** sample of laminated gypsum with white laminae of anhydrite (blue arrows). Red arrows indicate rosettes of recrystallized gypsum; **d)** sample of banded gypsum showing colors ranging from light to dark brown to white. Laminae are formed of fine grains of gypsum. Red arrows indicate recrystallized gypsum (rosettes).

form of massive lenses within gypsum beds, as isolated laminae in banded gypsum and as isolated nodules (Figs. 5 and 6). Facies interpretation herein proposed for the evaporites of the Ipubi Formation supports many ideas formerly presented by Silva (1986).

Two main types of diagenetic alterations are observed: 1 - fibrous gypsum that filled fractures; and 2 - gypsum rosettes formed by dissolution of primary deposits (Figs. 5, 6 and 7). The alteration of anhydrite to gypsum represents the main process that resulted in the formation of rosette gypsum

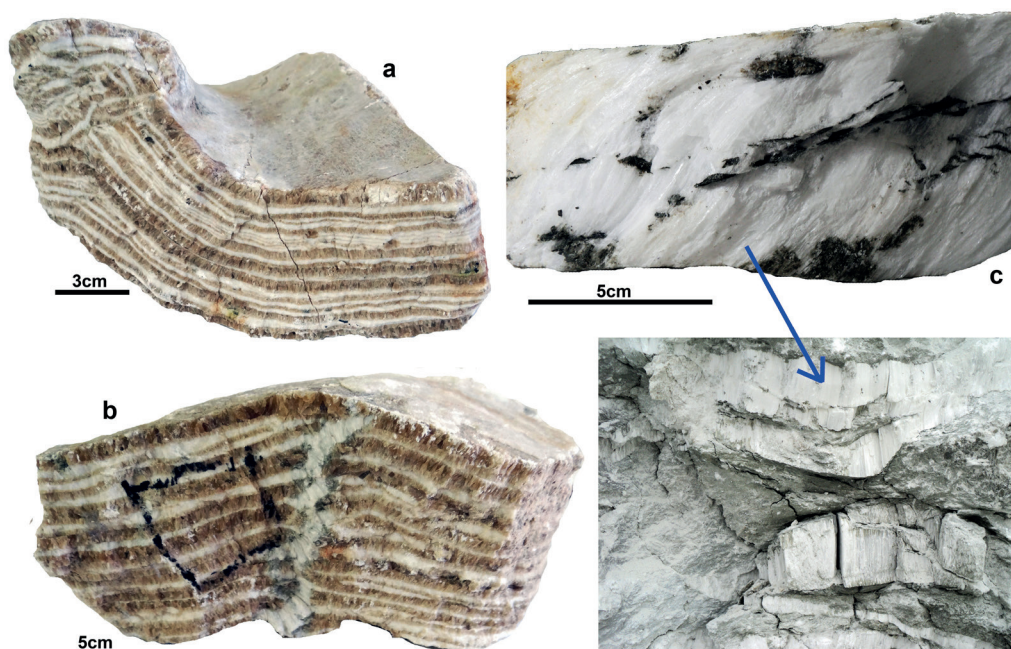


**Figure 6** - Samples of evaporites of the Ipubi Formation. **a)** Sample of massive anhydrite (anid), showing light brown branching veins of fine gypsum (gip) (diagenetic); **b)** sample of nodular anhydrite with diagenetic recrystallized gypsum veins and rosettes; **c)** samples of mosaic gypsum (gip); **d)** nodular anhydrite (anid) showing zones where it is altered to gypsum (gip).

and fine veins of gypsum within anhydrite masses (Fig. 6). Rosette gypsum also formed from primary gypsum deposits. Petrographic analyses of the present study suggest that part of the original gypsum was dehydrated during eo-diagenesis to form anhydrite; and anhydrite was altered again to form gypsum (mosaic gypsum, microcrystalline gypsum, and gypsum veins).

#### UPPER STRATIGRAPHIC BOUNDARY OF THE IPUBI FORMATION AND ITS RELATION WITH THE OVERLYING ROMUALDO FORMATION

In all quarries where the top of the uppermost evaporite layer is exposed, it records evidence of



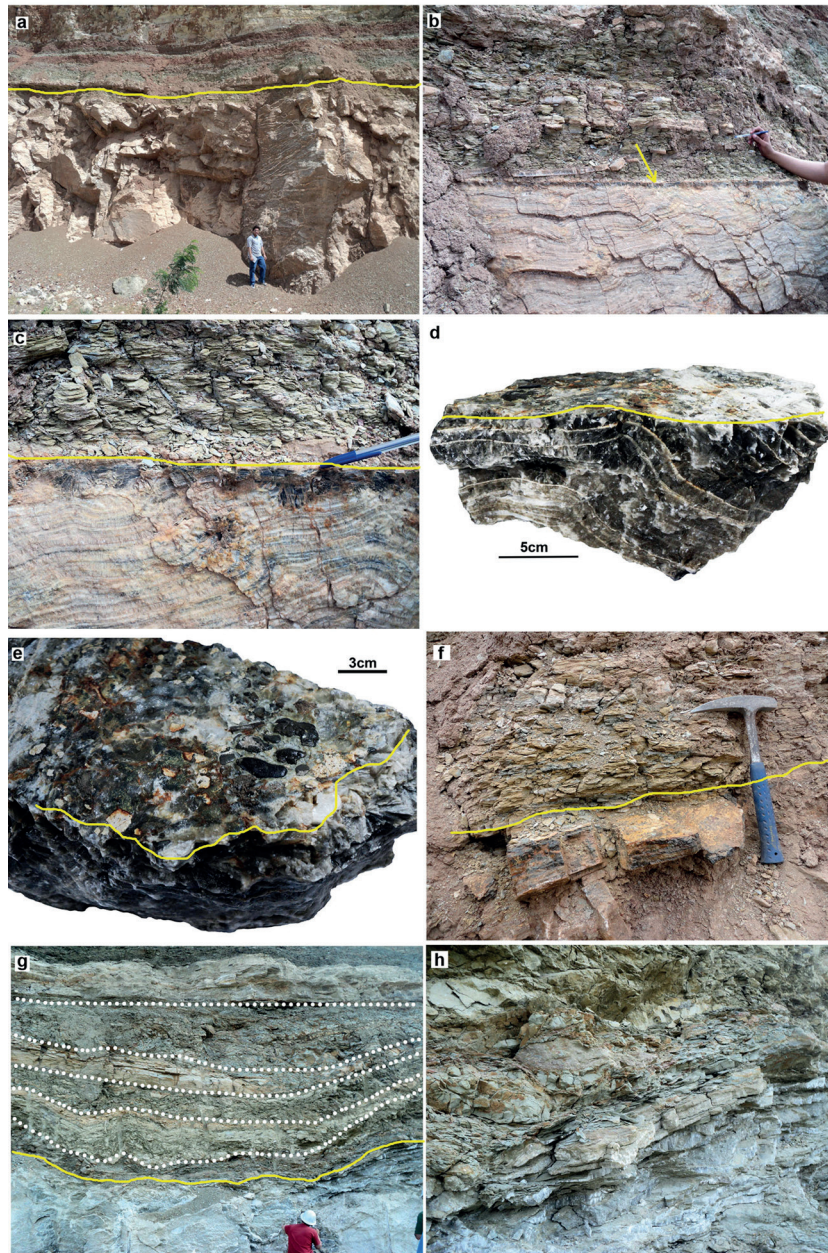
**Figure 7** - Samples of evaporites of the Ipubi Formation. **a)** Folded, laminated gypsum that has been deformed due to diagenetic processes (gypsum dehydration/anhydrite hydration); **b)** folded, laminated gypsum with a fracture that has been filled by fibrous gypsum; **c)** detail of fibrous gypsum filling a large fracture (vein). Black-greenish clay was injected in the fracture and formed thin laminae and lenses within the fibrous gypsum.

the subaerial exposure and erosion that preceded the deposition of the Romualdo Formation (Fig. 8). This stratigraphic surface is marked by the occurrence of reworked, angulated and oxidized clasts of gypsum, shale, quartz pebbles and fine-to-medium sand grains. Locally, it forms a cemented, usually few centimeters thick paleosol (gypcrete) (Fig. 8a, e). The subaerial exposure and erosion of the Ipubi evaporite layers had already been discussed by Silva (1983, 1986, 1988), who mentioned that the top of the Ipubi Formation is marked by a regional karst surface. This author suggested that after the deposition of the siliciclastic-evaporitic succession, the deposits of the Ipubi Formation were exposed and eroded, what created a karst paleorelief. Recent works have also associated this karst surface with a sequence boundary delineating the top of the Ipubi Formation (Fabín 2013, Assine et al. 2014).

In both studied areas a medium to coarse-grained, 20-30 cm thick sandstone bed occurs

above the unconformity bounding the Ipubi and Romualdo formations. It is locally conglomeratic and contains abundant clasts of gypsum, shale and sandstone formed by the reworking of Ipubi deposits (Fig. 8f, h). Evidences suggest that this bed represents a “transgressive lag”, formed during the new expansion of the lake (Fig. 8f).

The mechanical removal of Romualdo Formation deposits during the mining of the gypsum beds exposed the karst paleosurface formed at the top of the evaporite (Fig. 9). This surface records large isolated columns and scattered escarpments, pits and depressions (Fig. 9). The formation of the karst paleosurface may have lasted for thousands of years and once represented an impressive ruiniform landscape. The filling of the irregular karst topography caused large thickness changes in the basal strata at the base of the Romualdo Formation (Fig. 8g, h).



**Figure 8** - Sequence boundary at the top of the Ipubi Formation and the basal beds of the Romualdo Formation. **a)** Regional surface that marks the separation between the gypsum layers in the basal deposits of the Romualdo Formation; **b** and **c)** truncation surface at the top of the deformed gypsum layer; **d)** sample of banded gypsum from the top of the Ipubi Formation (São Jorge Quarry, Trindade), showing the truncation surface that formed a cemented pavement; **e)** cemented surface (gypsum crust) showed in **(d)**, which is a few centimeters thick and contains oxidized clasts of gypsum, shale, and quartz; **f)** detail of local coarse-grained sandstone at the base of the Romualdo Formation, that contains abundant reworked clasts of shale and gypsum; **g)** deposits of the Romualdo Formation deposited above an erosive surface, showing the influence of the syn-depositional dissolution of the gypsum (Vale do Gesso Quarry, Araripina); **h)** detail of the truncation surface showed in **(g)**. The Romualdo deposits rest directly on the unconformity (Pedra Branca Quarry, Nova Olinda).



**Figure 9** - Exposure of the top of the gypsum in the Sombra da Serra Quarry, Araripina, after the removal of the Romualdo Formation deposits. The exposed paleorelief appears to be a ruiniform landscape formed by intense karstification.

Bed thickness at the base of the Romualdo Formation reflects syn-sedimentary generation of accommodation space caused by the dissolution and collapse of upper evaporite beds of Ipubi Formation. This process created large folds and listric faults in the deposits of Romualdo Formation (Figs. 10 and 11). The structures seen in Figure 10b represent examples of syn-depositional sagging sinkhole structures (Gutiérrez et al. 2008a). The Romualdo transgression also caused the injection of water saturated siliciclastic deposits into fractures and vugs (Fig. 10d, e). As deposition continued, the load caused new failures and the collapse of karst, which generated the faulting of the Romualdo Formation strata to accommodate the syn-depositional deformation (Figs. 10, 11 and 12). Large areas over evaporite layers underwent collapse and subsidence, which generated continuous fault propagation (growth faults) within the Romualdo Formation. This deformation occurred when deposits were not completely consolidated, which created a series of soft-deformation structures, including convolute beds, microfaults and folds. The deformation of more ductile beds caused the propagation of listric faults

within isolated levels of the Romualdo Formation (Fig. 11).

Collapse and faulting continued after the Cretaceous, probably due to the exposure of the Romualdo and Ipubi formations caused by denudation of the basin during the Cenozoic, which increased the percolation of meteoric fluids. Examples of present active subsidence caused by evaporite karstification are well known in regions where underground evaporite deposits, especially gypsum, represent geological hazards in Spain, France, England and United States (Gutiérrez et al. 2002, 2008b, Yilmaz et al. 2011).

In Figure 12a, a series of moderate- to high-angle faults are seen in a large exposure of deposits from the Romualdo Formation. The geometry created by the faults and the collapse structure formed a sagging synform (Fig. 12) (Gutiérrez et al. 2008a). Although some features indicate that these faults are syn-depositional, the propagation of fault planes through Neogene deposits over the Romualdo Formation indicates that this process continued until recently, albeit on a smaller scale. In Figure 12b, a collapse structure is shown. It exhibits variation in the lateral thicknesses of the beds around the collapse indicating that this local subsidence is syn-depositional, caused by initial dissolution of the evaporite bed. However, the collapse probably occurred after deposition due to continued dissolution of the gypsum bed. This collapse structure can be classified as a sagging+suffosion structure (Gutiérrez et al. 2008a). Suffosion represents the downward migration of the cover through dissolution conduits and is coeval with ductile accommodation (Gutiérrez et al. 2008a).

## DISCUSSION

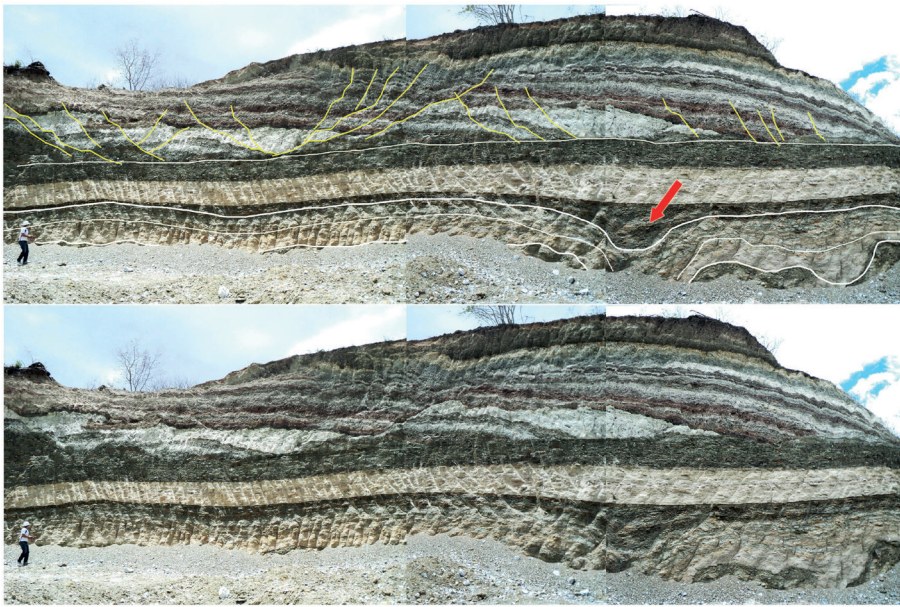
The results here presented indicate that the top of the Crato Formation is a regional unconformity caused by a relative lake level fall that exposed



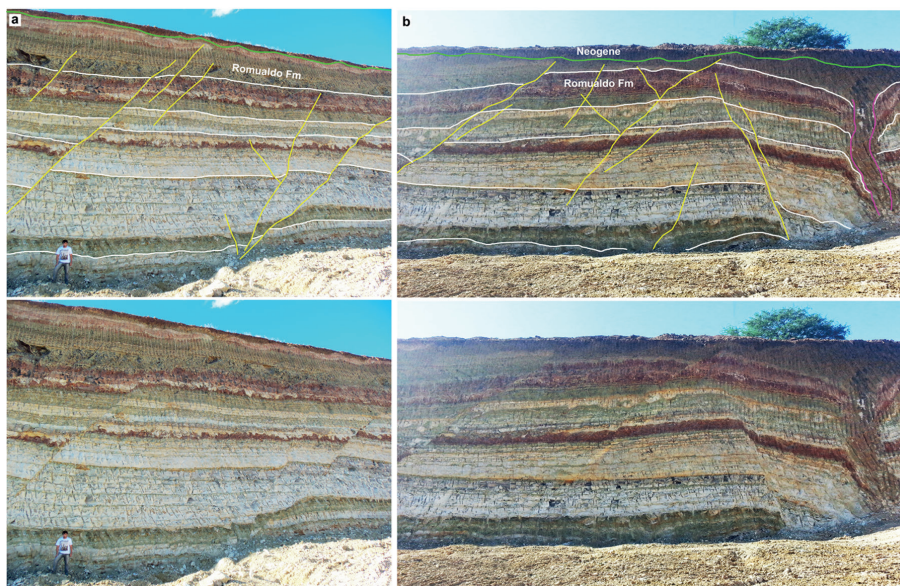
**Figure 10** - Contact between the Ipubi and Romualdo formations. **a)** Boundary between both units (yellow lines), with no evidence of karstification (Pedra Branca Quarry, Nova Olinda); **b)** example of dissolution feature formed at the top of the gypsum (synform sagging), with syn-sedimentary filling of the karst structure by the deposits of the Romualdo Formation (Conceição Preta Quarry, Santana do Cariri); **c)** the surface of the gypsum layer is exposed after the mechanical removal of the Romualdo Formation deposits on the right side. On the left side, the folded deposits of the base of the Romualdo Formation can be seen (Supergesso Quarry, Araripina); **d)** and **e)** clayey deposits infiltrated into fractures and small sinkholes during the transgression of the Romualdo Formation (Puluca Quarry, Ipubi).

these deposits in proximal areas. This unconformity marks a major retreat in the relative lake level (Neumann 1999, Assine et al. 2014), following a series of pulses of expansion that culminated with the formation of the uppermost interval of laminated limestones (C6 interval) (Fig. 3). The top of the C6 interval is marked by evidence of subaerial erosion, reworking and pedogenetic features (calcretes with local silicification) (Fig. 3).

Directly overlying the unconformity at the top of the Crato Formation are the bituminous black shales of the Ipubi Formation, which contain up to 25% TOC. This lithology represents evidence of a transgressive pulse caused by a relative lake level rise (Fig. 4). Occurrence of these shale beds is recorded across the basin in proximal domains, in wellbores and outcrops on the northern borders. On the northern border, these shale beds overlie the



**Figure 11** - Deposits of the Romualdo Formation exposed in the Pedra Branca Quarry, Nova Olinda. The paleorelief created by karstified surface of the gypsum controlled the geometry of the basal beds. Syn-sedimentary karstification (sagging+suffosion) caused collapse (red arrow) and influenced deposition by creating additional accommodation space. Additionally, the instability created by the continuous effect of karstification caused the deformation of beds that were not completely consolidated (upper bedding), thus forming complex sets of listric faults (yellow lines), folds, and rollovers.



**Figure 12** - Deposits of the Romualdo Formation in the Sombra da Serra Quarry, Araripina. **a)** Detail of a large exposure showing syn-sedimentary faults caused by the syn-depositional dissolution of the gypsum; **b)** syn-depositional faults (yellow lines) created by local subsidence due to the dissolution of the gypsum. The left side of the panel shows a collapse structure (suffosion) created by a sinkhole (pink lines) (Gutiérrez et al. 2008a, b). Note that the faults control bed thickness (accommodation space).

Crato Formation deposits, whereas at the southern border, they were deposited over the basement. On the southern border, these shale beds are more often intercalated with calciferous siltstones, sandstones and thin limestone beds. Deposition of shale beds over previously exposed proximal areas suggests that this new transgression expanded the domains of the lake beyond its previous limits. These bituminous black shales, formed under anoxic conditions, indicate that the water column was at least a few tens of meters deep (Tourtelot 1979, Farouk et al. 2016, Jiang et al. 2016). The abundance of organic matter and high sedimentation rates, as well as some restriction of circulation, are important processes that have also influenced the enrichment on organic matter (Tourtelot 1979). After the transgressive pulse, with the stagnation of the relative lake level (high stand conditions), arid conditions may have prevailed and influenced the formation of salinas, or coastal sabkhas, which allowed the formation of evaporite deposits (Figs. 5 to 7). Coastal sabkhas represent water bodies that are filled with brine and form during the retreat of seaways (Warren 2006, Warren et al. 2010). The present study found that during the diagenesis the alteration of anhydrite to gypsum within the Ipubi Formation caused pervasive folding and fracturing of the gypsum layers (Fig. 7). This process increased during the exhumation of deposits (under meteoric influence) along Cenozoic. Similar aspects regarding the effects of dehydration on primary gypsum are described by Abrantes Jr et al. (2016) for the Paleozoic siliciclastic-evaporitic deposits of the Parnaíba Basin, Brazil. Silva (1986) proposed that primary textures of evaporites from Ipubi Formation are represented by laminated gypsum composed of prismatic crystals, nodular anhydrite and laminated anhydrite. According to this author, secondary textures are represented by microcrystalline gypsum, rosette gypsum, and fibrous gypsum that fills veins. Nascimento Jr et al. (2016) studied the origin of the Ipubi Formation

deposits, and the diagenetic aspects involved in its evolution. They proposed that the shale and evaporite beds formed in a shallow environment, characterized by anoxic water bodies locally hypersaline under seasonal variations of relative lake level. Nascimento Jr et al. (2016) also suggested that the deposition occurred in playa lake systems under some influence of hydrothermalism, and that these rocks underwent shallow burial due to the frequent occurrence of primary gypsum.

The possible tectonic influences that may have triggered the Ipubi inundation, including marine incursions, remain a topic of debate (Assine et al. 2014, Nascimento Jr et al. 2016). The Ipubi and Romualdo formations are Aptian-Albian in age, which corresponds to the post-rift phase of this interior basin. However, the rift phase lasted until the Upper Aptian-Early Albian in the equatorial margin and the eastern margin of the South Atlantic (Matos 1992, 1999), which could have represented some post-rift influence in marine transgressions to the interior basins.

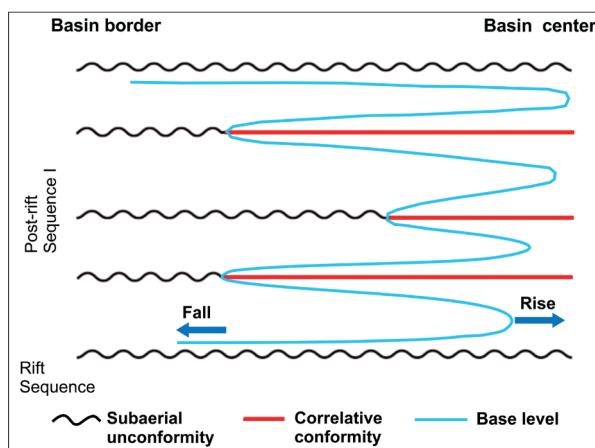
Evaporite deposits in modern salinas include halite, gypsum, laminites, organic carbon-rich siliciclastic sediments, and carbonates (Warren 2006). The occurrence of isolated brines that formed over small depressions, where restrictive conditions created stratified brines, could explain the formation of the discontinuous evaporite layers of the Ipubi Formation. Another important point, confirmed by available boreholes in the basin, is the fact that evaporites did not form in distal domains; this implies that the physiography and climate conditions drove evaporite deposition, which predominantly occurred in proximal regions (Fig. 14). The deposition of carbonate-prone or fine-grained siliciclastic sediments continued in distal regions.

Then, a new subaerial unconformity formed during the maximum of the subsequent relative lake level fall, and erosion affected the evaporite beds and other lithologies of the Ipubi formation

deposited in proximal zones. A correlative conformity overlying other lithologies certainly formed in the distal regions of the lake (Fig. 13), thus representing the continuation of the subaerial unconformity (Catuneanu 2006, Catuneanu et al. 2009, 2011) (Fig. 14). The formation of this correlative conformity may have been associated with low sedimentation rates caused by the reduction of hydraulic potential and the influx of sediments under arid conditions. Figure 13 shows a schematic model to represent the relations between the main changes in the relative lake level and the formation of unconformities. In this model, a tectonic-influenced basal unconformity separated deposits of the rift phase from those of the post-rift depositional sequences. Within the post-rift succession subaerial unconformities and correlative surfaces are formed in proximal and distal regions, respectively, and the composite surface created represent the idealized sequence boundaries between the Crato, Ipubi, and Romualdo formations (Figs. 13 and 14).

An important unknown aspect of the erosive event that affected the top of the siliciclastic-evaporitic depositional sequence is its temporal magnitude and the diachronism associated with the formation of the correlative conformity across the basin. The frequency of relative lake level cycles (Figs. 13 and 14) is greatly influenced by climate factors, which suggests that diachronism of stratigraphic events of the Araripe Basin could be shorter than observed in stratigraphic events in marginal basins (Pietras and Carroll 2006).

An important question still remains concerning the lateral relationships between the lithologies of the Ipubi Formation and their distal coeval counterparts, that formed within areas not affected by subaerial erosion. Bobco (2014) proposed that the Crato and Ipubi Formations were deposited contemporaneously and that their different lithologies are the result of lateral variations. The author pointed to the aerial distribution of these lithofacies and the common relationships between



**Figure 13** - Schematic model of variations in the relative base level of the lake and the formation of unconformities. The major basal unconformity separates the deposits of the rift phase from those of the post-rift sequences. The unconformities within the post-rift sequences were caused by variations in the relative base level of the lake driven mainly by climate fluctuations. These unconformities comprise subaerial erosional surfaces (proximal) and correlative conformities (distal) (modified from Catuneanu 2006).

carbonate and evaporites in evaporitic systems. However, the interdigitation of laminated limestones and evaporites is not observed in borehole records (Fig. 2), nor in outcrops. In addition, the existence of a regional erosive unconformity separating the facies associations of the Crato and Ipubi formations has been widely recognized (Neumann 1999, Assine et al. 2014). Thus, the proposition of a sequence boundary between these units that occurs in proximal areas is consistent.

#### STRATIGRAPHIC MODEL FOR THE IPUBI FORMATION

Here, a depositional model is proposed for the formation of the siliciclastic-evaporitic succession of the Ipubi Formation on the proximal regions of the Araripe Basin. The model shows how evolution of major changes in relative lake level influenced the deposition and the formation of regional unconformities, considering an adaptation of the original concepts of sequence stratigraphy.



The model is based in the assignment of the main relative lake level stages (Transgressive System Tract, High Stand System Tract and Low Stand System Tract) throughout the studied succession, encompassing six episodes (Fig. 14):

**Stage I** - Pulsating expansion of the Araripe Lake during the post-rift phase created few depositional sequences (Neumann 1999), including the Crato Formation (Neumann and Cabrera 2002, Silva et al. 2015) (Fig. 14). There is no evidence of major relative lake level falls during the deposition of the Crato Formation, although the presence of stratigraphic levels recording the mass mortality of young specimens of fishes (*Dastilbe elongatus*) and halite pseudomorphs suggests that hydrological/biological conditions (eutrophication, salinity and oxygenation) may have experienced oscillations. The formation of halite pseudomorphs (hoppers) (Martill 2007) may indicate that minor relative lake level falls or severe climate periods occurred, although carbonate deposition continued (Martill 2007, Heimhofer et al. 2010). These oscillations may have intensified the dense-stratified effect of the water column, thus increasing the anoxic conditions in the deeper regions of the lake.

**Stage II** - At the end of the cycle that formed the Crato Formation, a major fall in the relative lake level caused the subaerial exposure of proximal regions (Fig. 14). This caused an erosional process that affected the deposits of this unit (Neumann 1999). The lowest position of the relative lake level marks the maximum expression of the subaerial erosion and the first sequence boundary of the studied succession.

**Stage III** - A new relative lake level rise occurred and caused an important transgression over the proximal areas, including regions not previously covered by the basin domains. This event possibly caused the drowning of sedimentary sources. The balance of sedimentary influx and organic production influenced the establishment of anoxic conditions. Siliciclastic deposits, which are

dominated by calciferous organic-rich black shales, were deposited above the unconformity of the top of the Crato Formation. These deposits mark the base of the Ipubi Formation (Fig. 14).

**Stage IV** - After the transgressive pulse, the stagnation of the relative lake level established a high stand, under increasingly arid conditions, that led to the formation of isolated salinas or coastal sabkhas along the proximal regions. Increasing stagnation and small oscillations in the relative lake level possibly are the causes of the main phase of evaporites deposition of the Ipubi Formation (Fig. 14). Most of the evaporite deposits formed under subaqueous conditions and are intercalated with fine-grained siliciclastic deposits (Fig. 14). These isolated salinas or sabkhas may have been intermittently connected with the lake waters, which caused occasional interruptions in evaporite deposition.

**Stage V** - Another expressive relative lake level fall ended the deposition of siliciclastic-evaporitic succession in proximal regions. This forced regression exposed the proximal zones, and triggered the karstification processes of evaporite beds (Fig. 14). The consequent erosion and reworking of evaporite deposits, and other lithologies, created a new sequence boundary (Silva 1986, Fabin 2013) that marks the upper limit of the Ipubi Formation. According to the biostratigraphic record obtained from boreholes across the basin, siliciclastic sedimentation continued within the depocenters, what indicates that the relative lake level was not completely depleted, and a correlative surface probably formed across distal regions. The karstification processes of the evaporite layers, created a ruiniform relief featuring escarpments, depressions and sinkholes.

**Stage VI** - A new transgressive event triggered by a new relative lake level rise created the depositional sequence that comprises the Romualdo Formation what overlies the Ipubi Formation (Fig. 14). The marine influence on this

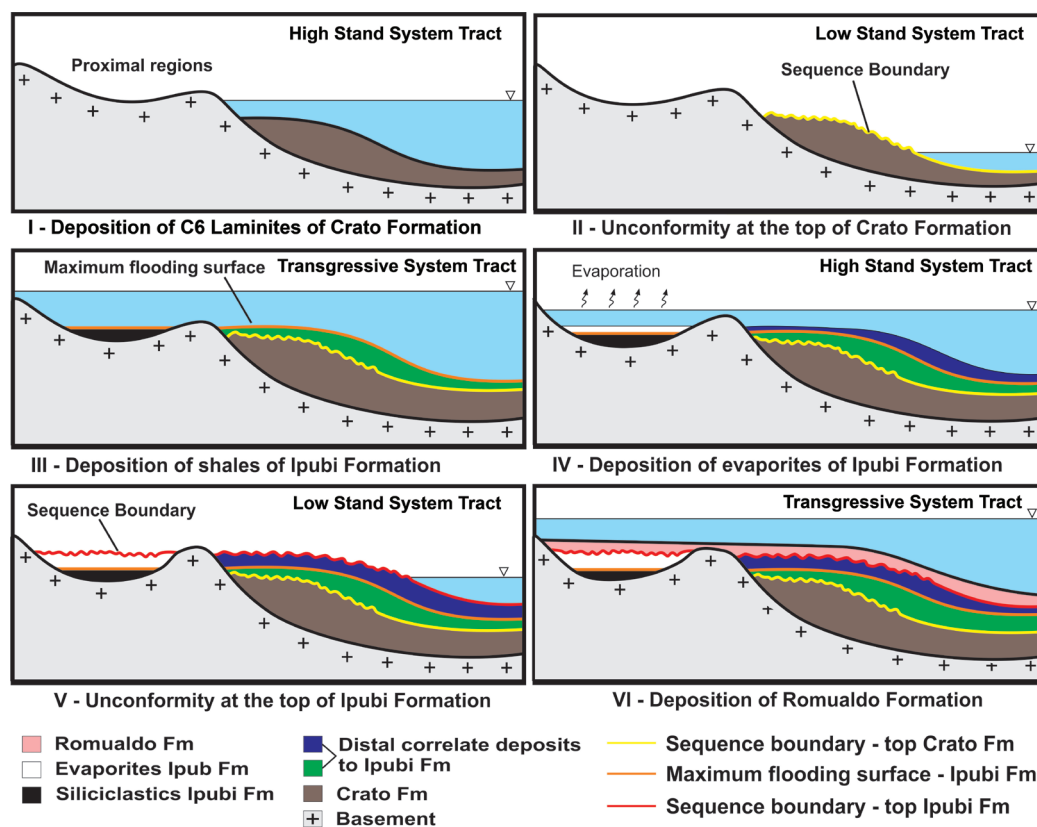
transgression, that established a seaway in the interior of Northeast Brazil, is well documented by abundant occurrence of marine fossils (sharks and rays) (Martill 1988, Kellner 2002, Saraiva 2008). This new transgression, that followed the erosion of evaporite beds, caused a renewed syn-depositional karstification of these deposits. The new inundation caused syn-depositional variations in accommodation space due to the increase in dissolution and collapse of the upper evaporite bodies, as well as the syn-depositional deformation of the strata of the Romualdo Formation.

#### PROPOSED CURVE OF RELATIVE CHANGES IN ARARIPE RELATIVE LAKE LEVEL DURING THE DEPOSITION OF THE IPUBI FORMATION

A curve comprising the changes in the Araripe relative lake level during the deposition of the

studied interval is proposed (Fig. 15). It represents a tentative approach based on the adaptation of concepts of sequence stratigraphy to establish a model for the Araripe Lake evolution during the studied interval, which can be further tested in future stratigraphic investigations with the addition of new borehole and/or seismic data.

The proposed relative lake level curve was divided into three main pulses of transgression bounded by two regional unconformities. The major trigger of the major and minor changes in the relative lake level may have been the climate. Tectonic pulses (post-rift reactivations) that could have influenced marine ingressions remain a topic of debate. Interpretation of the relative lake level changes presented here corroborates some propositions made by Neumann (1999) and Assine et al. (2014), about the establishment



**Figure 14** - Schematic model of the evolution of the depositional sequences corresponding to the Crato, Ipubi and Romualdo formations. Major variations in the Araripe Lake level controlled the formation of these sequences.

of depositional sequences controlled by the expansions and retractions of Araripe Lake during the post-rift phase I.

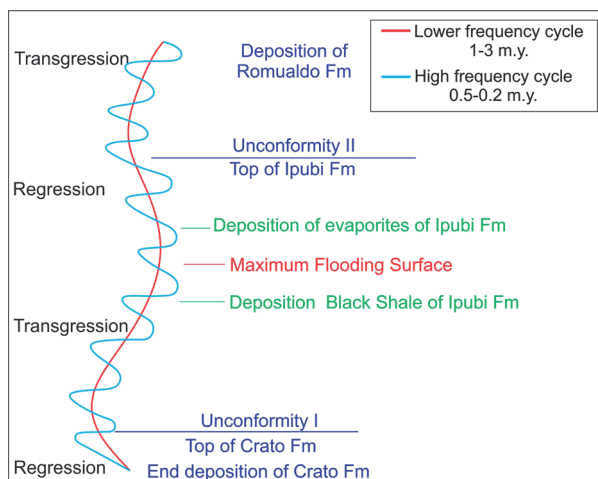
### FINAL CONSIDERATIONS

The application of sequence stratigraphy concepts guided the identification of the relationships between variations in the relative level of Araripe Lake and the formation of depositional sequences within the post-rift phase I during the Aptian-Albian. Data collected from outcrops and boreholes indicate that the Ipubi Formation is separated from the underlying Crato Formation and the overlying Romualdo Formation by regional unconformities in proximal domains. The lower unconformity separates the top of the Crato Formation, which is mainly represented by its uppermost interval of laminated limestones (C6), from the basal black shales and claystone deposits of the Ipubi Formation. These basal deposits formed due to the transgressive event that expanded the relative lake level beyond the previous extension of the Crato Formation over the adjacent basement areas. During the Ipubi transgression, anoxic conditions influenced the formation of basal black shales with

high values of TOC. The following relative lake level stagnation and increasingly arid conditions influenced the establishment of a high stand stage that led to the formation of coastal sabkhas or salinas. This high stand stage allowed the formation of isolated masses of gypsum and anhydrite to occur, which culminated in the deposition of discontinuous evaporite beds at the top of the succession. A second major relative lake level fall generated a regional subaerial unconformity that affected the Ipubi deposits (mainly the evaporites). Extensive pedogenetic processes and karstification then occurred, which created a paleorelief. A new transgression followed and caused the deposition of the carbonate-siliciclastic succession of the Romualdo Formation over the Ipubi Formation. The deposition of the Romualdo strata was influenced by the continuation of the karstification processes within the Ipubi evaporites. This process created collapse structures, the infiltration of siliciclastic sediments into the fractures and karsts of the Ipubi Formation, and the syn-depositional deformation of the Romualdo deposits with the formation of listric faults, local convoluted deformation and folding. The occurrence of syn-depositional deformation during the deposition of the Romualdo Formation, due to the dissolution and collapse of evaporite deposits, represents an important example of the influence that evaporite karstification can exert on depositional processes.

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**Figure 15** - Schematic curve of changes in the relative base lake level of Araripe Lake during the depositional period of the Ipubi Formation (time span related to the distinct cycle frequencies are from Neumann 1999).

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