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Tracking triggering mechanisms for soft-sediment deformation structures in the Late Cretaceous Uberaba Formation, Bauru Basin, Brazil

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Abstract

Soft-sediment deformation (SSD) structures are widespread in the sedimentary record, and numerous triggering mechanisms can induce its development, including glaciation, earthquakes, overloading, ground-water fluctuations, and wave movement. The Late Cretaceous Uberaba Formation preserves SSD structures as small- and large-scale load casts and associated flame structures, pseudonodules, and convolute laminations observed in the contact of three well-defined intervals among fine- to coarse-grained lithic and conglomeratic sandstone with fine-grained arkose and mudstone beds. Based on the morphology of the SSD structures, sedimentary facies of the Uberaba Formation, and similarities with previous observations in the geological record and laboratory models, these features are assigned to liquefaction-fluidization processes as the major deformational mechanism triggered by seismic and aseismic agents. We propose that a deformation occurred just after the sedimentation triggered by seismic shock waves and overloading, induced by the sudden deposition of coarse-grained sandy debris on fine-grained sediments. Some of these structures can be classified as seismites, providing evidence of intraplate seismicity within the inner part of the South American Platform during the Late Cretaceous. This seismic activity is likely related to the uplift of the Alto Paranaíba High along reactivations of regional structures inherited from Proterozoic crustal discontinuities and coeval explosive magmatism of the Minas-Goiás Alkaline Province.

KEYWORDS: Late Cretaceous; soft-sediment deformation structures; intraplate tectonism; seismicity; overloading; Bauru Basin.

INTRODUCTION

Soft-sediment deformation structures are conspicuous features found in both ancient and modern, shallowly buried, loose, and water saturated sediments (Allen 1982, Owen 1987). A wide range of natural triggers, including bioturbation, flooding, overloading, sudden oscillations of groundwater, slumping, storm waves, or seismic shaking (Lowe 1975, Allen 1986, Owen 1987, Shiki *et al.* 2000, van Loon 2009, Owen *et al.* 2011) can lead to the development of these structures. In the latter case, when liquefaction and/or fluidization are related to seismic activity, they can be designated as seismites (Seilacher 1969, 1984, 1991, Gibert *et al.* 2011, Moura-Lima *et al.* 2011, Rossetti *et al.* 2011). These earthquake-induced structures are of particular interest due to their implication for the tectonic history of sedimentary basins, including palaeoseismic studies and determination of tectonic reactivation cycles (Obermeier 1996, Moretti *et al.* 2014). However, identification and interpretation of seismites can be a complex task, since non-seismic triggers can produce structures that resemble those produced by earthquakes (Rust 1968, Maltman *et al.* 2000, Van Rensbergen *et al.* 2003).

The Coniacian to Santonian Uberaba Formation of the Bauru Basin (Fig. 1) was interpreted as deposited under semi-arid conditions in a large fluvial braided system (Batezelli and Ladeira 2016). Recent stratigraphic and sedimentological efforts conducted in the vicinities of the Uberaba city revealed that these sedimentary deposits contain several soft-sediment deformation structures concentrated, at least, along three deformed horizons. Considering the importance of these structures for the depositional, paleoseismic, and paleogeographic reconstruction of the Uberaba Formation, this contribution is focused on describing in detail the different types of soft-sediment deformations and discuss their driving force(s) and deformational and trigger(s) mechanisms. We also explore the geological evolution of alkaline provinces and structural uplifts that affected the Bauru Basin, aiming to associate tectonic and/or regional magmatic events with the intraplate tectonic activity.

REGIONAL GEOLOGICAL CONTEXT

The intracratonic Bauru Basin is located in central to southeastern Brazil and covers an area of approximately 370,000 km^2 (Fig. 1). Its geological evolution is closely tied to the continental

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breakup of Gondwana and the opening of the South Atlantic Ocean during the Early Cretaceous (Maisey 2000, Batezelli and Ladeira 2016). Initial subsidence within the basin is related to the eruption of almost 1,700-meter-thick basaltic lavas of the Valanginian-Hauterivian Serra Geral Formation (Thiede and Vasconcelos 2010). This massive volume of lavas putatively caused considerable thermal subsidence and lithospheric flexure rebound in the inner part of the South American Platform (Batezelli and Ladeira 2016), allowing the deposition of siliciclastic deposits of the Caiuá Group (Fig. 1). Menegazzo *et al.*
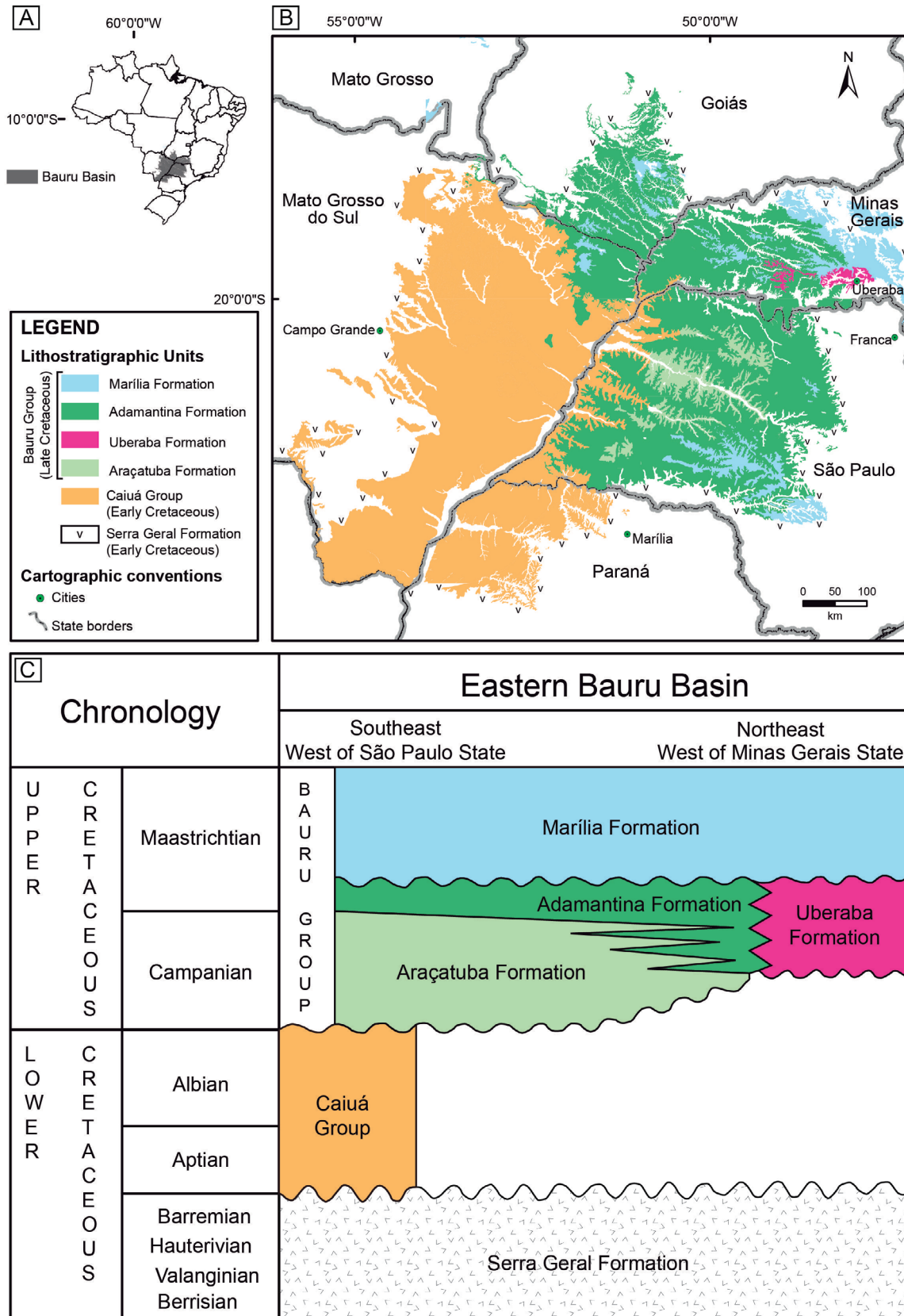

Figure 1. (A) Location of the Bauru Basin in Brazil. (B) Simplified geological map of the Cretaceous Bauru Basin. (C) Chronostratigraphic chart of the Bauru Basin in southeast Brazil. Modified from Batezelli and Ladeira (2016).

(2016) proposed that the Bauru Basin is a component of a retroarc foreland system developed during the early stages of the Andean evolution. Sedimentation within the Bauru Basin would have been developed in the back-bulge province of this system (Menegazzo *et al.* 2016). The Turonian-Campanian uplift of the Alto Paranaíba High (Hasui *et al.* 1975) and associated alkaline intrusions attributed to the activity of the Trindade Mantle Plume (Gibson *et al.* 1995) (Fig. 2), promoted a pronounced mechanical subsidence pulse affecting the Bauru Basin. Correlated intrusions also occur in the southern part of the Goiás State, and are related to the coeval Goiás Alkaline Province (Junqueira-Brod *et al.* 2002).

Two active tectonic features delimited the northwestern and northeastern borders of the Bauru Basin during the Late Cretaceous: the Rondonópolis Anteclise (Coimbra and Fernandes 1995) and the Alto Paranaíba High (Hasui *et al.* 1975, Hasui and Haralyi 1991), respectively (Fig. 2). The Alto Paranaíba High is a Jurassic to Late Cretaceous positive tectonic structure developed from Neoproterozoic discontinuities related to the Brasília Fold Belt (Riccomini *et al.* 2005). The uplift of this structure is related to the activity of the Trindade (Gibson *et al.* 1995) or Tristan da Cunha (VanDecar *et al.* 1995) mantle plumes within the subcontinental lithospheric mantle. During the Cretaceous, the Alto Paranaíba High acted as a barrier between the Bauru and Sanfranciscana basins (Batezelli and Ladeira 2016). With 250 km in length and 70 km in width, this province comprises alkaline plutonic

complexes, hypabyssal intrusions, lavas, and tuffs occurring along with an NW-SE fault system that acted as conduits for the potassic to ultrapotassic mafic to ultramafic magmatism (Almeida 1983, Gibson *et al.* 1995). The main faults reached great depths and were responsible for the upwelling for explosive alkaline magmatism that filled depressed areas generated by transtensional structures (Campos and Dardenne 1997). The associated volcanic rocks cover an area of approximately 4,500 km² (Leonardos *et al.* 1991) and are assigned to the Mata da Corda Group of the Sanfranciscana Basin. The plutonic complexes vary between 2 and 6 km in diameter and are named as Tapira, Araxá, Salitre I and II, Serra Negra, and Catalão I and II (Fig. 2). Available K-Ar ages of the plutonic carbonatite complexes range between 79 and 97 Ma (Amaral *et al.* 1967, Hasui and Cordani 1968, Sonoki and Garda 1988, Gomes *et al.* 1990). K-Ar radiometric dating performed on phlogopite crystals from the Mata da Corda Group provided an age of 83.6 ± 1.4 Ma (Gibson *et al.* 1995), whereas Ar-Ar analyses of olivine phenocrysts of the Serra do Bueno kamafugite yielded an age of 90 ± 4 Ma (Gibson *et al.* 1994).

The Rondonópolis Anteclise is a positive tectonic feature with a NE-SW trend (Coimbra and Fernandes 1995) that was also tectonically active during the Late Cretaceous, with uplift along discontinuities related to the Neoproterozoic Brasiliano Cycle (Riccomini *et al.* 2005). At that time, the Rondonópolis Anteclise acted as a barrier between the Bauru and Parecis basins (Coimbra and Fernandes 1995). Series of small pull-apart
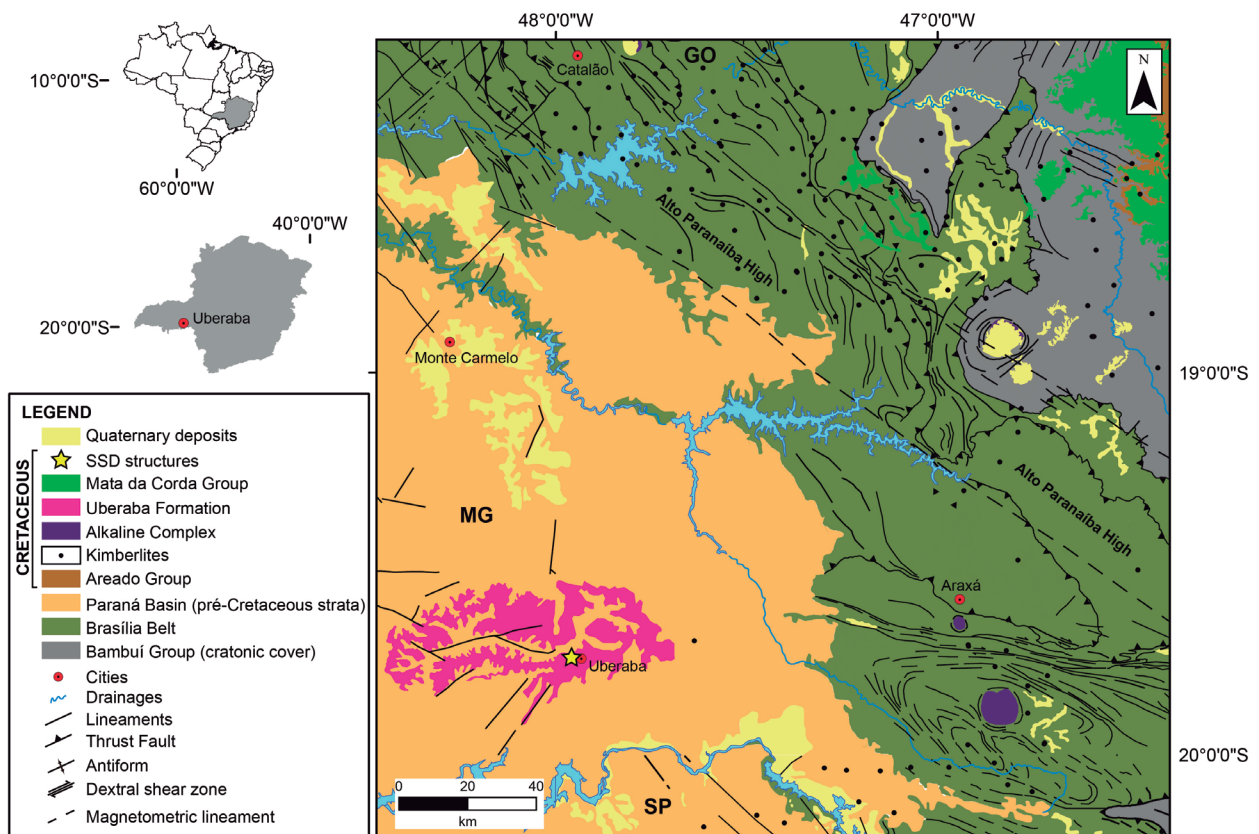
Source: adapted from Oliveira *et al.* (2004).

Figure 2. (A) Location of the study area in Brazil and State of Minas Gerais. (B) Simplified geological map of the Alto Paranaíba region showing locations of SSD structures of the Uberaba Formation, the distribution of the alkaline complexes and kimberlites in the Alto Paranaíba High, and the main tectonic features.

basins formed within the anteclise due to transtensional reactivation of NE to ENE and NW-trending faults (Riccomini *et al.* 2005). Additionally, the anteclise was affected by the emplacement of voluminous mafic alkaline magmatism during the Late Cretaceous (Gibson *et al.* 1995, 1997). This magmatism is related to the impact of the Trindade Mantle Plume and present minimum and maximum ages of 83.4 ± 2.4 Ma (Ar-Ar in a dyke from the Poxoreu Igneous Province in Mato Grosso State, Gibson *et al.* 1995) and 97.1 ± 1.1 Ma, respectively (Rb-Sr in syenites and granites of the Ponta do Morro alkaline intrusion, Souza 1997).

Geologic aspects of the Bauru Basin

The Early to Late Cretaceous Bauru Basin is composed of two second-order sequences delimited by regional unconformities (Batezelli 2015), comprising:

- the lower sequence, corresponding to the Goio Erê, Rio Paraná, and Santo Anastácio formations (Caiuá Group in the meaning of Fernandes and Coimbra 1994);
- the upper sequence constituted by the Araçatuba, Adamantina/Uberaba and Marília formations (Bauru Group) (Fig. 1C).

The Early Cretaceous Caiuá Group rests unconformably over a regional erosive surface developed on the volcanic rocks of the Serra Geral Formation (Fernandes and Coimbra 2017). This unit has a total thickness of approximately 280 m and was deposited between the Aptian and Albian (Batezelli and Ladeira 2016). It is composed of fine-grained cross-bedded sandstone, organized in meter-thick beds interpreted as complex eolian dunes and sand sheet deposits from the Goio Erê, Rio Paraná, and Santo Anastácio formations (Fernandes and Coimbra 1994). The contact with the overlying Bauru Group is characterized by a regional unconformity (Batezelli 2015).

The Campanian to Maastrichtian Bauru Group is constituted by the Araçatuba, Adamantina, Uberaba, and Marília formations (Fig. 1), encompassing a succession of about 300 m of exclusively siliciclastic units (Batezelli and Ladeira 2016). The basal Araçatuba and Adamantina formations were interpreted as deposited over local depocenters developed directly on basalts of the Serra Geral Formation (Batezelli and Ladeira 2016). In the western part of the basin, these units occur over eolian deposits of the Caiuá Group. In general, the Araçatuba Formation is composed of very fine, red to greenish fine-grained sandstone, siltstone, and shale (Basilici *et al.* 2016). Depending on their occurrence area, the Araçatuba Formation was interpreted as deposited in palustrine (Fernandes *et al.* 2003), lacustrine (Batezelli *et al.* 2016), or basinal evaporitic systems (Basilici *et al.* 2016). In the southern part of the Bauru Basin, the Adamantina Formation is composed of fine-grained sandstones interpreted as deposited in mid to distal parts of a distributary fluvial system. In the northern part, this unit is constituted by fine-grained sandstone with subcritical climbing translatent strata interpreted as wind ripples in eolian sand sheets (Basilici and Dal'Bó 2010). The Marília Formation occur above the Uberaba Formation (detailed in the next topic) and is mainly constituted by fine sandstone,

paleosoils, and conglomerates interpreted as deposited in alluvial system surrounded by a peripheral eolian sand sheet system (Batezelli *et al.* 2019).

Geology of the Uberaba Formation

The Uberaba Formation is exposed along the northeastern part of the Bauru Basin, mainly in the vicinities of the homonymous city. The succession is up to 70 m in thickness (Quintão *et al.* 2017) and constitutes the basal part of the Bauru Group (Batezelli and Ladeira 2016), resting on erosional unconformity over the underlying Serra Geral Formation. This contact is characterized by the occurrence of a polymictic conglomerate composed of basalt, sandstone, and mudstone clasts (Hussak 1906, Fernandes and Coimbra 2017, Batezelli and Ladeira 2016). The upper contact of the Uberaba Formation with the Marília Formation is abrupt and marked by the occurrence of a silexite bed and a quartz clasts-rich conglomerate cemented by calcite (Seer and Moraes 2017). A depositional age between 83.6 and 72.1 Ma (Campanian) has been suggested for the Uberaba Formation based on remains of titanosaurid herbivorous dinosaurs (Huene 1939, Santucci and Bertini 2001) and lithostratigraphic correlations with Vale do Rio do Peixe and Marília formations. Lithologically, the unit is composed of fine- to medium-grained sandstone, conglomerate, pebbly sandstone, and siltstone facies (Fig. 3) deposited in a huge alluvial braided river system (Batezelli and Ladeira 2016).

Coeval explosive volcanic activity in the Alto Paranaíba region, related to the Patos Formation (Mata da Corda Group), produced large volumes of tephra, which was mechanically infiltrated in the intergranular pores of the sediments during

Figure 3. Simplified columnar section of the studied outcrop of the Uberaba Formation in the vicinities of the homonymous town along the MG-050 (coordinates: 187612 mE/7816707 mS).

early diagenesis of the Uberaba Formation (Ferreira Jr. and Gomes 1999). In some cases, this volcanic clay matrix can reach up to 24.6% in the volume of the rock (Ferreira Jr. and Gomes 1999). According to Silva *et al.* (1994), Ferreira Jr. and Gomes (1999), and Quintão *et al.* (2017), the detrital components of the Uberaba Formation were also sourced from basalts of the Serra Geral Formation, quartzites, and schists of the Canastra, Ibiá and Araxá Groups, and intrusive rocks from the Minas-Goiás Alkaline Province. Exhumation of rocks from the Alto Paranaíba High started during the upper Lower Cretaceous to Upper Cretaceous (Costa and Sad 1968, Hasui 1968, Sad 1970, Riccomini *et al.* 2005), and probably provided the detrital components for the northeastern part of Bauru Basin (Ferreira Jr. and Gomes 1999, Quintão *et al.* 2017).

SOFT SEDIMENT DEFORMATION STRUCTURES IN THE BAURU BASIN

Despite previous descriptions of soft-sediment deformation structures in the Bauru Basin, all occurrences described in the literature are restricted to the lower sequence, correspondent to the Caiuá Group. The soft-sediment deformation (SSD) structures in the Caiuá Group was firstly reported by Suguio and Barcelos (1983), who described and interpreted boudinage features confined between undeformed sandstone beds of the Santo Anastácio Formation as earthquake-induced structures. Fernandes *et al.* (2007) reported two well-defined horizons characterized by large-scale deformations in eolian sandstone of the Early Cretaceous Rio Paraná Formation in the São Paulo and Mato Grosso do Sul States. These deformations comprise complex recumbent and convolute folds, clastic dikes, and pillar-like features, interpreted as a product of tectonic activity probably related to the emplacement of the Goiás Alkaline Province (Fernandes *et al.* 2007). Here, we describe and discuss for the first time SSD structures-bearing horizons in the Late Cretaceous Uberaba Formation of the Bauru Basin.

Driving forces and deformational mechanisms

Soft-sediment deformation structures develop in water-saturated, non-consolidated sediments, and prior to significant compaction (Mills 1983, Owen 1987, 1996). These structures are formed when a driving force, a deformation mechanism, and a trigger are collectively present (Owen *et al.* 2011, Owen 1996), sediments lose grain-contact and are temporarily supported by intra-pore fluids (Allen 1982). In this way, such non-consolidated deposits lose internal friction and behave like a fluid, originating its characteristically ductile-like structures (Owen 1987). Different driving forces have been proposed to explain deformation in cohesionless sediments, comprising:
- gravity influence on slopes;
- uneven loading due to topographic irregularities in the sediment-water interface;
- variations in gravitational potential energy due to a reverse density gradient;
- shear by aqueous or other currents; and
- biological or chemical agents (Owen *et al.* 2011).

For cohesionless sediments (*i.e.*, sandy deposits), the most important deformational mechanisms are liquefaction (loss of grains contacts and temporary transfer of grain weight to the pore fluid) (Allen 1982, Owen 1987, Owen and Moretti 2011) and fluidization (support of grain weight by the upward component of fluid drag) (Allen 1982, Nichols *et al.* 1994, Owen and Moretti 2011).

MATERIAL AND METHODS

The studied outcrop is a road cut along the MG-050 highway in the outskirts of Uberaba city, western region of the Minas Gerais State, SE Brazil. Facies description follows the proposal of Miall (1996) for fluvial deposits, with punctual adaptations. The classification of SSD structures was based on Alfaro *et al.* (1997), Owen (2003), and Moretti and Sabato (2007). The determination of the triggering mechanism(s) for soft-sediment deformation followed the proposal of Owen *et al.* (2011, and references therein).

RESULTS

Sedimentary facies from the fluvial deposits of the Uberaba Formation

The detailed outcrop corresponds to the intermediate part of the Uberaba Formation, well exposed in a road cut (BR 050), with about 300 m of lateral extension and 4 m of height. The metric tabular beds of the outcrop correspond to amalgamated lenticular and channelized decimeter scale of beds, commonly showing erosive base. The deposits are organized in metric scale thinning upward cycles characterized by massive and through-cross bedded very coarse to coarse sandstone facies at base grading to fine sandstone with parallel lamination, and culminating in mudstone facies at the top (Fig. 3). Despite the limited size of the studied section, the sedimentary facies described (see Tab. 1) and the architecture of the deposits, suggest deposition of longitudinal fluvial bars (Miall 2010), probably related to a huge alluvial braided river system (Batezelli and Ladeira 2016).

Soft-sediment deformation structures in the Uberaba Formation

A great variety of SSD structures is observed in the irregular interfaces between greenish, fine- to coarse-grained lithic sandstone, conglomeratic sandstone with red, fine-grained arkose and mudstone from the intermediate part of the Uberaba Formation. At least three distinct stratigraphic horizons with widespread SSD structures have been recognized in the study area (Figs. 4 to 7). It is possible to distinguish five types of SSD structures based on their morphology:
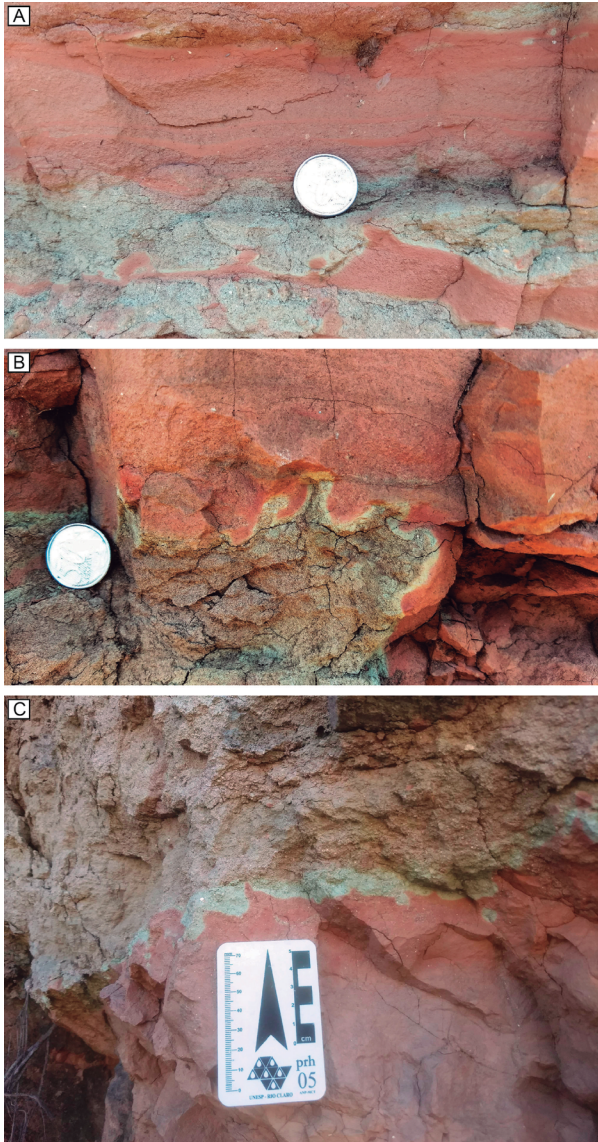- small-scale load structures;
- large-scale load structures;
- pseudonodules;
- flame structures; and
- convolute lamination.

Table 1. Description of sedimentary facies recognized in Uberaba Formation and interpretation of depositional processes.

| Code	Facies	Description	Depositional Process
Gm	Matrix-supported massive conglomerate	Decimeter to meter-scale lenticular beds of polimitic and matrix-supported massive conglomerate. The clasts are mainly constituted by basalt, alkaline rocks, and quartzite. The matrix is a secondary element and is composed of medium to coarse sandstone	Gravel bedforms deposited in fluvial channels by inertial bedflows
St	Through cross-bedded sandstone	Decimeter to meter-scale tabular and lenticular beds of medium to very coarse through cross-bedded sandstone. Occasionally, granules and thin conglomerate lens occur interbedded in the lower part of the series of through cross-stratification.	Migration of linguoid 3D sand dunes under unidirectional flows
Sp	Sandstone with planar cross-stratification	Decimeter to meter-scale tabular and lenticular beds of sandstone with planar cross-stratification	Migration of transverse 2D sand dunes under unidirectional flows
Sh	Sandstone with parallel lamination	Decimeter to meter-scale tabular beds of fine to coarse sandstone with parallel lamination, sometimes showing streaming lineation in the bedding	Migration of low amplitude bedforms formed under upper flow regime in the top of fluvial bars
Fm	Massive silststone	This facies include tabular beds, of massive siltstone usually light to dark grey or yellow, occasionally with centimetric poligonal dissecation cracks. The laminated variety presents very fine sparse sand grains.	Settling of siliciclastic mud in calm water
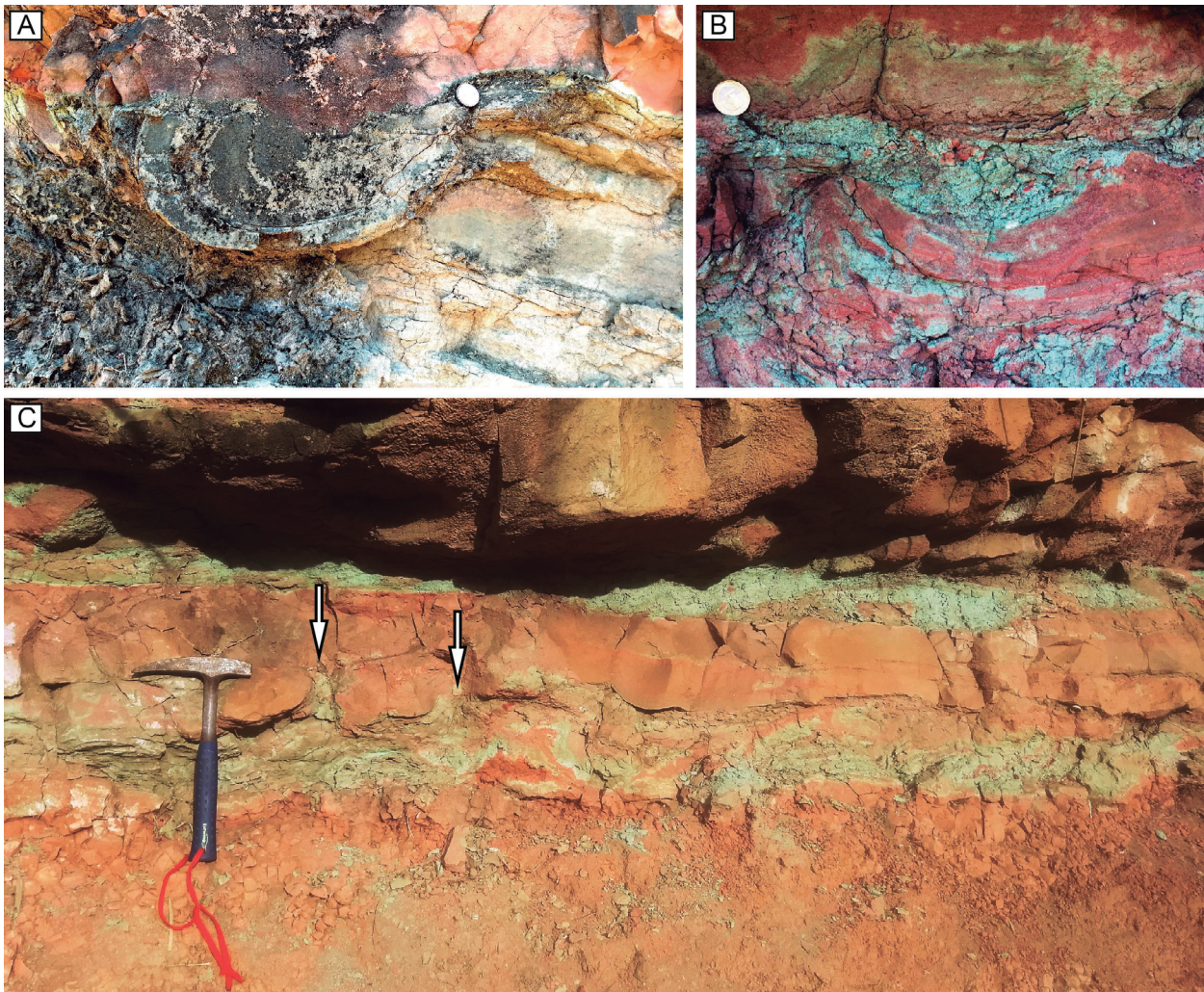
Figure 4. (A) Large-scale load structure formed by fine grained arkose overlying fine-grained lithic sandstone. Note the deformed internal lamination. (B) Large-scale load structure formed by medium- to coarse-grained lithic sandstone overlying fine-grained arkose. (C) Large-scale load casts composed of fine-grained arkose overlying coarse-grained lithic sandstone and associated with flame structures (black and white arrows).

Figure 5. (A) Small-scale load structure composed of medium-grained lithic sandstone overlying very-fine grained arkose and associated with flame structures. (B) Small-scale load structure formed by fine-grained arkose overlying fine-grained lithic sandstone and associated with flame structures. (C) A deformed surface bearing small-scale load structures composed by coarse-grained lithic sandstone overlying very-fine grained arkose and associated with flame structures. Note the difference in the texture of the two sandstone layers in B and C. The coin in A and B is 2.4 cm in diameter.
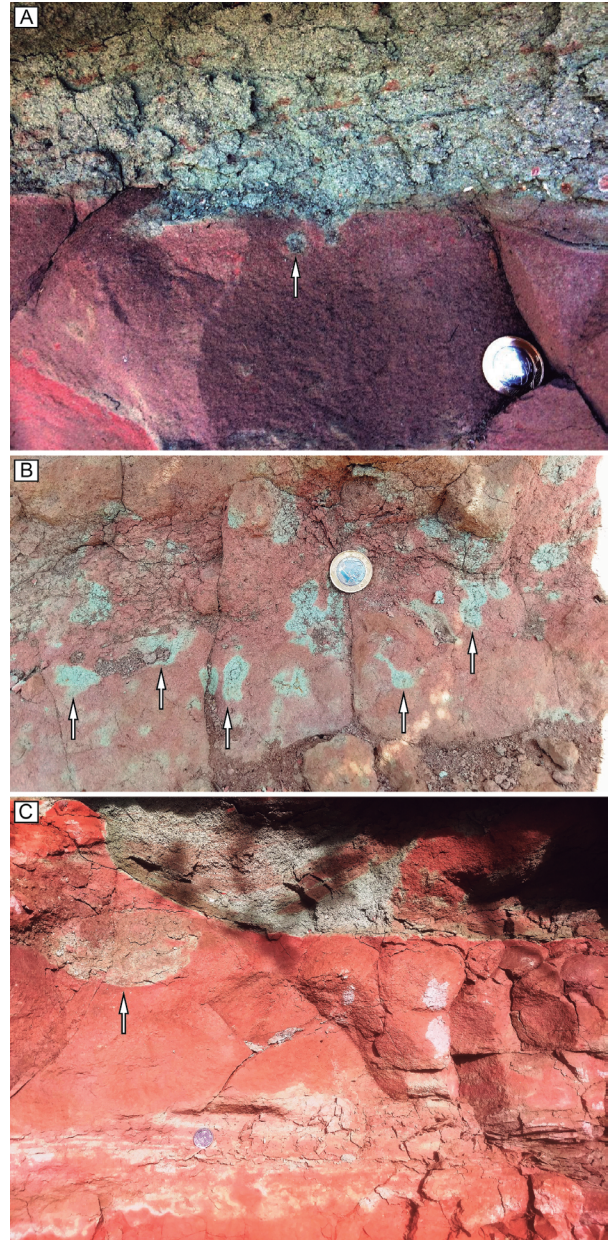
Figure 6. (A) Interface between coarse-grained lithic sandstone and fine-grained arkose showing small-scale detached pseudonodule. (B) Detached pseudonodules with irregular morphology and composed of lithic sandstone dispersed in fine-grained arkose. (C) Ball-and-pillow. Coin in A and C is 2.4 cm in diameter. The graphic scale in B is 10 cm long. Black and white arrows indicate SSD structures.
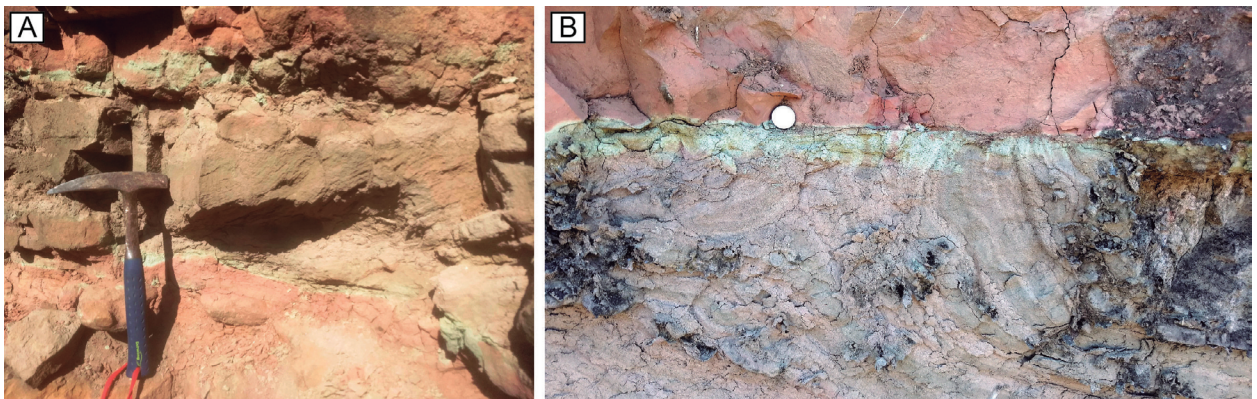
Figure 7. (A) A 30-cm thick bed of fine-grained lithic sandstone bearing small-scale antiforms and synforms. (B) Well-developed convolute laminations developed internally in the previously mentioned deformed bed. Note that the convolute laminations are confined to a single bed that was eroded by the non-deformed overlying layer.

Load structures

Load casts

Load structures are very common features found in sand-stones of the Uberaba Formation. These structures usually occur at the irregular contact between fine- to coarse-grained lithic sandstone and conglomeratic sandstone and very-fine to fine-grained arkose and mudstone. Following the nomenclature proposed by Moretti and Sabato (2007), they can be classified into large-scale load-structures (Fig. 4) and small-scale load-structures (Fig. 5).

Large-scale load structures range from 15 to 45 cm in length and have a concave-up semi-spherical geometry (Fig. 4). They may penetrate up to 20 cm into the underlying bed, and internal laminations are commonly deformed (Fig. 4A). They occur in distinct lithologies but more frequently are described in coarse-grained lithic sandstone and conglomeratic sandstone overlying very-fine grained arkose (Fig. 5A and 4B). Occasionally, such deformations are observed in fine-grained arkose overlying fine- to medium-grained lithic sandstone (Fig. 4C).

Small-scale load structures have dimensions ranging vertically between 1.0 and 6 cm. They always appear in association with diapirs and flame structures. This structure occurs at contacts between fine- to coarse-grained lithic sandstone overlying fine-grained arkose (Fig. 5A and 5C) and contrariwise (Fig. 5B). They slightly penetrate the underlying bed and show a typical concave profile upward. These load structures lack internal lamination and resemble the "pendulous load casts" described by Owen (2003).

Flame structures and diapirs

Flame structures of the Uberaba Formation are wedge-shaped and range from few centimeters to decimeters, intruding between individual small- and large-scale load structures (Fig. 5). Most of them are formed by fine-grained arkose intruded in greenish lithic medium- to coarse-grained sandstone (Fig. 5A and 5C). Occasionally, an injection of greenish lithic medium sandstone into fine-grained arkose is also observed (Fig. 5B). These structures are morphologically related to flame and diapirs (sensu Owen 2003) and usually occur in contacts between sandstone overlying mudrock. On the other hand, flame structures of the Uberaba Formation are quite uncommon because the SSD structures are found mostly in the contacts between sandstone beds.

Pseudonodules

Pseudonodules are less frequently found than load structures, and attached pseudonodules (sensu Owen 2003) were not described in the studied outcrop. The dimensions of the detached pseudonodules range between 0.5 (Fig. 6A) and 12 cm (Fig. 6C). They are composed of fine- to medium-grained lithic sandstone, arranged in elliptical, rounded to irregular bodies completely disconnected from the overlying sandstone, and encapsulated by the underlying fine-grained arkose (Fig 6B). The pseudonodules may penetrate up to 30 cm into the lower bed.

Convolute lamination

This structure is very rare in the studied outcrop and only occurs in very fine- to fine-grained lithic sandstones (Fig. 7). The maximum thickness of deformed beds may reach up to 30 cm (Fig. 7A). The lamination is highly contorted, resembling irregular synclines and anticlines (Fig. 7B). The intensity of deformation tends to decrease toward the base of and into undisturbed laminae (Fig. 7B).

DISCUSSION

Features such as load structures, pseudonodules, and ball-and-pillow are commonly interpreted to be formed in response to gravitational instability (Moretti et al. 1999, Owen 2003, Moretti and Sabato 2007). They commonly occur along the interface separating sand or sandstone from underlying mud, mudstone, or shale. However, in some cases, there is a little density contrast of these lithologies across the contact (Allen 1982, Owen 2003, Owen and Moretti 2011, Santos et al. 2012, Owen and Santos 2014). According to Owen et al. (2011), this type of deformation is dominated by vertical displacements and driven by gravitational forces coupled with a reverse density system (sensu Anketell et al. 1970). The driving forces for the origin of the small-scale load structures, pseudonodules, diapirs and flame structures in the Uberaba Formation are probably related to a reverse density system (sensu Anketell et al. 1970), generated by the density difference between fine- to coarse-grained lithic sandstone and conglomerates and fine-grained arkose and mudstone.

In the deformed intervals, the gravitationally unstable density gradient provided by fluvial bedforms allowed the denser fine- to coarse-grained lithic sandstone to sink into less dense fine-grained arkose and mudstone when it liquidized. Pseudonodules characterize an advanced stage in the process of deformation and displacement. With the continuity of the diapiric motion of underlying liquefied sediments, the load casts tend to be encapsulated by the low-density sediment, forming detached (or locally connected with narrow necks) pseudonodules.

Moretti and Sabato (2007) argued that water-escape structures (flame structures sensu Owen 2003) are formed by fluidization in response to an increase in the gradient of pore water pressure. According to Owen (1987), fluidization is initiated just after liquefaction, and re-sedimentation of suspended grains at lower levels take place due to an increase in pore-water pressure. Consequently, both water and sediments moved upward forming water-escape structures, sectioning and deforming the overlying bed. Thus, the presence of these structures in the Uberaba Formation (Fig. 5) can be best explained as the result of local liquefaction and fluidization of the medium- to coarse-grained lithic sands related to a water escape process. During the development of the medium- to coarse-grained load casts, the underlying finer arkose compensated its loss of volume with upward intrusions.

Convolute lamination was originally described by Kuenen (1953) as internally contorted, laminated, silt to fine-sand features bounded by upper and lower undeformed planar surfaces. Although known for a long time, the driving force mechanism for convolute laminations is still not well understood.

Interpretations vary from current drag or bed shear, slumping, thixotropic behavior, and rapid sedimentation (see Sanders 1960, Allen 1977, Mills 1983, Neuwerth *et al.* 2006). In the Uberaba Formation, convolute laminations are not related to muddy beds, and the possibility of thixotropic behavior is consequently reduced. On the other hand, the deformation of primary lamination coupled with convolute folding of the sands suggests that the decrease of shear strength was induced by liquefaction.

Triggering mechanism

Liquefaction and fluidization can be induced by both endogenic and exogenic natural trigger mechanisms, including storm waves, bioturbation, floods, groundwater oscillations, overloading, rapid sedimentation, volcanic eruptions, and seismic shocks (Allen and Banks 1972, Obermeier 1996, Owen *et al.* 2011). Field evidence shows that most of the described SSD structures in fine- to coarse-grained lithic sandstone and fine-grained sandy rocks from the Uberaba Formation were induced by liquefaction-fluidization processes. Prior to considering an exogenic trigger, it is fundamental to exclude the influence of endogenic sedimentary processes in the unconsolidated sediments (Moretti 2000, Moretti and Sabato 2007). The action of storm waves can be easily excluded due to the exclusively continental (fluvial) depositional setting interpreted for the Uberaba Formation (Batezelli *et al.* 2019). The semi-arid to arid climate inferred for this part of South America during the Late Cretaceous (Batezelli *et al.* 2019), similarly precludes the possibility of liquefaction and fluidization promoted by unequal loading associated with glaciers or ice caps. Likewise, there is no evidence of associated bioturbation, such as invertebrate burrows and vertebrate tracks, capable of generating localized liquefaction and fluidization. Evidence of slumps and gravitational slides are also absent and can be discarded.

Thus, considering this context, a plausible trigger mechanism could be associated with sediment loading related to rapid deposition (in terms of Owen 1996). The preserved unstable minerals (*i.e.*, pyroxene, amphibole, and volcanic clasts), low rounded grains, and lack of syndepositional muds within the framework of the terrigenous rocks from the Uberaba Formation point to deposition under high energy conditions (Batezelli 2003). The occurrence of matrix-supported massive conglomerate and conglomeratic sandstone also reinforce the rapid sedimentation, probably in fluvial channels, by inertial bedflows. Moretti *et al.* (2001) showed that rapid sedimentation is a common trigger mechanism for liquefaction in sand-on-sand and sand-on-clay systems. According to this model, the rapid deposition of sand could induce liquefaction in great depths below the sediment-water interface at the same time as the excess of pore-water pressure remains very high in the underlying sediments for hours, causing subsequent expulsion of fluid. In this way, the small-scale load structures formed by lithic sandstone and conglomeratic sandstone overlying arkose and mudstone (Fig. 5) can be interpreted as the product of the sudden deposition of decimeter-thick beds of conglomerate and conglomeratic sandstone in fluvial channels promoting a rapid increase in interstitial pore-water pressure in the underlying fine-grained arkose and mudstone (Moretti and Sabato 2007).

On the other hand, the small and large-scale load structures composed of fine-grained arkose overlying medium- to coarse-grained lithic sandstone are not necessarily related to beds deposited by punctual and energetic processes. Thus, it is necessary to propose distinct exogenic triggers for the generation of SSD structures, as deformation induced by tsunami waves, impact of extraterrestrial bodies, and seismic shaking (Obermeier 1996, Owen *et al.* 2011). The first two can be discarded due to the nonexistence of impact craters with Campanian age in the Bauru Basin and the exclusively continental deposition inferred for the Uberaba Formation. Thus, excluding all aforementioned possibilities, we conclude that seismic shaking must have been induced the formation of the aforementioned SSD structures described in the Uberaba Formation. In this way, the horizons bearing SSD structures could be considered as true seismites (*sensu* Mills 1983, Obermeier 1996, Moretti 2000, Ettensohn *et al.* 2002, Røe and Hermansen 2006, Owen *et al.* 2011, Santos *et al.* 2012, Moretti *et al.* 2014, Rossetti *et al.* 2017). Evidence that supports this hypothesis are:

- wide lateral continuity of deformed layers (c.f. Santos *et al.* 2012, Røe and Hermansen 2006, Moretti *et al.* 2014) for hundreds of meters to kilometers. It is important to note that this study was focused on one single outcrop, but tens of other were visited in the surroundings and presented deformational structures similar to those detailed here;
- presence of deformed layers bounded by undeformed beds (*e.g.,* Ettensohn *et al.* 2002, Santos *et al.* 2012, Moretti *et al.* 2014);
- the deformed beds are restricted to a unique stratigraphic interval (the intermediate part of the Uberaba Formation);
- recurrence of deformed beds through time (Santos *et al.* 2012, Moretti *et al.* 2014, Rossetti 1999);
- compatible morphology of the described structures and seismites;
- reactivation of regional structures (Riccomini *et al.* 2005) coeval with alkaline explosive magmatism (Campos and Dardenne 1997).

Searching for Late Cretaceous intraplate earthquakes

Based on the study of liquefaction-induced features of distinct Holocene geological settings from the USA, Obermeier (1996) demonstrated that SSD structures can be a powerful tool to estimate the recurrence interval and magnitude of moderate to great (*sensu* Richter magnitude scale) earthquakes. The epicentral distance (radius) to the farthest liquefaction feature (km) can be correlated with the earthquake moment magnitude (M) for both shallow and deep-focus earthquakes. Earthquakes with at least M > 5 are required to generate liquefaction-induced features (Obermeier 1996). The analysis of the tectono-magmatic context of the Alto Paranaíba region during the Late Cretaceous reveals a potential tectonic active area for the origin of paleo-earthquake events related to the origin of the Uberaba Formation SSD structures.

During the Late Cretaceous, the Bauru Basin was infilled by ~300 meters of siliciclastic sediments deposited in exclusively continental settings (Fernandes and Coimbra 1994,

Milani and De Wit 2008, Batezelli and Ladeira 2016, Basilici *et al.* 2016, Dal'Bó *et al.* 2018). The sedimentation of the Uberaba Formation occurred during the Campanian Age, between 83.6 and 72.1 Ma (Huene 1939, Santucci and Bertini 2001, Tamrat *et al.* 2002), strongly coinciding with the ages of fault reactivations along the Neoproterozoic basement and the alkaline magmatism in the Alto Paranaiba High and the Rondonópolis Anteclise. Thus, considering that the uplift along basement discontinuities, alkaline plutono-volcanic activity, and deposition of the Uberaba Formation are coeval, we conclude that the liquefaction and fluidization responsible for the formation of the studied SSD structures were most probably triggered by Late Cretaceous seismicity. The distance between the study area and the Poxoreu Igneous Province is about 850 km; thus we discard this setting as the main source of the paleo-earthquakes that generated the SSD structures. On the other hand, due to their proximity to the study area, the uplift of the Alto Paranaíba High and/or magmatism in the Minas-Goiás Alkaline Province are the most promising candidates as seismicity sources. Despite the reduced number of data presented in this study, considering the magnitude-bound method proposed by Obermeier (1996), it is possible to estimate that earthquakes that produced the SSD structures had a moment of magnitudes (M) greater than 5.0 (the minimum required to generate liquefaction-induced features).

CONCLUDING REMARKS

The Uberaba Formation of the intracratonic Bauru Basin is interpreted as deposited in a large alluvial braided river system during the Late Cretaceous. At that time, the northeastern border of the basin was affected by the uplift of the Alto Paranaíba High and plutono-volcanic magmatism of the Minas-Goiás Alkaline Province. At least three distinct surfaces along the contact between lithic sandstone and conglomerate with fine-grained arkose and mudstone contain widespread soft-sediment deformations interbedded with undeformed strata. The SSD structures described here occur in the intermediate part of the Uberaba Formation and can be classified into two main groups: load structures (load casts, flame structures, and pseudonodules), and convolute laminations.

These deformations are attributed to liquefaction-fluidization processes. Driving forces for the generation of small-scale load structures are associated with gravitationally unstable density gradients triggered by overloading (*sensu* Moretti and Sabato 2007). Gravitational forces, coupled with a reverse density system, are also the driving-force system for large-scale load structures. However, in this case, liquefaction and fluidization were produced by seismic shocks. Pseudonodules are associated with gravitational instabilities related to density differences. Flame structures are associated with fluidization and injection of sands into surrounding load structures. As convolute laminations within the Uberaba Formation are clearly confined to deformed beds that were eroded by non-deformed overlying bed, this structure is most probably related to earthquakes.

In sum, the studied intervals bearing large-scale load structures and convolute laminations can be classified as seismites (*sensu* Mills 1983, Obermeier 1996, Moretti 2000, Ettensohn *et al.* 2002, Røe and Hermansen 2006, Owen *et al.* 2011, Santos *et al.* 2012, Moretti *et al.* 2014, Rossetti *et al.* 2017). The Late Cretaceous reactivation of the Precambrian basement (*i.e.*, Brasília Fold Belt), which led to the uplift of the Alto Paranaíba High, and the magmatism of the Minas-Goiás Alkaline Province, were the most probable sources of the seismicity. Estimated magnitudes of the paleo-earthquakes that affected the study area are surely bigger than 5.0 (M). The seismites previously described in the Caiuá Group (Fernandes *et al.* 2007) and the recognition of new occurrences in the studied section reinforces the influence of tectonic activity during the deposition of the Late Cretaceous Bauru Basin. Finally, the study of the Uberaba Formation SSD structures provides an excellent opportunity to investigate the relationships between reactivation of regional intraplate discontinuities, coeval magmatism, sedimentary processes, and their influence in the continental deposition during the Late Cretaceous of the central-southeastern South American Platform.

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