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ARTICLE

Facies analysis, sequence stratigraphy and chemostratigraphy of the Sete Lagoas Formation (Bambui Group), northern Minas Gerais State, Brazil: evidence of a cap carbonate deposited on the Januária basement high

Análise de fácies, estratigrafia de sequências e quimioestratigrafia da Formação Sete Lagoas (Grupo Bambuí), norte do Estado de Minas Gerais, Brasil: Evidência de um carbonato de capa depositado sobre o Alto de Januária.

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ABSTRACT: Sedimentary rocks of the Sete Lagoas Formation, exposed in the left margin of the São Francisco river (Minas Gerais State, Brazil), were deposited on the Januária-Itacarambi basement high. They show both lateral and vertical rock stacking along continuous outcrops, allowing us to carry out detailed facies analysis and sequence stratigraphy studies. Our studies also integrate data from geological mapping, macro and microscopic petrography and high-resolution C and O isotope analysis. Eight facies and four facies associations make up a sequence composed by a transgressive tract in the base, and a high stand tract in the upper portion, separated by a maximum flooding surface. The high stand tract shows a progradation stacking from the basement high apex towards progressively deeper basement areas. This stratigraphic framework, associated with others stratigraphic and isotopic features, indicates that the now exposed Januária basement high also represents a paleo-high during the sedimentation event. Aragonite pseudomorphs and dolomites coupled with $\delta^{13}C$ values of -5‰ characterize the basal carbonate of the transgressive tract as a cap carbonate. Records of the *Cloudina* fossil, recognized in the high stand tract, indicate a Late Ediacaran age for the upper portion of the studied stratigraphic sequence.

KEYWORDS: sequence stratigraphy; chemostratigraphy; cap carbonate.

RESUMO: *Rochas sedimentares da Formação Sete Lagoas afloram na margem esquerda do Rio São Francisco, na região de Januária–Itacarambi, Minas Gerais, em seções relativamente contínuas, tanto lateralmente como no empilhamento vertical. Boas exposições associadas à preservação de estruturas/texturas primárias favorecem o estudo de fácies, e de estratigrafia sequencial. Este estudo estratigráfico foi realizado com a integração de dados de mapeamento geológico, petrografia macro e microscópica e de três perfis estratigráficos chaves, onde foram realizados levantamentos quimioestratigráficos (C e O) de alta resolução. Foram reconhecidas oito fácies e quatro associações de fácies distribuídas em uma sequência composta por um trato de sistema transgressivo na base, e um trato de sistema de mar alto na porção superior, separados por uma superfície de inundação máxima. O padrão de empilhamento do trato de mar alto apresenta uma progradação das fácies, do alto do embasamento, em direção a áreas onde o topo do embasamento é progressivamente mais profundo. Este arcabouço estratigráfico, associado com outras feições estratigráficas e isotópicas, indica que o alto de Januária atuou como um alto do embasamento durante o evento sedimentar da Formação Sete Lagoas. Estudos quimioestratigráficos e petrográficos permitiram caracterizar o carbonato basal da Formação Sete Lagoas como um carbonato de capa na base do trato transgressivo, onde ocorrem dolomitos e pseudomorfos de aragonita associados a valores de δ13C de até -5‰. Registros do fóssil Cloudina, recuperados no trato de mar alto, indicam uma idade associada ao Ediacarano Superior para a porção superior da sequência estratigráfica estudada.*

PALAVRAS-CHAVE: *estratigrafia de sequências; quimioestratigrafia; carbonato de capa.*

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INTRODUCTION

One of the largest areas with good exposure of the Sete Lagoas Formation is located in the Januária-Itacarambi region (northern Minas Gerais state, Brazil), along the eastern sector of the São Francisco craton (Fig. 1). A major feature of this region is the Januária high, where the crystalline basement is relatively shallow and crops out in restricted stratigraphic windows (Alkmim and Martins-Neto 2001). The study area (latitudes 15°30'S – 15°12' S, longitudes 44°30'W – 44°00'W) encompasses the southern portion of the Januária map sheet (Uhlein *et al.* 2015).

The Sete Lagoas Formation is the lowermost unit of the Bambuí Group, the characteristic stratigraphic unit of the São Francisco basin (Alkmim and Martins-Neto 2001). The Bambuí Group has its genesis associated with the subsidence caused by the overload of Brasiliano orogenic belts on the borders of the São Francisco craton, in a foreland basin context (Castro and Dardenne 2000; Alkmim and Martins-Neto 2001; Sial *et al.* 2010; Uhlein 2013) (Fig. 1).

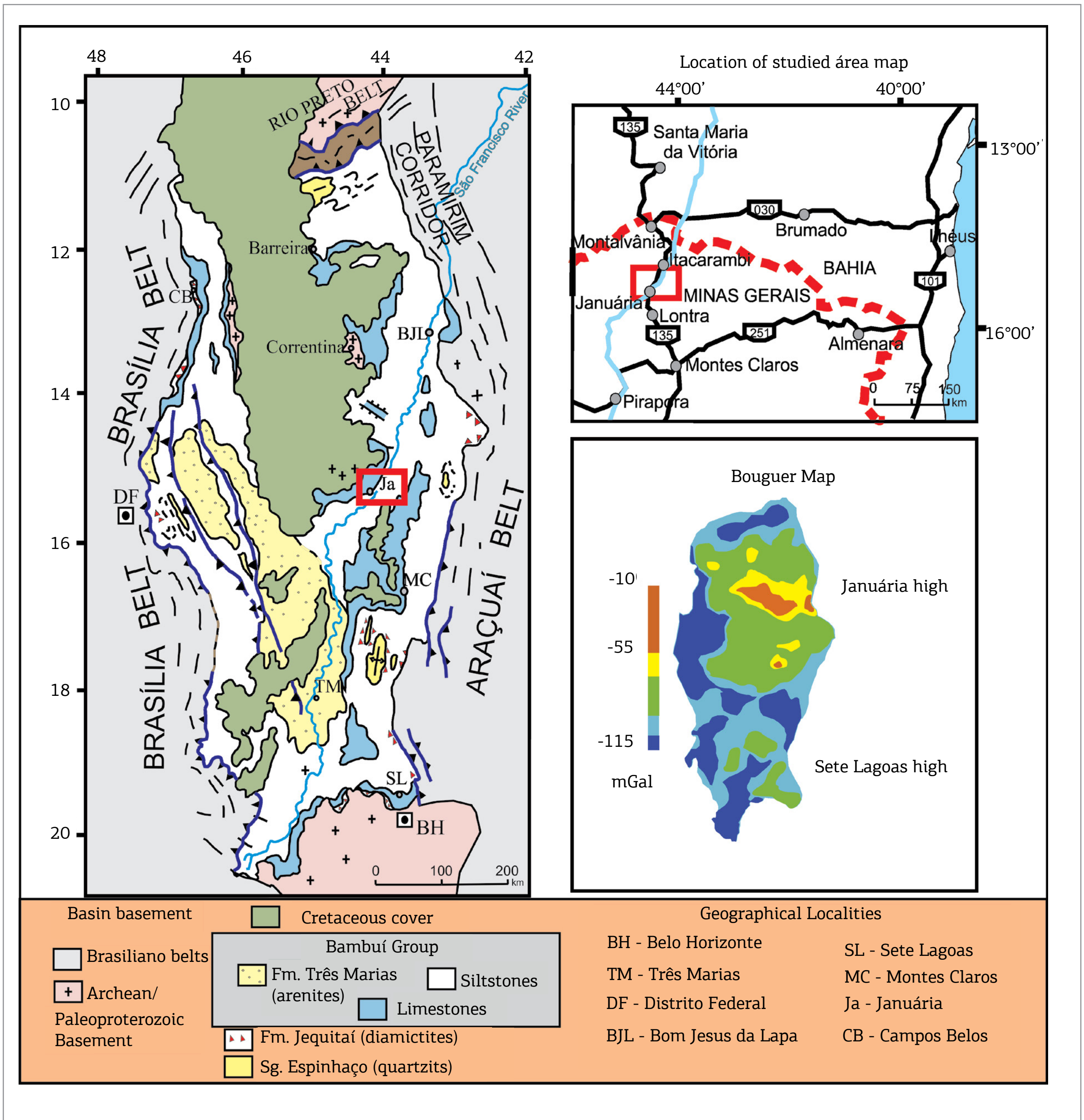

Figure 1. Simplified geological map of the São Francisco Basin bordered by adjacent mobile belts (modified from Uhlein, 2013). The red quadrangle represents the studied area. The location of the Januária high is shown in the bouguer anomaly map to the right (modified fom Reis and Suss, 2016).

The Sete Lagoas Formation lies unconformably on the Archean-Paleoproterozoic basement of the São Francisco craton and, locally, it conformably overlies glaciogenic diamictites of the Jequitaí Formation and its correlative units (Dardenne 1978; Dardenne and Walde 1979, Uhlein *et al.* 1995, 2004; Caxito *et al.* 2012).

In the Januária region, the Sete Lagoas Formation comprises a continuous horizon inside a cratonic stable area (Dardenne 1978), which outcrops on the left side of the São Francisco river. Dardenne (1978) named this unit "Januária Formation". He described a carbonate package, with marl and pelite intercalations, consisting of characteristic facies succession, comprising from base to top:

1. laminated dolomites;
2. purple to beige finely laminated argillaceous limestone;
3. finely laminated gray argillaceous limestone;
4. finely laminated gray limestones;
5. dark gray limestones with ooliths or tabular intraclasts,
6. dolomites with ooliths and intraclasts and
7. beige laminated dolomites with tabular intraclasts and rare columnar stromatolites.

Iglesias (2007) conducted a regional mapping (1:250,000) in the São Francisco Valley, northern Minas Gerais, and registered thicknesses around 200 m for the Sete Lagoas Formation. Brandalise (190) and Abreu-Lima (1997) worked with well data drilled to the north and south of the study area, and reported thickness of 486 and 360 m, respectively. Dardenne (1979) and Nobre-Lopes (2002) presented petrographic and isotopic studies, focusing on Pb-Ag-Zn-F mineralization of the Sete Lagoas carbonates at the Januária region. Dardenne (1981) assigned a transgressive-regressive megacycle for the Sete Lagoas Formation. Martins and Lemos (2007) performed regional sequence stratigraphic study in the São Francisco basin, and proposed a limit of sequences in the upper third of the Sete Lagoas Formation, subdividing it in lower and superior sequences. This unconformity, probably associated with a second order surface, is recognized at basin level, and encompasses subaerial exposure indicative features, isotopic shift of 5‰ in $\delta^{13}C$ curve (Martins and Lemos 2007; Caxito *et al.* 2012; Uhlein 2013), and a change in the seismic velocity (Zálan and Romeiro-Silva 2007). Vieira *et al.* (2007) made a detailed stratigraphic and chemostratigraphic survey of the Sete Lagoas Formation in the type area, the Sete Lagoas high, in the south of the basin.

Several studies reported dolomitic facies with sharply $\delta^{13}C$ negative values, some of them concordantly superimposed on glaciogenic diamictites (Misi *et al.* 2011; Caxito *et al.* 2012; Paula-Santos *et al.* 2015). Such deposits at the base of the Sete Lagoas Formation have been interpreted as cap carbonates (Misi 2001; Martins and Lemos 2007; Lima 2011; Misi *et al.* 2011; Caxito *et al.* 2012; Paula-Santos *et al.* 2015; Kuchenbecker *et al.* 2016). The Sete Lagoas cap carbonates have been related to the Sturtian glaciation (~740 Ma; Babinski *et al.* 2007; Vieira *et al.* 2007), Marinoan glaciation (~635 Ma, Caxito *et al.* 2012), and Marinonan or younger glaciation (Lima 2011).

Age determinations for the Bambuí Group have experienced important advances in the last decade, with new data originated mainly from the Sete Lagoas Formation. Most data published before the 2000's only suggested a wide time span (600 – 790 Ma; cf. Martins-Neto and Alkmin 2001). Babinski *et al.* (2007) published a whole-rock Pb-Pb isochronic age of ca. 740 Ma, obtained from aragonite pseudomorphs facies of the lower Sete Lagoas Formation, and interpreted them as cap carbonates of the Sturtian glaciation. Thereafter, younger ages have been suggested by U-Pb analysis on detrital zircons and discoveries of fossiliferous records. Rodrigues (2008), Lima (2011) and Kuchenbecker *et al.* (2015) obtained a maximum depositional age of ca. 610 Ma, based on U-Pb data from detrital zircon grains. Warren *et al.* (2014) discovered the index fossil *Cloudina* in grainstones of the Sete Lagoas basal sequence of the Januária region, determining an Upper Ediacaran age (550 – 542 Ma) for this section. More recently, Paula-Santos *et al.* (2015) published U-Pb ages of detrital zircons from the lower and upper sequences of the Sete Lagoas Formation, which provided a maximum depositional age around 550 Ma for the southeastern part of the Bambuí basin, in agreement with the *Cloudina* fossil record.

The discovery of late Ediacaran index fossil, in the Sete Lagoas basal sequence, has raised important questions concerning the age/correlation of the Sete Lagoas cap carbonate. As a consequence, Warren *et al.* (2014) and Paula-Santos *et al.* (2015) suggested the existence of an unconformity within the Sete Lagoas lower sequence, to justify the time span between a possible Sturtian cap carbonate and the *Cloudina*-bearing layer.

The objective of this paper is to discuss geological features of the Januária area, focusing on the results of a detailed facies and sequence stratigraphic analysis, coupled with high resolution chemostratigraphic survey. In this area, continuous outcrops encompassing both the strata bearing the fossil *Cloudina* and the cap carbonate favored a better understanding of the stratigraphic framework of the Sete Lagoas basal sequence, allowing us to evaluate the possibility and magnitude of discontinuities.

Januária sheet geological overview

The studied area can be divided in two geological compartments, geographically separated by the São Francisco river NE course (Fig. 2). In the western compartment, the Sete Lagoas Formation dominates, with outcropping thicknesses between 100 and 140 m. The Sete Lagoas Formation comprises sub-horizontal layers containing the first 2/3 of the classic succession established by Dardenne (1978), and is limited at the base and at the top by unconformities that separate it, respectively from the Archean/Paleoproterozoic Basement and from the Urucuia Group, of Cretaceous age. The basement consists of gneiss and monzogranites, and outcrops in small extensions associated with secondary drainages in the northern area. The Urucuia Group comprises texturally mature, weathered sandstones mapped on the polygon western border.

On the right side of the river, in the southeast, the Bambuí Group is represented by a younger succession of sub-horizontal layers, consisting of Serra de Santa Helena, Lagoa do Jacaré and Serra da Saudade formations. Along the river margins, there is a wide plain with Neogene cover separating the compartments above mentioned.

SETE LAGOAS FORMATION FACIES ASSOCIATIONS IN THE JANUÁRIA REGION

in the eastern area, where the Sete Lagoas Formation has excellent exposure, three locations indicated on the map (Fig. 2) were selected for stratigraphic profiles. These stratigraphic profiles (Fig. 3), integrated with geological mapping data, formed the basis for the study of facies, or facies association, of the Sete Lagoas Formation. This study recognized four facies associations distributed in eight facies (Figs. 4A, 4B, 4C, 5A, 5B, 6A, 6B, 6C, 6D, 6E, 6F, 7A, 7B, 7C, 7D, 7E, 7F, 7G, 7H, 8A, and 8B) as shown in Table 1.

Outer platform facies association (OTP)

The OTP facies association was deposited directly on the basement, through angular unconformity. It encompasses dolomite (DOL), hybrid stromatolite (ETR-hb), and argillaceous stratiform stromatolite (ETR-ag).

Facies DOL and ETR-hb are inserted in the first 15 meters of the Sete Lagoas Formation. The facies DOL comprises beige to reddish pink thinly laminated dolomites, recrystallized, locally massive (Fig. 4C), presenting peloidal microtexture where original fabric was preserved (7A).

The facies ETR-hb comprises light gray to purple finely laminated limestone with an alternation of sparry and micritic layers. The sparry layers include centimetric to decimetric fans (Fig. 4A and 4B) of acicular calcite and milimetric isopachous laminas constituted by upright acicular calcite crystals. These calcite crystals show

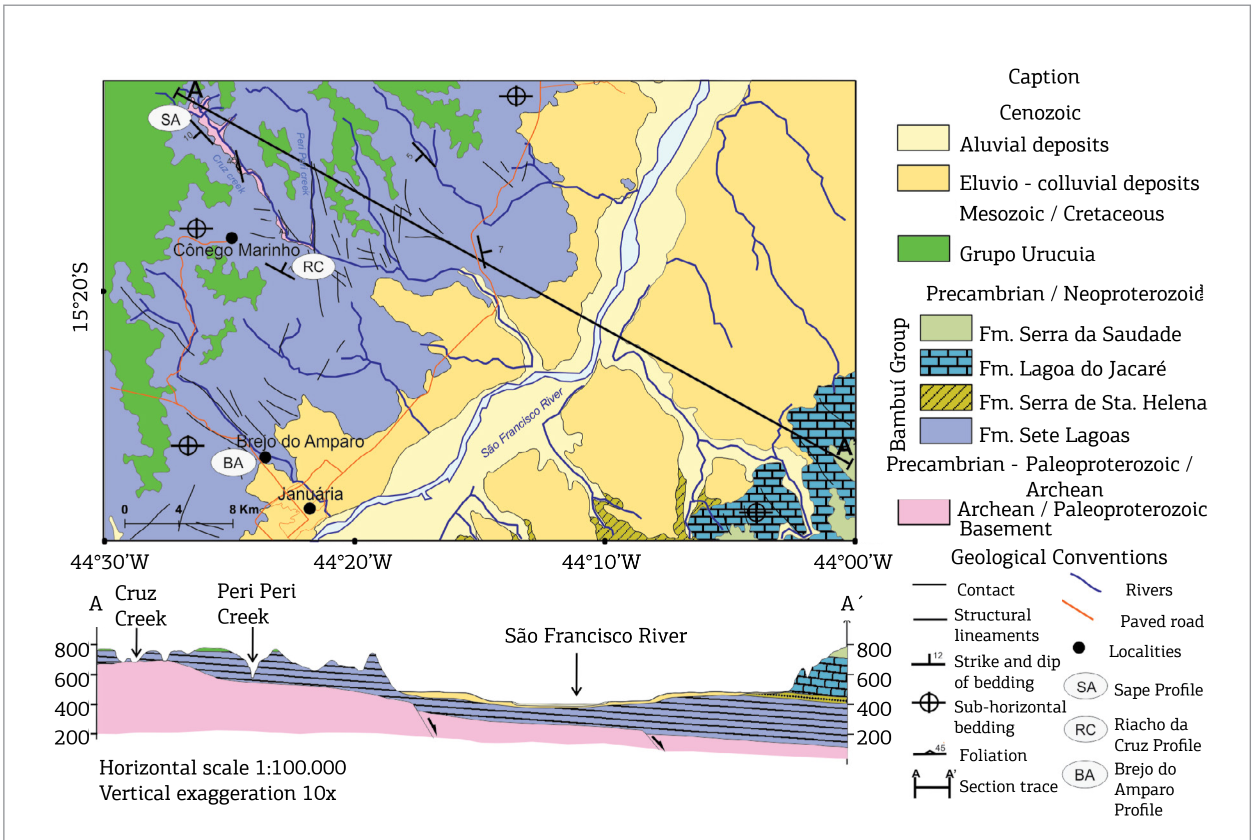

Figure 2. Geological map (1:100,000) of the Januária region with NW-SE section illustrating the relationships between the different geological units.

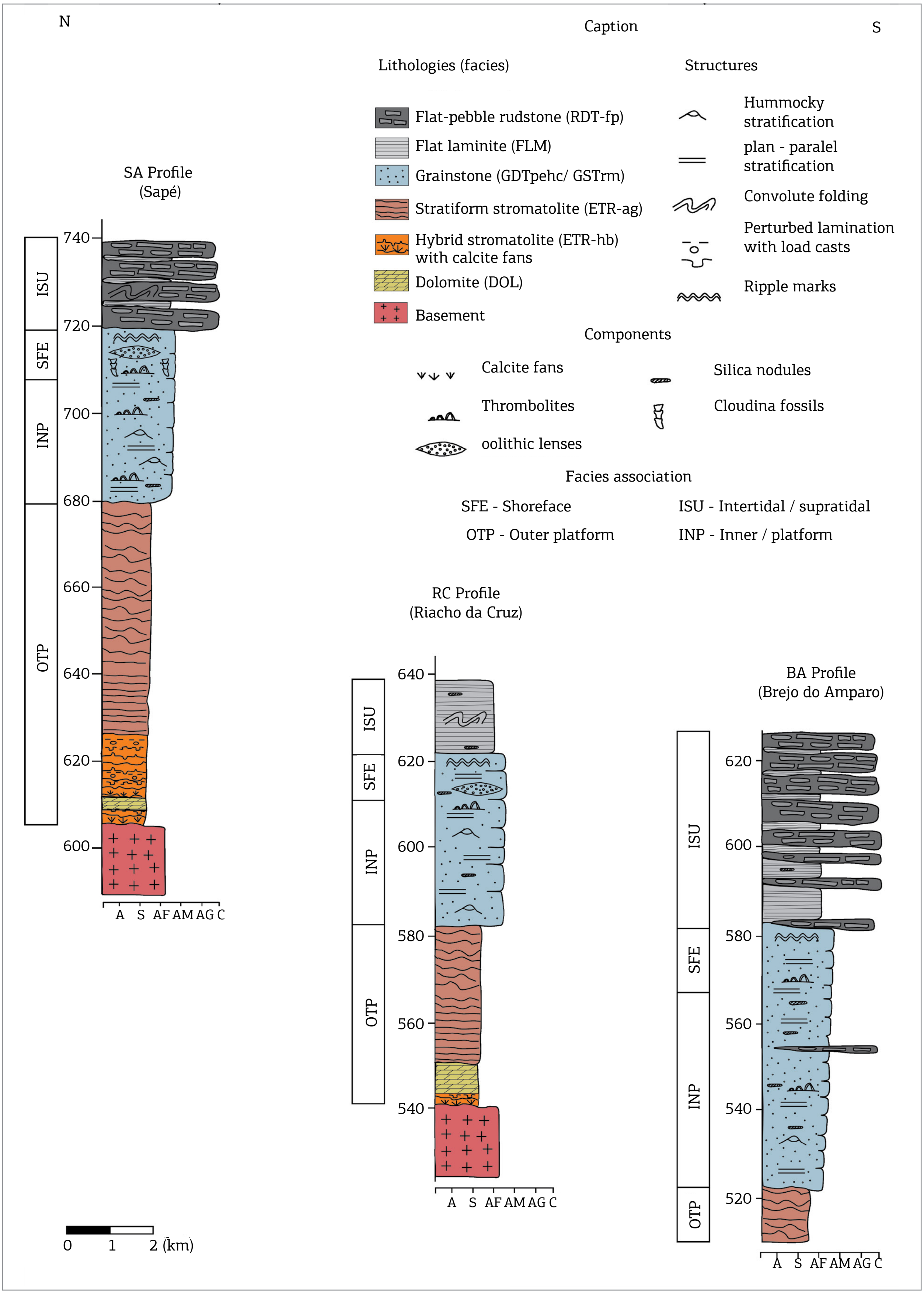

Figure 3. Detailed stratigraphic profiles of the Sete Lagoas Formation in the Januária region. The profiles are presented in depth.

characteristic features that suggest the original composition was aragonite, possibly precipitated on the seafloor. These features include slender to tapering acicular crystal habit, blocky to square crystal terminations, and internal mosaic texture with elongated equant crystals (Fig. 7B) (Sumner and Grotzinger 2000; Pruss et al. 2008). The micritic layers are composed of dark micro-clotted micrite that covers the sparry layers (Fig. 7B) and possibly constitutes lithified microbial mat. Riding (2008) labeled "hybrid stromatolite" the rocks composed of alternating dark micrite laminae and sparry calcite laminae, with probable microbial and abiotic origins, respectively. In a trench in the north of the area, the contact of the basement with this facies is well exposed showing decimetric botryoidal fans onlapping the basement (Fig. 4A).

The facies ETR-ag is the most representative of the studied area, with packages of up to 45 m in thickness. This is a relatively monotonous finely laminated gray rocks series, characterized by millimetric alternation of light gray with reddish to brownish beige laminas. The lamination is typically wrinkled, and locally constitutes small upward convexity domes (Fig. 5A and 7C).

Light laminas are predominantly calcitic, constituted by micro-clotted and micro-peloidal micrite, locally presenting peloids and calcified filaments that may occur surrounded by microspar (Fig. 7D and 7E). These features suggest processes associated with filaments, bacterial cells, and EPS calcification (Riding 2000). Dark laminas have higher contributions from clay minerals, iron hydroxides, and organic matter. These layers usually show dark micrite with micro-clotted/peloidal texture, marked by a dense arrangement of peloids intermingled with sinuous filaments (Fig. 7F). The main processes involved are filaments/EPS calcification and the settling of pelagic sediments (mud/clay) suspended in the water column.

The irregular wrinkled lamination of this facies suggests rocks formed by lithified microbial mats (Schieber 1986). In addition to this structure, the presence of internal fabrics and components, such as micro-clotted/peloidal micrite, peloids and calcified filaments are described by several authors as prerequisites for organic origin recognition (Monty 1976; Riding 2000; Schollen and Schollen 2003). This facies was classified as stromatolites, in the sense of Riding (2000), which implemented the term as "laminated benthic deposits" with varying external morphologies, such as planar, domal or columnar.

The absence of domal and columnar morphologies is a recurrent feature in deep water microbialites (Playford *et al.* 1976; Grotzinger and Al-Rawahi 2014), where low sedimentation rates and water energy favor planar, laterally extensive facies formation and preservation (Dromart 1992). The presence of pelitic intercalations and the lack of dessecative features, or intercalated higher energy facies as grainstones and rudstones, corroborate one calm, deep water environment for this facies, probably deposited below the storm wave base level.

Inner platform facies association (INP)

The INP facies association conformably overlies the OTP facies association, and has approximated thickness of 30 m. This succession is predominantly composed of GST-pehc facies, comprising medium to dark gray peloidal grainstones, with fine sand and silt sized particles. The characteristic structures are small/medium size hummocky cross stratification, formed by decimetric to metric wavelengths hummocks and swales with low angle truncation (Fig. 6A). The thrombolite facies (TRO) occurs subordinately as fine layers with millimetric to few centimeters thickness, and are characterized by macroscopic clotted fabric (Fig. 5B) with millimetric to centimetric rounded patches enveloped by organic matter containing well preserved fossils of cyanobacteria cells and filaments (Fig. 7H).

Shoreface facies association (SFE)

This association, with approximated thickness of 10 m, conformably succeeds INP association, and consists of grainstones (facies GST-rp) with ripple marks (Fig. 6B), oolithic lenses (Fig. 6C), plane-parallel stratification, and thrombolitic layers (facies TRO). Secondarily, medium size hummocky cross stratification occurs at the base, and rare structures suggestive of desiccation cracks towards the top (Fig. 6D).

These features indicate proximal and shallower conditions in relation to facies association INP, probably in the shoreface environment under the influence of fair weather waves and longshore currents.

In this association, thrombolytic levels are thicker reaching thicknesses up to 10 cm, and present rare levels containing fossil index *Cloudina*. These fossils ranging in lengths between 1.0 and 8.0 mm and diameters between 0.5 and 1.5 mm, are characterized by calcareous tests of elongated and tubular forms, with basal occlusion and apical opening, locally showing cone in cone structure (Fig. 7G). These features are characteristic of *Cloudina* fossils (Gaucher and Germs 2010; Warren *et al.* 2014).

Intertidal/supratidal facies association (ISU)

The ISU facies association has thicknesses up to 40 m and is composed of interbedded flat laminites (FLM) and flat-pebble rudstones (RUD-fp). Contact with lower facies association is gradational, marked by progressively thicker lenses intercalation of rudstones and laminites. The rudstones form predominantly tabular beds with thicknesses of

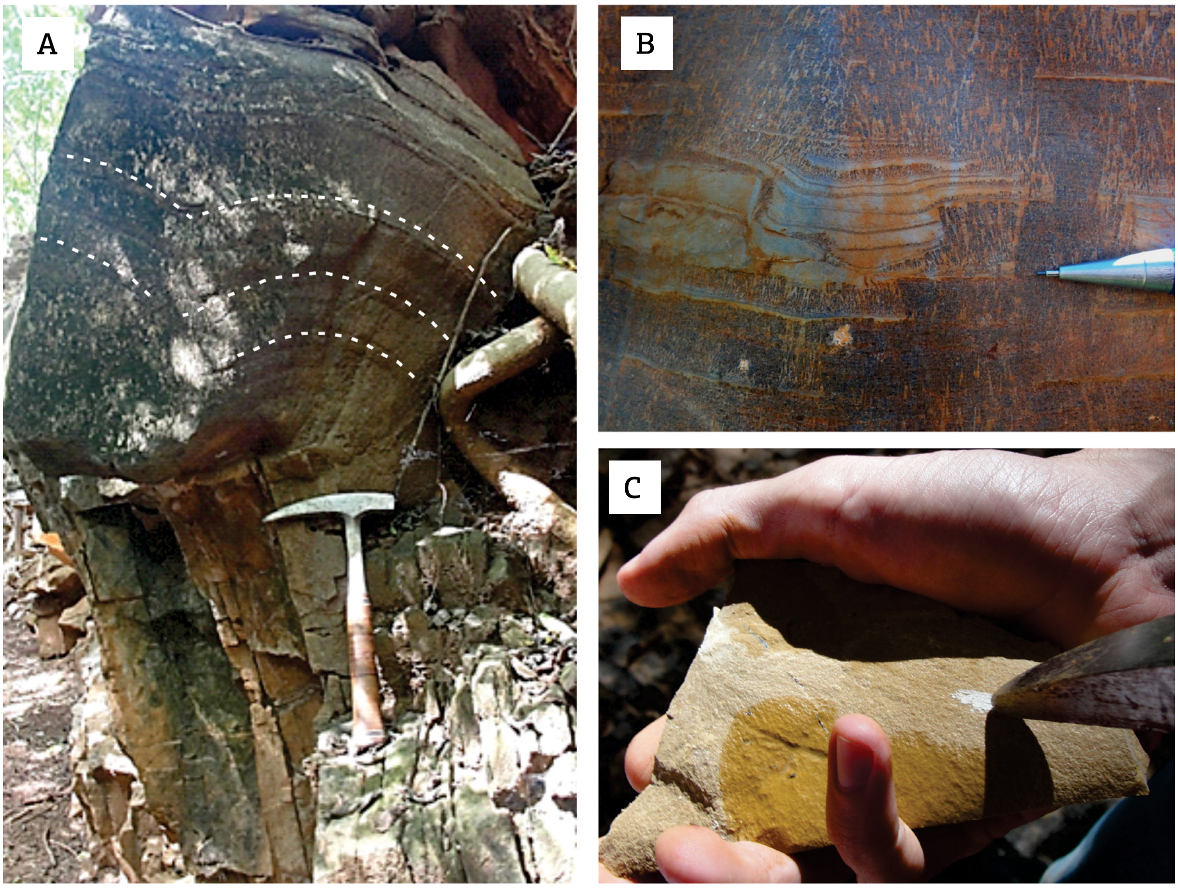

Figure 4. Macroscopic features of OTP facies association. A) Decimetric botryoidal fans of aragonite pseudomorphs onlapping the basement. The dashed line highlights the internal lamination (ETR-hb facies). B) Aragonite pseudomorphs in millimetric to centimetric layers, locally forming fans, intercalated with gray micritic layers (ETR-hb facies). C) Beige dolomite, not dissolved in HCl test (DOL facies).

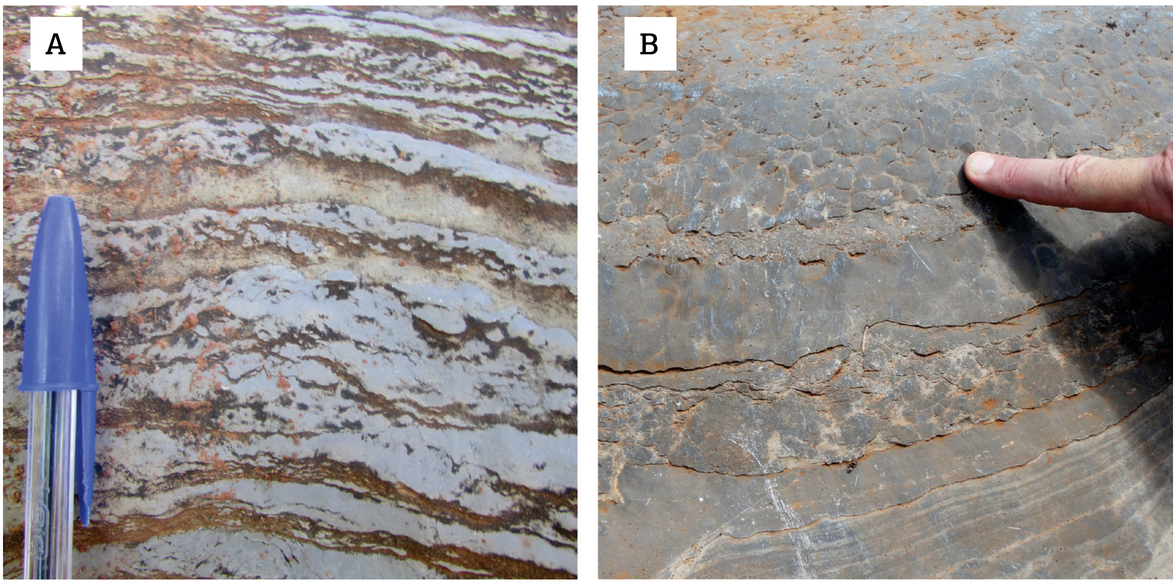

Figure 5. Macroscopic aspects of stratiform stromatolite (OTP facies association) and thrombolite (INP and SFE facies associations). A) Irregular wrinkled lamination of facies ETR-ag interlayered with beige/brown argillaceous films. B) Macroscopic clotted texture in thrombolite of TRO facies.

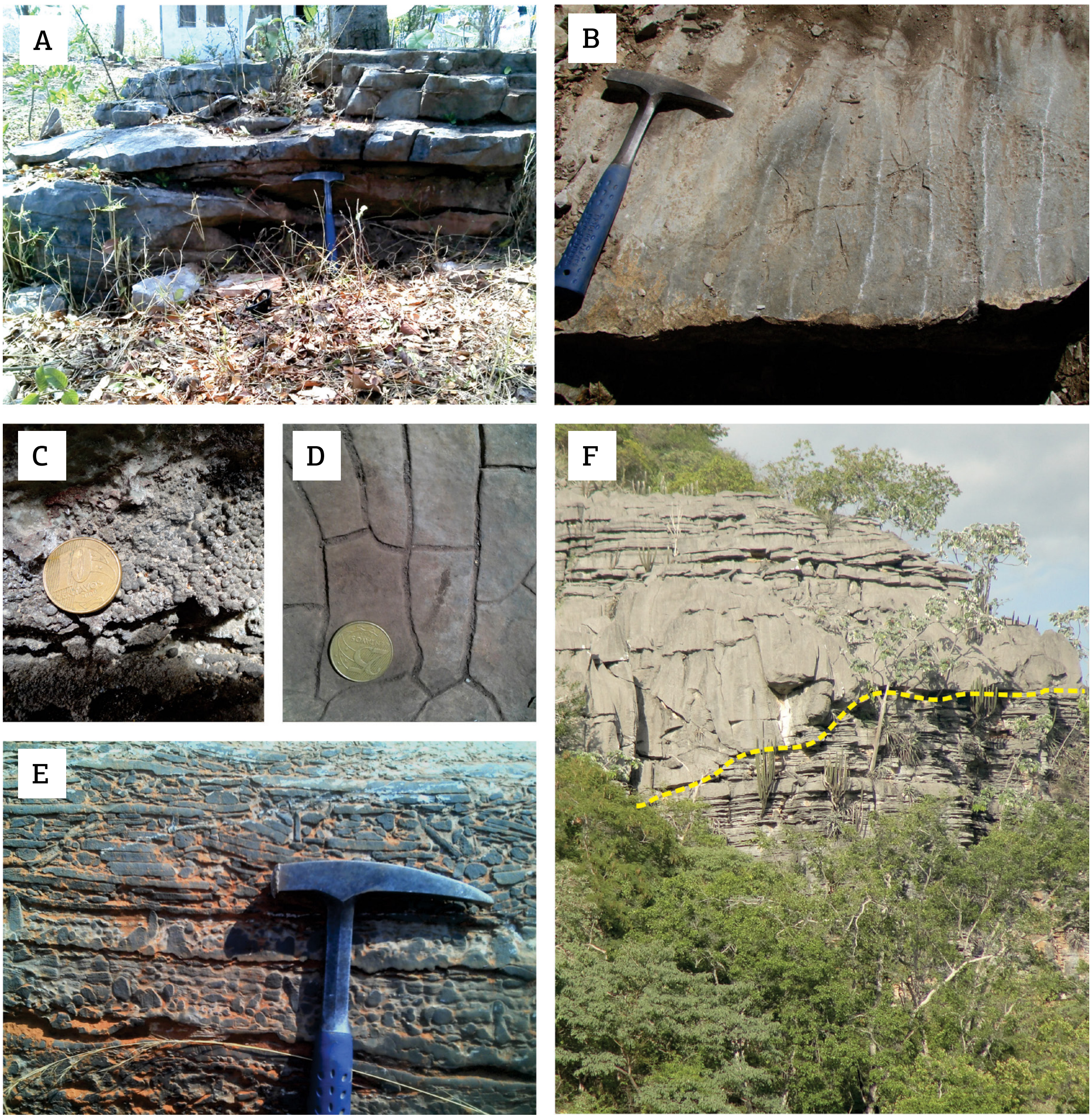

Figure 6. Macroscopic aspects of facies associations INP, SFE and ISU. A) Midsize hummocky cross stratification (facies GST-pehc). B) Ripple Marks (facies GST-rm). C) Detail of oolithic lens (facies GST-rm). D) Dessecation cracks (facies GST-rm). E) Detail of flat – pebble rudstone (facies RUD-fp). F) Channel infilled by RUD-fp facies truncating underlying laminites. The yellow dashed line highlights the channel incision (FLM facies). Width of view, 10 m.

up to 2 m. These layers locally show channel incisions truncating the underlying laminites (Fig. 6F).

The FLM facies is characterized by regular intercalation of centimetric light laminas with few millimeters thickness brownish laminas. Light layers have micritic texture and locally present fine grained components suggestive of peloidal ghosts. Brownish laminas are filamentous, with clay minerals contribution, dolomite, and organic matter. V-shaped fractures cut light laminas and are interrupted in the contact with the dark layers (Fig. 8A). These features suggest interplay process of suspension sediments settling down, with events of higher energy and subaerial exposure that are characteristic of a tidal flat environment. The facies RUD-fp consists of rudstones with tabular intraclasts of uniform thickness around 1cm, preferably occurring sub-horizontal, locally imbricated (Fig. 6E). These intraclasts present micritic texture, locally clotted and with scattered filaments. Vertical fractures in V, filled with sparry calcite

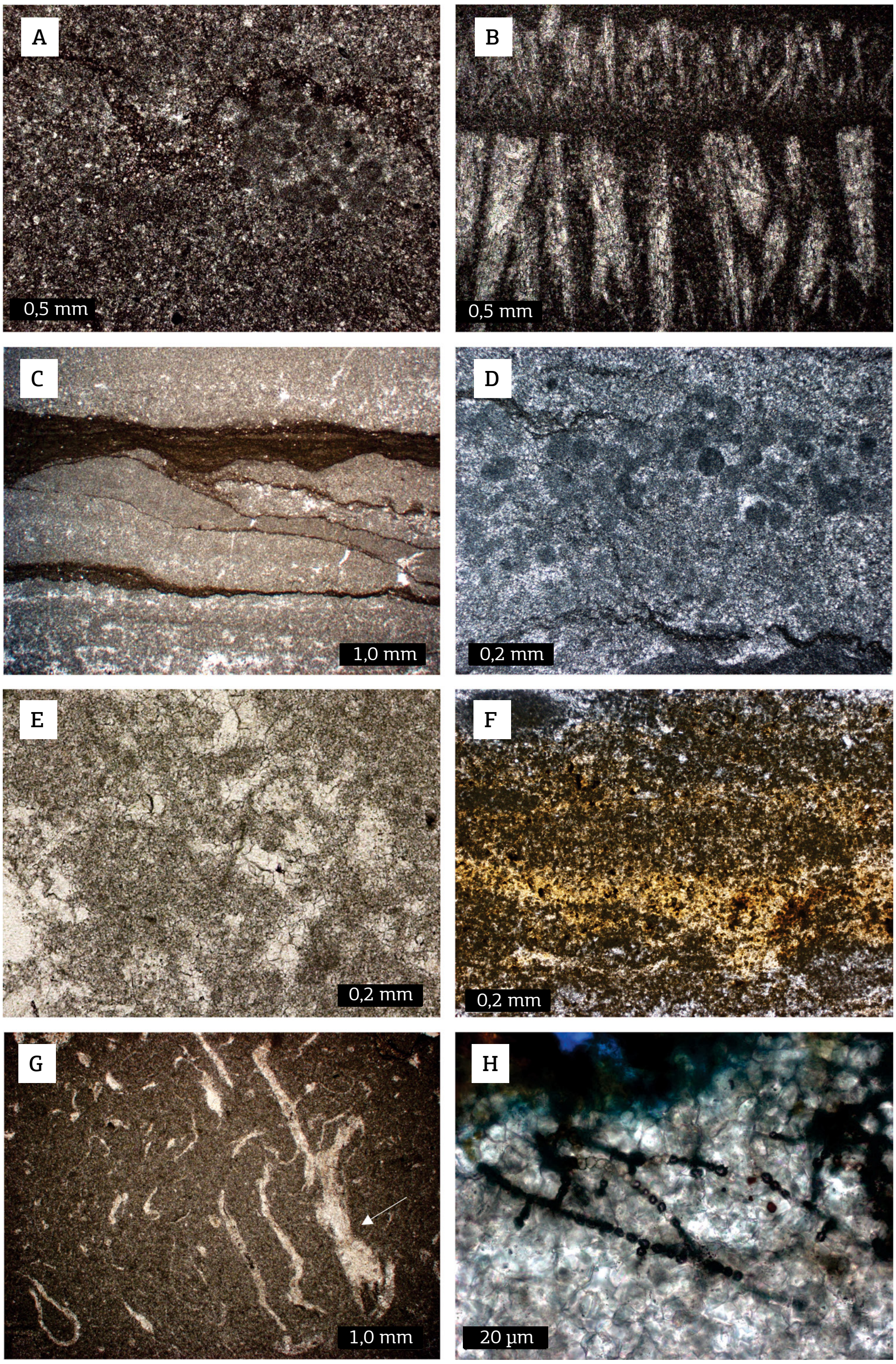

Figure 7. Microscopic aspects of facies associations OTP, INP, and SFE, pp (parallel polarizers), px (crossed polarizers). A) Detail of peloids in dolomite (facies DOL), 5x, pp. B) Acicular tapering calcite crystals, with square terminations and internal mosaic texture of elongated crystals, interspersed with micro-clotted micrite (facies ETR-hb), 2,5x, pp. C) Intercalation of light, locally dome-shapped, laminas with dark filamentous clayey layers (facies ETR-ag), 1.25x, pp. D) Micro-clotted fabric and peloids in light layers (facies ETR-ag), 5x, pp. E) Relict filaments in light lamina (facies ETR-ag), 10x, pp. F) Micro-clotted/dense peloidal micrite interspersed with clay minerals (facies ETR-ag), 5x, pp. G) Fossil Cloudina in thrombolite (facies TRO) with basal occlusion and apical opening, locally showing cone in cone structure (white arrow), 1.25x, pp. H) Fossil filaments consisting of aligned rounded cells in thrombolite (facies TRO), 50x, pp.

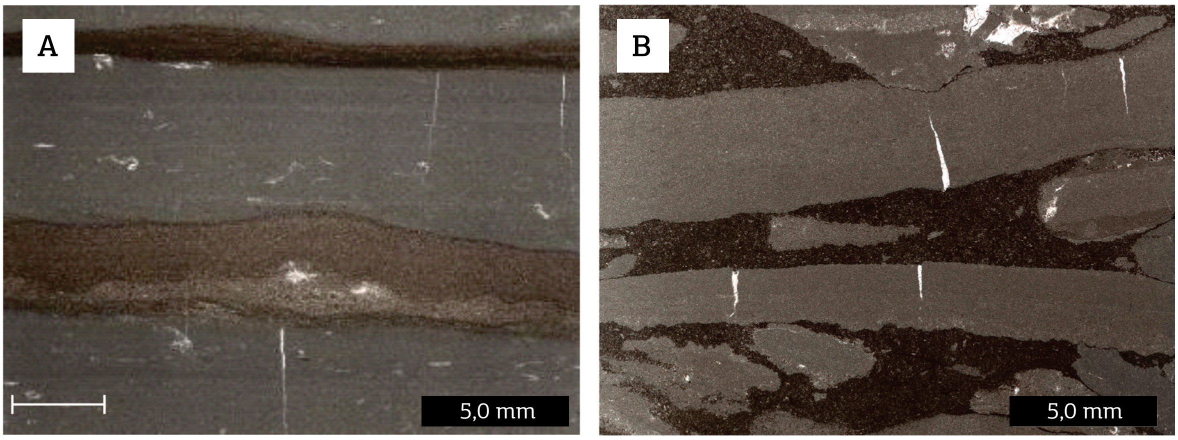

Figure 8. Microscopic features of ISU facies association, pp (parallel polarizers), px (crossed polarizers), FM (Photomosaic). A) Laminite with intercalation of micritic V-shaped fracture laminas and argillaceous brownish lamina, pp, 2,5x, pp, FM. B) Detail of rudstone composed by tabular micritic intraclasts with V-shaped fractures, and argillaceous brownish matrix, 2,5x, pp, FM.

Table 1. Description and interpretation of carbonate facies of the Sete Lagoas Formation identified in the Januária region.

Facies association	Facies	Structures	Features (collor, fabric)	Environment	Process
(OTP) Outer Platform	Hybrid stromatolite with sparry calcite (aragonite pseudomorphs) interspersed with micritic calcite (ETR-hb)	Finely laminated. Bearing centimetric to decimetric fans of probable aragonite pseudomorphs	Micro-clotted fabric; Acicular crystals with square terminations; Reddish purple to light gray	Subtidal bellow the storm wave level, in the photic zone	Chemical precipitation; EPS/ cells calcification
	Dolomite (DOL)	Finely laminated. Locally massive.	Micro-clotted fabric with peloids. Redish pink to beige		EPS/cells calcification
	Argillaceous stratiform stromatolite (ETR-ag)	Wrinkle discontinues lamination. Dark and light laminas intercalation	Micro-clotted/ peloidal fabric with scattered filaments; Presence of argillaceous/ filamentous levels		EPS/cells/filaments calcification. Settling of sediments in suspension
(INP) Inner Platform	Peloidal grainstone with hummocky (GST-pehc)	Small to medium size hummocky cross stratification	Medium to dark gray; Silexite nodules	Subtidal between fair weather and storm waves base levels	Suspension settling (fallout); Oscillatory flow reworking
(SFE) Shoreface	Thrombolite (TRO)	Rare anastomosed laminations	Macro-clotted/ nodular fabric. Presence of Cloudina fossils, and cyanobacteria filaments	Subtidal above the fair weather base level	EPS/cells/ filaments calcification; Trapping of carbonatic shells
	Grainstone with ripple marks (GST-rm)	Ripple marks	Oolithic lenses Medium to dark gray		Suspension settling (fallout) ; Oscillatory flow/longshore currents reworking
(ISU) Intertidal/ Supratidal	Rudstone with flat-pebble intraclasts (RUD-fp)	Tabular, locally channeled layers. Rarely presents sin sedimentary deformation structures	Tabular sub-horizontal, locally embricated intraclasts. Brownish argillaceous matrix	Tidal flat/ supratidal	Rip-up of finely laminated sediments
	Flat Laminite (FLM)	Planar flat lamination	Intercalation of brownish argillaceous and light gray laminas		Suspension settling (fallout) and traction deposition

are common. The intraclasts occur interspersed with brownish color matrix consisting of clay minerals, iron hydroxides, and organic matter (Fig. 8B).

The petrographic features indicate some similarities between rudstones and laminites, such as:

1. similar thickness between intraclasts and laminite laminas,
2. textural and compositional affinity between intraclasts and laminite light layers, and between rudstone matrix and dark laminite layers,
3. the presence of V fractures in rudstone intraclasts and in laminite light laminas.

This set of features indicates rudstones as the reworking product of laminites, where more brittle light laminite layers correspond to rudstone intraclasts and the more ductile clayey dark laminas formed the rudstone matrix. A possible interpretation of these "flat-Pebble conglomerate" type deposits is that they were formed by storm wave currents rip-ups of previously lithified laminites as conceptual model proposed by Sepkosky (1982).

SETE LAGOAS FORMATION CHEMOSTRATIGRAPHY – ISOTOPIC GEOLOGY (C, O)

Methodology

Isotopic survey was performed over three stratigraphic profiles indicated in the geological map (Fig. 2). In total, 116 samples were collected, at regular intervals of two meters, for $\delta^{13}C$ and $\delta^{18}O$ analyses. This range couldn't always be kept as sampling points with fractures, veins and pronounced diagenesis were avoided.

The isotope analyses were conducted at the NEG LABISE laboratory of Federal University of Pernambuco. For isotopic analysis of carbon and oxygen were collected 300 micrograms of rock dust for each sample. These samples were provoked into reacting to orthophosphoric acid (H_3PO_4) at 25°C to release CO_2. The values of $\delta^{13}C$ and $\delta^{18}O$ were measured in CO_2 after cryogenic cleaning in a mass spectrometer with a triple collector SIRA II, or Delta V Advantage. The isotopic data of C and O are reported as parts per thousand (‰) deviations with reference to V-PDB and V-SMOW, respectively (Table 2). Uncertainties were 0.1‰ for carbon, and 0.2‰ for oxygen.

Analysis of results

The $\delta^{13}C$ data presented an overall uniform behavior without extreme fluctuations (Fig. 9), suggesting they represent the water body chemical composition where the Sete Lagoas Formation was deposited. The $\delta^{18}O$ data showed more accentuated oscillation behavior, especially in the RC profile, suggesting these data are, at least, partially affected by later diagenetic events.

The Sete Lagoas Formation basal portion, which includes facies DOL and ETR-hb, was sampled in profiles Sapé (SA), and Riacho da Cruz (RC) (Fig. 9). In both profiles, this interval showed a strongly negative excursion, with $\delta^{13}C$ values starting milder, reaching the minimum and rising again before steping in the ETR-ag facies. Profile SA initial value is -3.5, and the minimum is -4.2; profile RC initial value is -1.5, and the minimum is -5.1. The $\delta^{18}O$ data also showed accentuated negative values in these facies, which after reaching the minimum, increase in a continuous gradient that enters facies ETR-ag.

The negative excursion of the base of the Sete Lagoas Formation is followed by an approximated 45 m sequence of laminated stromatolites (facies ETR-ag), with $\delta^{13}C$ values relatively constant around -1 (Fig. 9, Table 2). The $\delta^{18}O$ data showed greater variation, with distribution of values in a positive gradient, aligned with the lower facies trends. In RC profile, the values range from -13 to -5.3, and in SA profile, they range from -11 to -7.5. These negative values suggest large water bodies with low evaporation rate. The uniform values of $\delta^{13}C$, around -1, in the ETR-ag facies suggest a preferential association with the medium they were deposited, instead of located fractionation phenomena.

The basis of grainstones from facies association INP is marked by a shift of approximately 1.0 in the $\delta^{13}C$ curves (Fig. 9, Table 2), that is succeeded by relatively constant values around 0 in profiles RC and BA, while in the SA profile, the isotopic curve showed a slightly positive gradient. This behavior was not so clear in the $\delta^{18}O$ curves, and the RC profile showed greater oscillation.

The facies associations SFE and ISU show no significant changes in the pattern of isotopic curves, and $\delta^{13}C$ values remained between 0.0 and 0.6, and the $\delta^{18}O$ remained between -8.5 and -6.5, except for RC profile where the $\delta^{18}O$ data showed accentuated oscillation (Fig. 9, Table 2).

In the analyzed profiles was not observed the isotopic shift of 5‰ in $\delta^{13}C$ curve, suggesting this sequence was deposited below the unconformity correlated over large areas of the basin (Martins and Lemos 2007; Zálan and Romeiro-Silva 2007; Caxito *et al.* 2012).

The grainstones of SA Profile show a gradual enrichment of $\delta^{13}C$ toward the top not observed in other profiles. This pattern may reflect a greater increase of restriction at this point, in response to a more proximal position.

Table 2. Isotopic data (δ13C and δ18O) of Sete Lagoas Formation in Januária region.

ID Stratigraphic Profile	Sample	Facies	Elevation (m)	$\delta^{13}C‰_{VPDB}$	$\delta^{18}o‰_{VPDB}$	$\delta^{18}O‰_{Vsmow}$
Facies association OTP (ETR-hb+DOL + Etr-hb)						
SA	SA 1	Etr-hb/Etr-hb	600	-3.51	-12.04	18.45
SA	SA 2	Etr-hb/Etr-hb	605	-4.10	-12.19	18.29
SA	SA 3	Etr-hb/Etr-hb	610	-4.18	-10.33	20.21
RC	RC 01	DOL/Etr-hb	542	-1.46	-13.25	17.21
RC	RC 02	DOL	543	-0.59	-13.51	16.93
RC	RC 03	DOL	544	-4.25	-7.78	22.84
RC	RC 04	DOL	545	-4.33	-8.50	22.10
RC	RC 05	Etr-hb	550	-5.15	-13.97	16.46
RC	RC 06	Etr-hb/Etr-hb	552	-4.94	-13.94	16.49
RC	RC 07	DOL	553	-2.92	-7.78	22.84
Facies association OTP (ETR-ag)						
BA	BA 01	ETR-ag	512	-0.35	-10.83	19.7
BA	BA 02 B	ETR-ag	514	-0.07	-10.16	20.38
RC	RC 08 A	ETR-ag	555	-0.84	-13.11	17.35
RC	RC 08B	ETR-ag	570	-0.67	-11.25	19.26
RC	RC 09	ETR-ag	557	-0.99	-12.39	18.08
RC	RC 10	ETR-ag	560	-0.87	-10.99	19.53
RC	RC 11	ETR-ag	561	-1.04	-11.00	19.63
RC	RC 12	ETR-ag	563	-1.10	-9.74	20.82
RC	RC 13 A	ETR-ag	570	-1.07	-10.06	20.49
RC	RC 13 B	ETR-ag	570	-0.66	-9.16	21.42
RC	RC 14	ETR-ag	575	-0.75	-9.03	21.55
RC	RC 15	ETR-ag	577	-0.82	-8,96	21.62
RC	RC 27	ETR-ag	566	-0.8	-8.47	22.13
RC	RC 26 A	ETR-ag	573	-1.10	-8.19	22.41
RC	RC 26 B	ETR-ag	573	-1.64	-7.21	23.42
RC	RC 25	ETR-ag	578	-1.04	-7.15	23.49
RC	RC 24	ETR-ag	582	-0.39	-5.26	25.44
RC	RC 16	ETR-ag	579	-1.12	-5.7	24.98
SA	SA 4	DOL	620	-3.73	-11.91	18.58
SA	SA 5	ETR-ag	634	-1.31	-10.81	19.72
SA	SA 6	ETR-ag	637	-1.29	-11.05	19.47
SA	SA 7 A	ETR-ag	640	-2.65	-11.27	19.25
SA	SA 7 B	ETR-ag	640	-1.10	-6.86	23.79
SA	SA8	ETR-ag	642	-1.26	-10.81	19.72
SA	SA 9 A	ETR-ag	646	-1.55	-8.78	21.8
SA	SA9 B	ETR-ag	646	-1.17	-9.36	21.21
SA	SA10 A	ETR-ag	649	-2.74	-8.45	22.15
SA	SA10 B	ETR-ag	649	-1.10	-8.97	21.61
SA	SA11 A	ETR-ag	651	-1.17	-9.29	21.27
SA	SA11 B	ETR-ag	651	-1.46	-9.26	21.31
SA	SA12	ETR-ag	655	-1.06	-8.92	21.66
SA	SA13 A	ETR-ag	657	-2.47	-7.92	22.69
SA	SA13 B	ETR-ag	657	-1.21	-9.01	21.57
SA	SA14	ETR-ag	659	-1.14	-9.33	21.24
SA	SA15 A	ETR-ag	660	-1.08	-8.74	21.85
SA	SA15 B	ETR-ag	660	-0.69	-6.8	23.85
SA	SA16 A	ETR-ag	662	-0.97	-8.44	22.15
SA	SA16 B	ETR-ag	662	-0.43	-5.63	25.06
SA	SA17	ETR-ag	665	-1.01	-8.33	22.27
SA	SA18	ETR-ag	668	-1.06	-7.99	22.62
SA	SA19	ETR-ag	670	-1.04	-7.92	22.70
SA	SA20	ETR-ag	671	-0.83	-7.46	23.17
SA	SA21	ETR-ag	673	-0.87	-7.78	22.84
Facies association INP (GST-pehc)						
BA	BA 03	GST-pehc	516	-0.01	-10.54	19.97
BA	BA 04	GST-pehc	525	0.24	-6.95	23.70
BA	BA 05	GST-pehc	530	0.11	-7.34	23.29
BA	BA 06	GST-pehc	533	0.32	-7.18	23.45
BA	BA 07	GST-pehc	536	0.21	-7.18	23.46

Continue...

Table 2. Continuation.

ID Stratigraphic Profile	Sample	Facies	Elevation (m)	$\delta^{13}C‰_{VPDB}$	$\delta^{18}o‰_{VPDB}$	$\delta^{18}O‰_{Vsmow}$
BA	BA 08	GST-pehc	543	0.29	-7.01	23.63
BA	BA 08 A	GST-pehc	552	0.76	-7.06	23.59
BA	BA 09	GST-pehc	555	-0.31	-8.75	21.84
BA	BA 10	GST-pehc	560	0.51	-6.96	23.68
BA	BA 11	GST-pehc	565	0.43	-7.22	23.42
BA	BA 12	GST-pehc	569	0.37	-7.39	23.25
RC	RC 23	GST-pehc	586	0.61	-1.96	28.84
RC	RC 22	GST-pehc	591	-0.07	-4.03	26.70
RC	RC 21	GST-pehc	597	0.29	-7.57	23.06
RC	RC 20	GST-pehc	603	0.30	-4.43	26.29
RC	RC 29	GST-pehc	589	0,22	-7.37	26.26
RC	RC 30	GST-pehc	593	0,3	-8.92	21.66
RC	RC 31	GST-pehc	598	-0,02	-8.82	21.77
SA	SA22	GST-pe	673	-0,18	-7.82	22.80
SA	SA23	GST-pe	678	-0,14	-7.65	22.98
SA	SA24	GST-pe	683	-0,02	-7.21	23.43
SA	SA25	GST-pe	685	0,16	-7.07	23.57
SA	SA26	GST-pe	687	0,08	-7.29	23.34
SA	SA27	GST-pe	690	0,22	-7.11	23.53
SA	SA28 A	GST-pe	694	0,20	-7.06	23.59
SA	SA28 B	GST-pe	694	0,25	-6.70	23.96
SA	SA29	GST-pe	699	0,18	-7,34	23.90
SA	SA30	GST-pe	700	-0,20	-6,71	23.97
SA	SA31	GST-pe	705	0,28	-7,06	23.59
SA	SA22	GST-pe	673	-0,18	-7,82	22.8
Facies association SFE (GST-rm)						
BA	BA 13	GST-rm	573	0,35	-7,28	23.36
BA	BA 14	GST-rm	579	0,44	-6,98	23.67
BA	BA 15	GST-rm	582	-0,58	-8,06	22.55
BA	BA 16	GST-rm	587	0,33	-6,91	23.73
BA	BA 17	GST-rm	592	-0,42	-8,38	22.23
BA	BA 18	GST-rm	597	0,12	-7,10	23.54
RC	RC 32	GST-rm	602	-0,09	-8,58	22.02
RC	RC 33	GST-rm	610	0,36	-7,58	23.04
SA	SA32	GST-rm	706	0,28	-7,13	23.50
SA	SA33	GST-rm	711	0,40	-7,40	23.23
SA	SA34	GST-rm	716	0,60	-6,73	23.92
SA	SA36	GST-rm	719	0,56	-6,94	23.70
Facies association ISU						
BA	BA 19	ISU (FLM)	602	0,21	-7,97	22.65
BA	BA 20 A	ISU (RUD matrix)	603	0,47	-8,45	22.14
BA	BA 20 B	ISU (RUD intraclast)	603	0,26	-7,8	22.82
BA	BA 21	ISU (FLM)	616	0,33	-8,23	22.37
BA	BA 22	ISU (FLM)	621	0,42	-8,06	22.55
BA	BA 23	ISU (FLM)	623	0,31	-7,7	22.92
RC	RC 34	ISU (FLM)	616	0,43	-7,69	22.93
RC	RC 35	ISU (FLM)	623	0,12	-8,52	22.09
RC	RC 36	ISU (FLM)	630	0,54	-7,68	22.95
RC	RC 17	ISU?	623	0,1	-3,5	27.25
RC	RC 18	ISU?	625	0,14	-5,12	25.58
RC	RC 19	ISU?	632	0,41	-3,88	26.86
SA	SA35	ISU (FLM)	720	0,6	-6,91	23.74
SA	SA37 A	ISU (RUD intraclast)	720	0,47	-6,96	23.69
SA	SA37 B	ISU (RUD matrix)	720	0,59	-6,65	24.00
SA	SA38	ISU (FLM)	722	0,68	-6,58	24.07
SA	SA39	ISU (FLM)	726	0,17	-7,18	23.45
SA	SA40	ISU (RUD)	732	0,37	-7,26	23.37
SA	SA41	ISU (FLM)	736	0,34	-6,91	23.73

SEQUENCE STRATIGRAPHY

In the Januária Region, the Sete Lagoas Formation comprises a sequence composed by a lower Transgressive System Tract (TST) and an upper High Stand System Tract (HSST), separated by a Maximum Flooding Surface (MFS). It is ranked as second-order sequence in the São Francisco Megasequence (Martins and Lemos 2007), as evidenced by the stratigraphic surface hierarchy, as well as the magnitude of the facies shift.

This stratigraphic framework was constructed with three profiles located along an N-S alignment (Figs. 2 and 3) and integrates data from petrography and chemostratigraphy. It can be divided into four stages, designated T1, T2, T3 and T4, which altogether represent a transgressive-regressive cycle deposited in a context of continuously base level raising (Fig. 10). The stages T1 and T2 illustrate the TST, whilst the stages T3 and T4 represent the HSST.

According to Jones and Desrochers (1992), the antecedent topography is a major intrinsic feature controlling the carbonate deposition and the resulting architectural framework of the carbonate sequences. Therefore, the development of the Januária high is an essential element to understand the stratigraphic evolution of the studied area.

Brandalise (1980) and Iglesias (2007) observed that the Sete Lagoas Formation thickens in all directions, as distance increases from the Januária high. This assertion is supported by outcrop and well core data collected from the north, in the surroundings of Montalvânia, and from the south, in the town of Lontra. These successions are similar to that observed in the shallowest portion of the Januária-Itacarambi Region. The occurrence of thinner strata in these positions may suggest, according to Abreu-Lima (1997), a reduced accommodation space reflecting a paleo-high position.

In this study, new evidences suggest that the Januária high acted as paleo-high at the time of the Sete Lagoas Formation deposition. The accentuated restriction pointed out by isotopic data from the SA profile, the lack of deformed beds, the basement onlap of the Sete Lagoas Formation and the prograding facies of the HSST towards deeper basement corroborate to this hypothesis.

Transgressive system tract (TST)

The TST comprises facies association OTP, deposited in a retrogradational stacking pattern (Fig. 10), reflecting eustatic rising rate and increase in relative sea level, which exceeded the sediment supply.

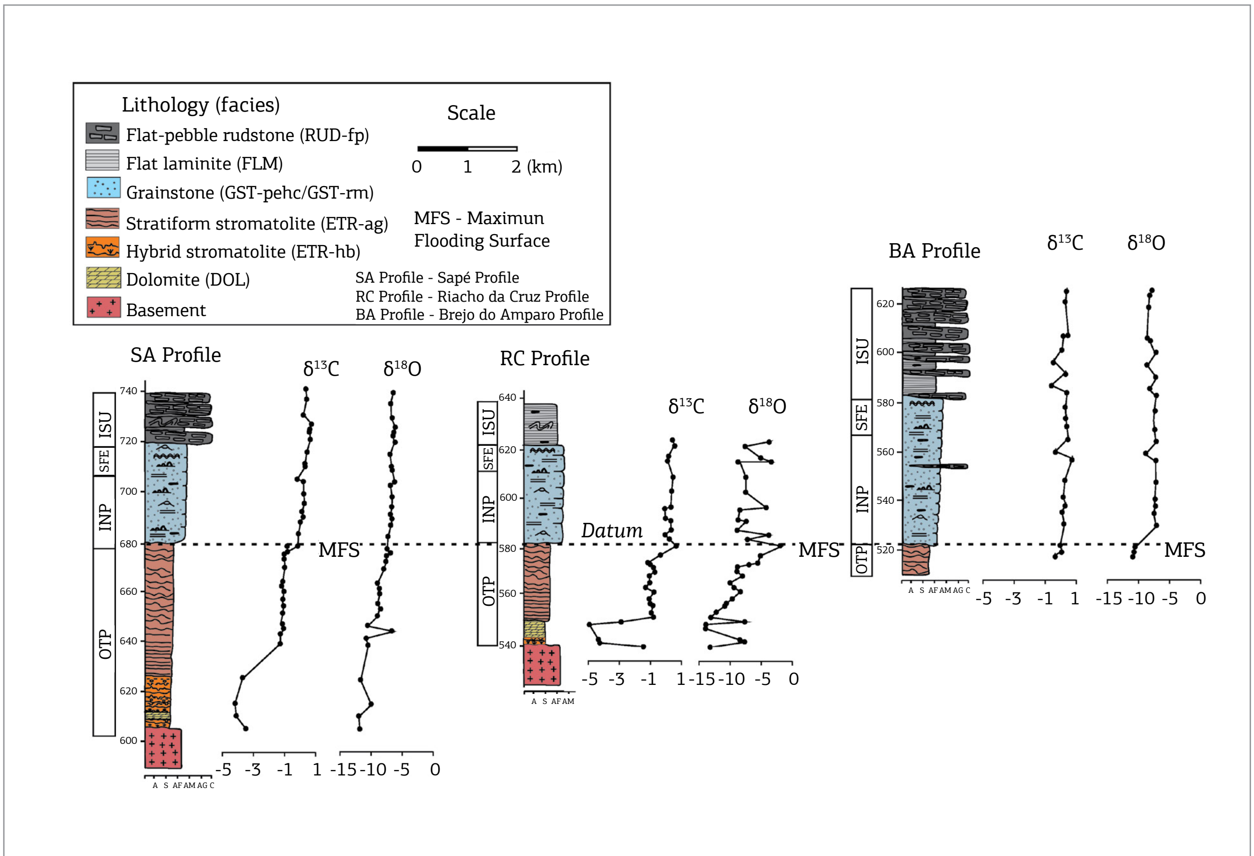

Figure 9. Chemostratigraphyc (δ13C and δ18O) profiles of the Sete Lagoas Formation in Januária region. The profiles were flattened on facies association INP basis, which coincides with the maximum flooding surface.

The period T1 (Fig. 10) presents a transgressive surface that marks the onset of a transgressive event, in response to a rapid sea level rise caused by global warming and general ice melting, after the Jequitaí glaciation. It comprises the deposition of facies DOL/ETR-hb onlapping directly onto the basement. Although this sequence does not overlies diamictites of Jequitaí Formation, it presents isotopic and lithological features identical to other cap carbonates, such as the ones in contact with the Jequitaí Formation, and others around the globe. These elements include a sharply negative $\delta^{13}C$ anomaly, layer thickness inferior to 30 m, presence of peloidal grains, microbial structures, fan-shaped aragonite

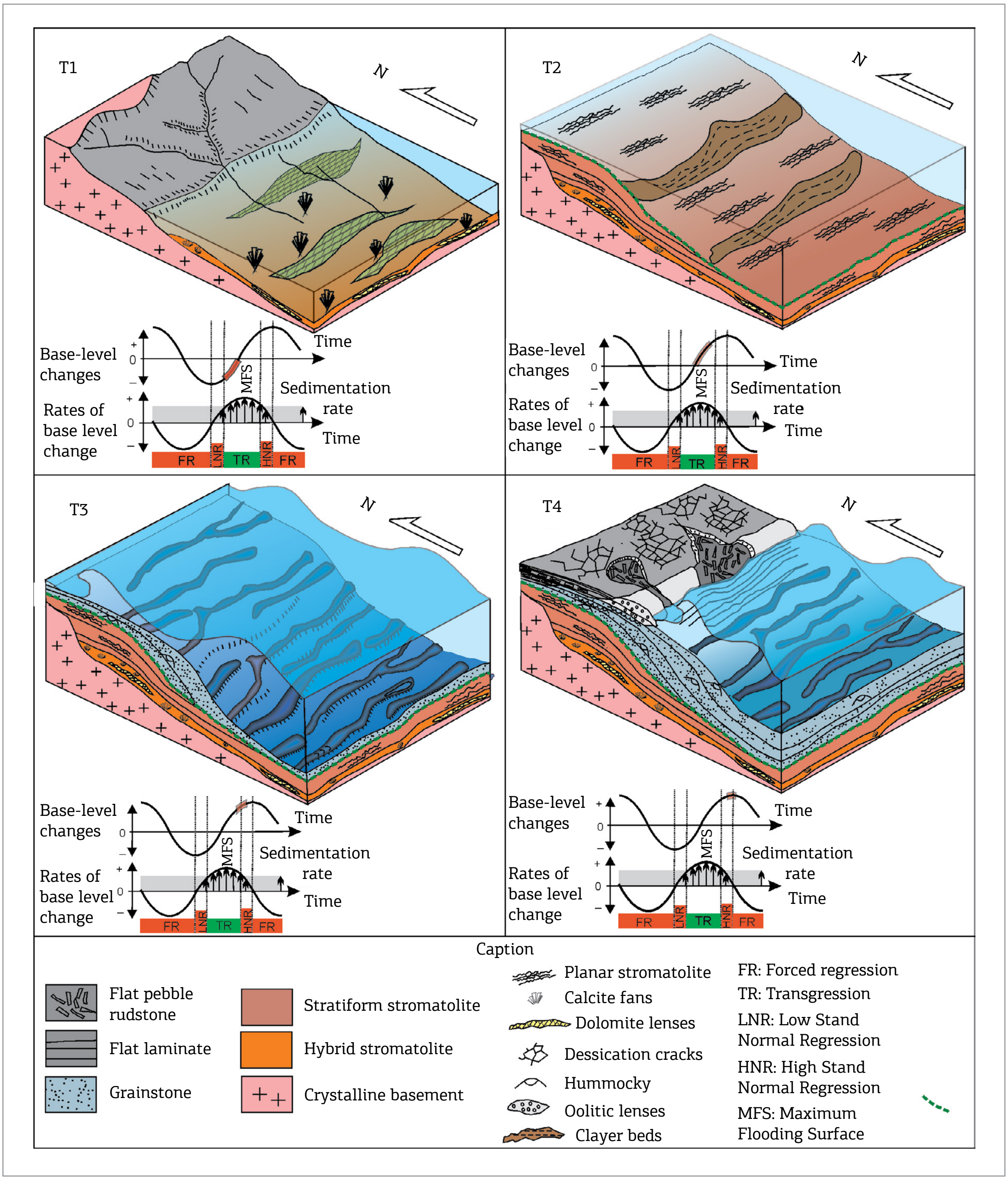

Figure 10. Diagrams of the periods T1 to T4, ilustrating the evolution of the second order-sequence of the Sete Lagoas Formation in the surroundings of Januária.

pseudomorphs, dolomite layers, and finely laminated beds (Kennedy 1996; Hoffman and Schrag, 2002 Vieira *et al.* 2007; Lima 2011).

Hoffman and Schrag (2002) drew attention to the fact that the cap carbonates exceed by far the limits of aerially restricted glacial rocks, overlying the pre-glacial rocks separated by an unconformity.

The period T2 (Fig. 10) encompasses a thick package of clay-rich stratified stromatolites (ETR-ag), conformably succeeding the cap carbonate in a backstepping pattern, indicating successive drownings of the carbonate factory. This stage is also characterized by uniform, slightly negative $\delta^{13}C$ values (~-1‰), suggesting a ventilated ocean. The absence of desiccation features and reworked facies may indicate sedimentation below the storm waves base level. Moreover, this facies (ETR-ag) shows typical deep water stromatolite features, such as thin lamination, presence of iron oxides, and absence of flaked breccias (Playford *et al.* 1976; Kennedy 1996). These elements, coupled with higher clay content, imply a deeper water column when compared to facies ETR-hb/DOL.

Dromart (1992) associates these laterally extensive layered stromatolites with external ramp/slope deposits, stating that the build-up of these biostromes requires slow rates of sedimentation and low energy environment. Therefore, the facies ETR-ag could represent a condensed section, marking a starved basin period, submitted to accentuated eustatic rise. The upper limit of period T2 is represented by the Maximum Flooding Surface (MFS) (Fig. 10), which depicts the change from transgressive to normal regression high stand tract stacking pattern (Posamentier and Vail 1988; Van Wagoner *et al.* 1988).

High stand system tract (HSST)

The MFS marks the beginning of the HSST and comprises INP, SFE and ISU facies associations, generally on shallowing upwards patterns, in a storm wave-influenced environment. The stacking pattern is progradational, resulting from sediment supply overcoming the eustatic sea level rise (Fig. 10).

The most distinctive feature of the INP association is the hummocky cross-stratifications, which suggests an inner platform environment, between the storm and fair weather wave base levels. In the later part of period T3, the transition to facies association SFE is marked by the occurrence of oolitic grainstones with ripple marks, and dessecation cracks towards the top. This set of structures indicates the evolution to shoreface environment influenced by fair weather waves.

Period T4 represents the final stage of the normal regression, which displays the progradation of the intertidal/supratidal (ISU facies association) over the shoreface. This transition begins with the interbedding of flat laminites and flat-pebble rudstones, leading to the onset of tidal flats in an intertidal/supratidal environment.

The absence of build-ups, evaporites and lagoon protected facies might suggest that the wave energy was dissipated throughout the platform, without the presence of barriers, in a non-rimmed shelf (James and Kendall 1992).

DISCUSSION AND CONCLUSIONS

In the investigated area, the Sete Lagoas Formation comprises one second-order depositional sequence correlated to the 2nd sequence of the São Francisco Megassequence, deposited below a regional unconformity (Martins and Lemos 2007). This sequence is composed of a lower transgressive tract and an upper high stand tract, featuring respectively transgressive and normal regressive events, separated by the maximum flooding surface.

Although glacio-eustatic cycles result in depositional sequences, a long-term subsidence is necessary to preserve these sequences, as glacio-eustatic cycles themselves do not generate permanent accommodation spaces (Hoffman and Schrag 2002). New publications about the age of the Sete Lagoas Formation indicate that deposition occurred concomitantly with Brasiliano Orogeny development (Pedrosa-Soares *et al.* 2011, Paula-Santos *et al.* 2015), reinforcing the character of a foreland basin, and the subsidence mechanism responsible for the preservation of the deposited sequences in glacio-eustatic cycles.

The nature of transgressive-regressive cycle is coherent with preceding works in this sector of the basin and with more regional works (Dardenne 1981; Abreu-Lima 1997; Martins and Lemos 2007; Lima 2011), suggesting a relatively similar stratigraphic evolution of the Sete Lagoas Formation in different portions of the basin. Notwithstanding the data from the Sete Lagoas high, southern basin compartment, presents significant stratigraphic differences. In the Sete Lagoas high, the cap carbonate is devoid of dolomitic facies, and is not succeeded by finely laminated deep water facies carrying isotopic signature around -1‰ ($\delta^{13}C$). Instead, the cap carbonate is succeeded by storm and tide influenced carbonate facies, with $\delta^{13}C$ isotopic values around 0‰ (Vieira *et al.* 2007), better correlated with INP and SFE facies associations. The absence of argillaceous laminated facies may reflect a more proximal context for the Sete Lagoas Formation in the Sete Lagoas high, where the transgressive cap carbonate is immediately succeeded by higher energy facies.

The data collected in this study, along with those from previous works (Brandalise 1980; Abreu-Lima 1997; Iglesias 2007), indicate the Sete Lagoas Formation basis presents very low gradient (less than 1º) in all directions, from the apex of a paleo-basement high located north of the town of Januária. This structural framework of a paleo-high in the central portion of the basin suggests that the Sete Lagoas Formation, in the Januária region, could be deposited in an isolated platform, surrounded by deep water (Read 1985) and cutoff by terrigenous clastic sedimentation (James and Kendall 1992). Although the most widespread examples of this type of platform present steep margins, such as the Bahamas islands (Read 1985), there are also isolated platforms with smooth margins, similar to carbonate ramp models in terms of gradient and facies associations (Wilson 1975; Read 1985). These systems can be developed on structural highs of epicontinental seas during periods of high sea level (Read 1985), and provide a model compatible with the facies distribution typical of carbonate ramps that can also explain the absence of deltaic and fluvial facies.

The presence of the cap carbonate and the fossil *Cloudina* in the same second order sequence makes remote the hypothesis concerning an unconformity of almost 200 Ma, between the zircon/fossil carrier beds and a Sturtian cap carbonate, as suggested by Paula-Santos *et al.* (2015) and Warren *et al.* (2014). The time interval attributed to second-order sequences, normally ranges between 3-50 Ma (Mitchum Jr. and Van Wagoner 1991; Vail *et al.* 1991), which suggests that the Sete Lagoas basal strata should not be much older than those ages obtained by Paula-Santos *et al.* (2015) and by Warren *et al.* (2014) in the upper portion of the lower Sete Lagoas sequence. Even though there may be gaps and paraconformities not detected by chemostratigraphy or field survey, and the difficulty of estimating Precambrian sequences time spans (Catuneanu 2006), a gap of this magnitude seems very unlikely because it is usually associated with boundaries between first-order sequences. The data obtained in this study indicate that the Jequitaí glacial event provides a more consistent correlation to Marinoan glaciation as suggested by Caxito *et al.* (2012), or a younger glaciation (Lima 2011).

The cap carbonate studied presents Marinoan glaciation characteristic features including aragonite pseudomorphs, light, locally reddish pink color, and persistent $\delta^{13}C$ negative values (Kennedy *et al.* 1998) that could be correlated with Marinoan cap carbonates described in the others portions of the São Francisco basin (Caxito *et al.* 2011). However, even considering an age around 600 Ma for the Sete Lagoas Formation basal facies, we still have a pronounced gap to the end of the Marinoan glaciation, well established in 635 Ma (Prave *et al.* 2016), being necessary to assume a few tens of millions years hiatus, not yet detected, for this correlation.

The correlation with a younger glaciation event, like the Gaskiers (ca. 580 Ma), can be established based on relatively continuum sedimentation, without requiring considerable hiatus. However the features reported from these cap carbonates are very distinct from those observed in Januária. The Gaskiers glaciation comprises sparse occurrences of cap carbonates in Newfoundland and northern China, which are very thin, extremely discontinuous, and not characterized by dolomites and seafloor cements (Myrow and Kaufman 1999; Xiao *et al.* 2004; MacGabhann 2005). Corsetti and Lorenz (2006) argue that whilst some Marinonan style cap carbonates are synchronous, some are not, being distributed in an interval between 709 – 580 Ma. However, this is not a consensual matter, as some data used are subject of debate.

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