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Non-marine ostracod biostratigraphy of Cretaceous rift lake deposits (Sousa Basin, Brazil): Paleogeographical implications and correlation with Gondwanic basins

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ABSTRACT

The Cretaceous section of the Sousa Basin represents alluvio-fluvio-lacustrine deposits from rift lakes generated in NE Brazil as a consequence of the West Gondwana break-up process, marked by progressive separation of the African and South American plates. The chronostratigraphic age of the sedimentary succession is controversial due to the few biostratigraphic data available, based on palynomorphs, ostracods and 'conchostracans' (Spinicaudata), and taxonomic problems of some of the fossils. Non-marine ostracods (microcrustaceans) are useful index fossils and have been used for a regional biozonation of the lacustrine deposits. Due to this factor non-marine ostracods from the core 2-FC-01-PB, which comprises rocks of the Sousa Formation (Rio do Peixe Group), were analysed. The core 2-FC-01-PB assemblage includes index taxa for biozones RT-002 to RT-005 (*Alicenula leguminella*, *Brasacypris ovum*, *Cypridea ambigua* and *Reconcavona swaini*), indicating a Berriasian to Hauterivian age (Rio da Serra/Aratu local stages). The previous assignment of a Jurassic age to the early stage of deposition of the Rio do Peixe Group is refuted here. We discuss and revise the stratigraphic range and paleogeographical distribution of relevant index ostracods. Our revised non-marine ostracod biostratigraphy facilitates correlations of non-marine strata of the Sousa Basin with those of Brazilian (Recôncavo, Tucano and Sergipe) and African (Gabon and Congo) sedimentary basins of West Gondwana.

1. Introduction

The Gondwana break-up process at the onset of the Cretaceous is marked by progressive separation of the African and South American plates and is related to the events of opening and development of the South Atlantic Ocean (Castro, 1987; Basile et al., 2005; Castro et al., 2007). The rifting process started in the Jurassic and persisted through the Early Cretaceous (Sénant and Popoff, 1991; Ponte, 1992; Françolin et al., 1994; Silva et al., 1997). This led to the creation of small rifts on a large depositional basin that developed in central and northern Gondwana (Pre-Rift Stage), named the Afro-Brazilian Depression (Cainelli and Mohriak, 1999; Matos, 1992; Silva et al., 1997, 2012; Kuchle et al., 2011). The numerous small rift-valleys captured the drainage, creating lakes and consequently depositional space (Carvalho and Melo, 2012). Therefore, the Sousa Basin's alluvio-fluvio-lacustrine deposits record the depositional environments through the time of the rifting event in northeastern Brazil.

The chronostratigraphic positioning and correlations of the three formations from the Rio do Peixe Group, Sousa Basin, and those from the near rifts were obtained through fossil remains, mainly ostracods (Braun, 1969; Mabesoone and Campanha, 1974; Lima and Coelho, 1987; Regali, 1990; Carvalho, 2000; Carvalho and Carvalho, 1990). Ostracods (Arthropoda, Crustacea – microcrustaceans with a calcified bivalved shell) are the most useful group for dating and correlating Cretaceous non-marine sections, as they are among the most common fossils and can provide high biostratigraphic resolution (Viana, 1966a, 1966b; Viana et al., 1971; Moura, 1972; Grosdidier and Bignoumba, 1984; Grosdidier et al., 1996; Poropat and Colin, 2012). Non-marine ostracods provide the stratigraphic framework and support the development of depositional models as well as contributes for the architectural and tectonic understanding of half-grabens inside Gondwana (Braun, 1969; Albuquerque, 1986, 1970; Françolin and Szatmari, 1987; Lima-Filho, 1990; Françolin et al., 1994; Srivastava and Cavalcante, 2001; Nogueira et al., 2004; Rocha and Amaral, 2006; Sousa et al., 2007; Córdoba et al., 2008; Silva et al., 2014).

Despite previous efforts, the ages attributed for the Rio do Peixe

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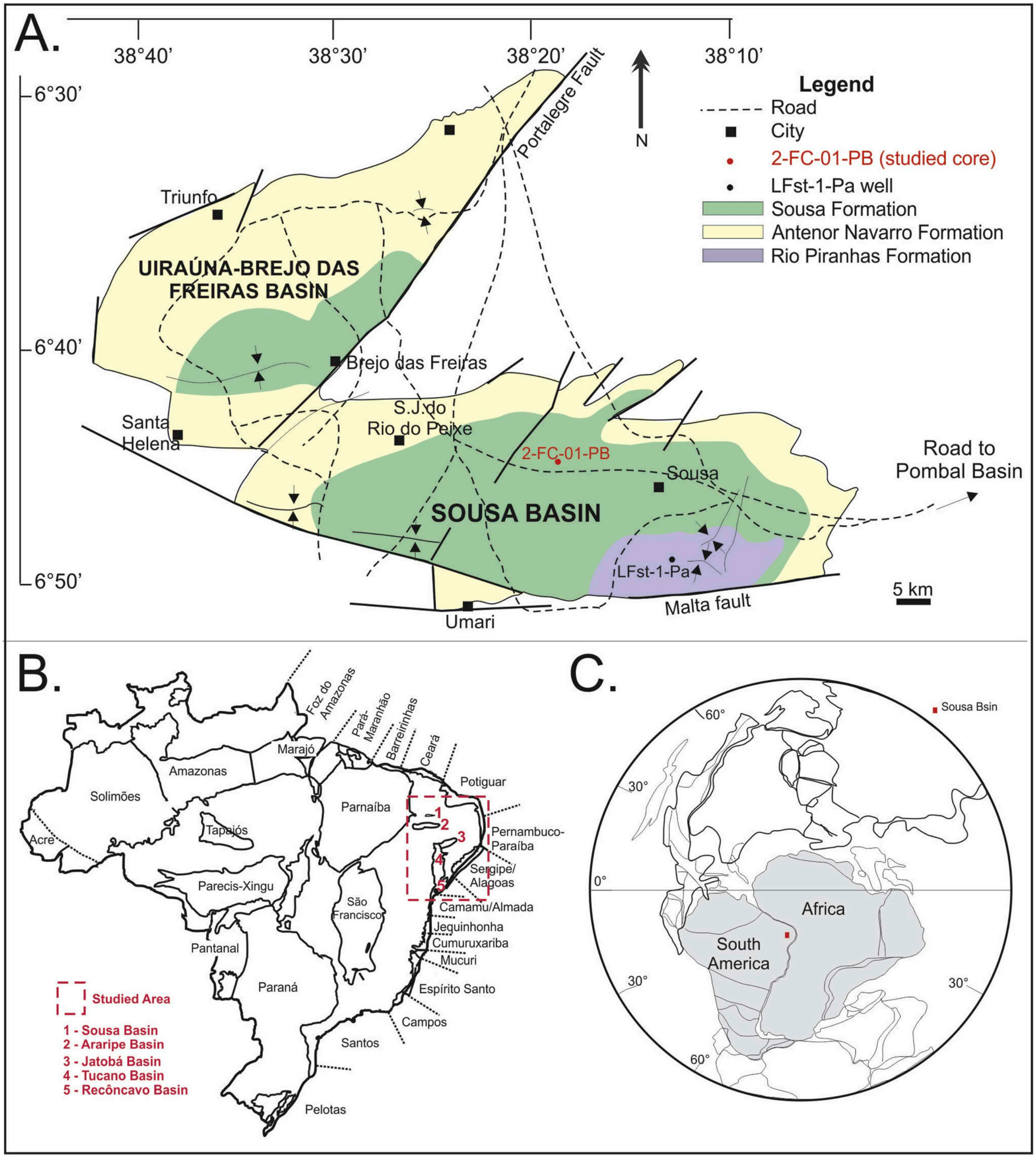

Fig. 1. Geological context of the (**A**) Sousa Basin and the core studied (after Srivastava and Carvalho, 2004), in (**B**) Northeastern Brazil, and (**C**) the Early Cretaceous Gondwana paleogeographic map (mod. http://www.odsn.de/cgi-bin).

Group are still controversial lacking sufficient taxonomic and biostratigraphic analyses. Previous studies suggested that ostracods indicate a Late Jurassic age for the beginning of the deposition (Mabesoone and Campanha, 1974), while Regali (1990), using palynomorphs, suggested a Berriasian age. However, the youngest biostratigraphic ages were assigned to the final stage of deposition as Hauterivian (Rio da Serra local stage) (Regali, 1990) and Hauterivian/Barremian (Aratu Local Stage) (Mabesoone and Campanha, 1974; Tinoco and Katoo, 1975), based on palynomorphs, ostracods and 'conchostracans', respectively. Here we re-evaluate the utility of non-marine ostracods for an accurate biostratigraphy of the lacustrine deposits of the Sousa Formation of the Rio do Peixe Group, sampled by a core drilled in the central region of the Sousa Basin (Fig. 1A).

2. Geological setting and stratigraphy

The Sousa Basin is located in the extreme west of the State of Paraíba, in northeastern Brazil (Fig. 1A, B, C). The basin has a sedimentary succession similar to the Uiraúna-Brejo das Freiras and Pombal half-grabens, being part of the region known as Rio do Peixe Basins. The half-grabens are separated by a structural basement high (Françolin and Szatmari, 1987; Rocha and Amaral, 2006), with its edges located along the Portalegre and Malta faults (Patos Lineaments) (Matos, 1992; Rocha and Amaral, 2006; Córdoba et al., 2008).

The total thickness of the sedimentary succession estimated for the Sousa Basin may exceed 2,000 m in its depocenter (Sousa et al., 2007). The succession is composed of Devonian marine deposits of the Santa

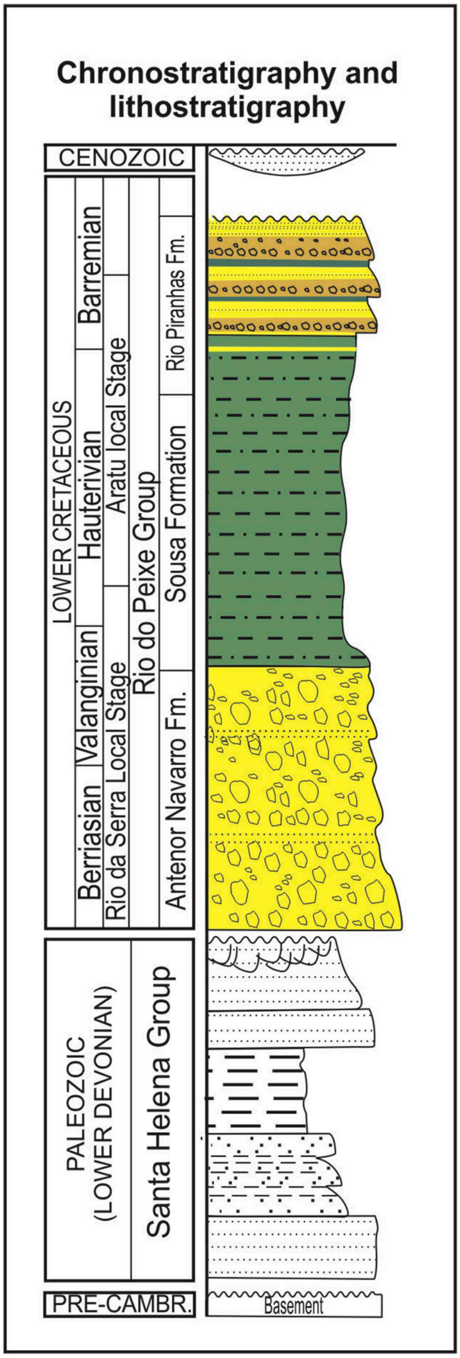

Fig. 2. Stratigraphic chart proposed for the Rio do Peixe Basins (Srivastava and Carvalho, 2004; Silva et al., 2014).

Helena Group (Roesner et al., 2012; Silva et al., 2014), overlain by Cretaceous fluvio-lacustrine and Recent alluvial deposits. The basement of this Paleozoic and Mesozoic successions are metamorphic and magmatic rocks from the Borborema Province. These are gneisses, marbles, quartzites, phyllites and granites of Late Pre-Cambrian age.

The Cretaceous succession was informally divided into three lithostratigraphic units (Braun, 1969). Later were formalized as the Antenor Navarro, Sousa and Rio Piranhas formations, and included in the Rio do Peixe Group (Albuquerque, 1986) (Fig. 2). Fossils are abundant in the respective deposits, such as dinosaurs tracks (Carvalho, 2000; Leonardi and Carvalho, 2002), fragments of fishes or saurian bones and teeth (Lima-Filho, 1991, 1990; Hessel et al., 1994; Carvalho et al., 2013); ‘conchostracans’ (Tinoco and Katoo, 1975; Carvalho and Carvalho, 1990), ostracods (Braun, 1969; Mabesoone and Campanha, 1974), and palynomorphs (Lima, 1983; Lima and Coelho, 1987; Regali, 1990). The fossil remains are usually best preserved in the Sousa Formation.

The Antenor Navarro Formation comprises conglomerates, conglomeratic sandstones and sandy conglomerates with tabular and trough cross-stratification. These structures represent alluvial fans, or braided or distributary fluvial systems that developed on the flexural margins and directional ramps. The Rio Piranhas Formation comprises fine to coarse grained sandstones with cross-stratification interbedded with claystones and conglomerates, depicting alluvial fans and faulted borders, which are associated with braided fluvial systems (Córdoba et al., 2008).

The Sousa Formation has a wide geographic extent, covering about 70% of the Sousa and Pombal basins and 50% of the Uiraúna-Brejo das Freiras basin (Fig. 1A). It is characterized by the predominance of siltstones and reddish brown shales interbedded with fine to medium calciferous sandstones, marl and limestone, and displays wave ripples, planar-parallel or crossed lamination, mudcracks, and calcretes (Córdoba et al., 2008; Nogueira et al., 2015). According to Vasconcelos (1980), the upper and lower contacts of the formation are concordant and gradational with the Antenor Navarro and Rio Piranhas formations, respectively.

The Sousa Formation includes different depositional systems, from subaqueous systems to those formed by ephemeral drainages (Córdoba et al., 2008). The rocks are representatives of a lacustrine environment and a meandering fluvial environment, with occasional floods of their plains, deposited under a semi-arid climate with alternating rainy and dry seasons (Lima-Filho, 1991).

3. Methods and material

3.1. Core, sample and laboratorial procedures

Core 2-FC-01-PB (Fazenda Carnaúba: 6° 44′ 47.4″ S and 38° 18′ 52.6″ W), with a 210 m in length, is located in the eastern area of the Sousa Basin, near Sousa City, State of Paraíba (Fig. 1A). The core was drilled by the Federal University of Rio de Janeiro (Rio de Janeiro, RJ) and comprises the pelitic rock section of the Sousa Formation. The 189 sampled levels for the biostratigraphic study based on ostracods are displayed in Fig. 3.

The samples, 60 g each, were macerated, subjected to a solution of hydrogen peroxide (130 vl) and acetic acid (125 vl), sieve-washed with a 62-μm mesh, dried (60 °C) and stored in plastic bags. The sorting step comprised the removal of all ostracods from each sample. The taxonomic analyses were performed with a ZEISS-Discovery V12 stereoscopic microscope in reflected light. Specimen photomicrographs were obtained with a Scanning Electron Microscope (SEM), Zeiss EVO 40. All the above steps were performed in the Petrobras/Biostratigraphy and Paleoecology Management laboratories (Rio de Janeiro, RJ). The ostracod specimens are housed in the repository of the Federal University of Rio de Janeiro, the holotypes and paratypes can be consulted under the label UFRJ-DG-LMOS 0001 to UFRJ-DG-LMOS 0039, and the microcells with all the picked ostracods specimens can be consulted under the label UFRJ-DG-LM180001 to UFRJ-DG-LM180059. The taxonomic details of the main non-marine ostracods recorded in core 2-FC-01-PB can be found in Sousa et al. (2018).

3.2. Biostratigraphic framework

In this study, we adopted the biostratigraphic framework (Fig. 4) elaborated by Moura (1972), based on the biostratigraphic proposals for the Recôncavo and Tucano basins (Viana, 1966a; Viana et al., 1971), in which the biozones are defined by the last occurrence event of non-marine ostracods. The correlation between the local stages and the International Time Scale was proposed by Regali and Viana (1989) and

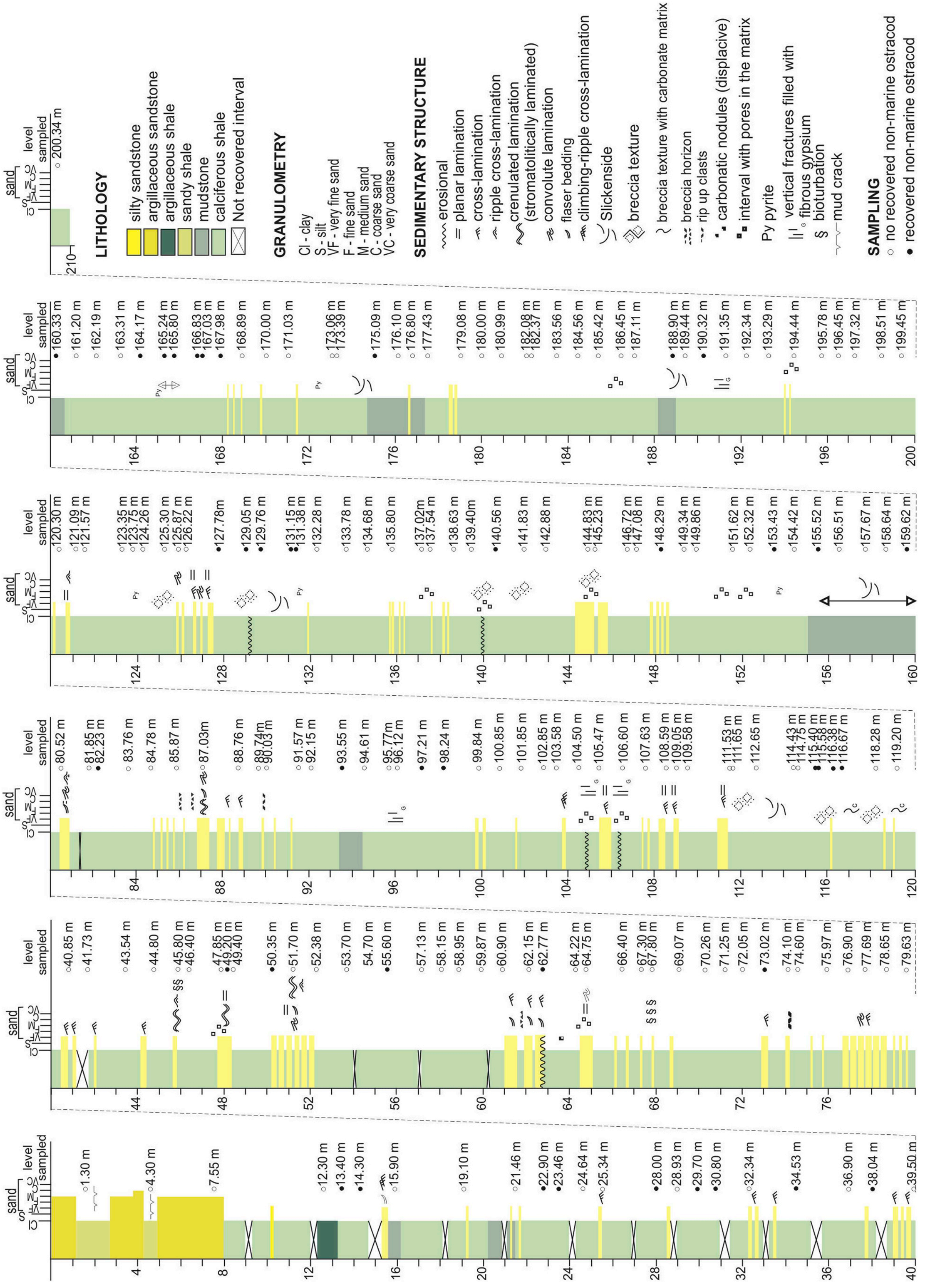

Fig. 3. Lithologic section of core 2-FC-01-PB (modified from Silva-Filho, 2009) with depth sampled for non-marine ostracods indicated.

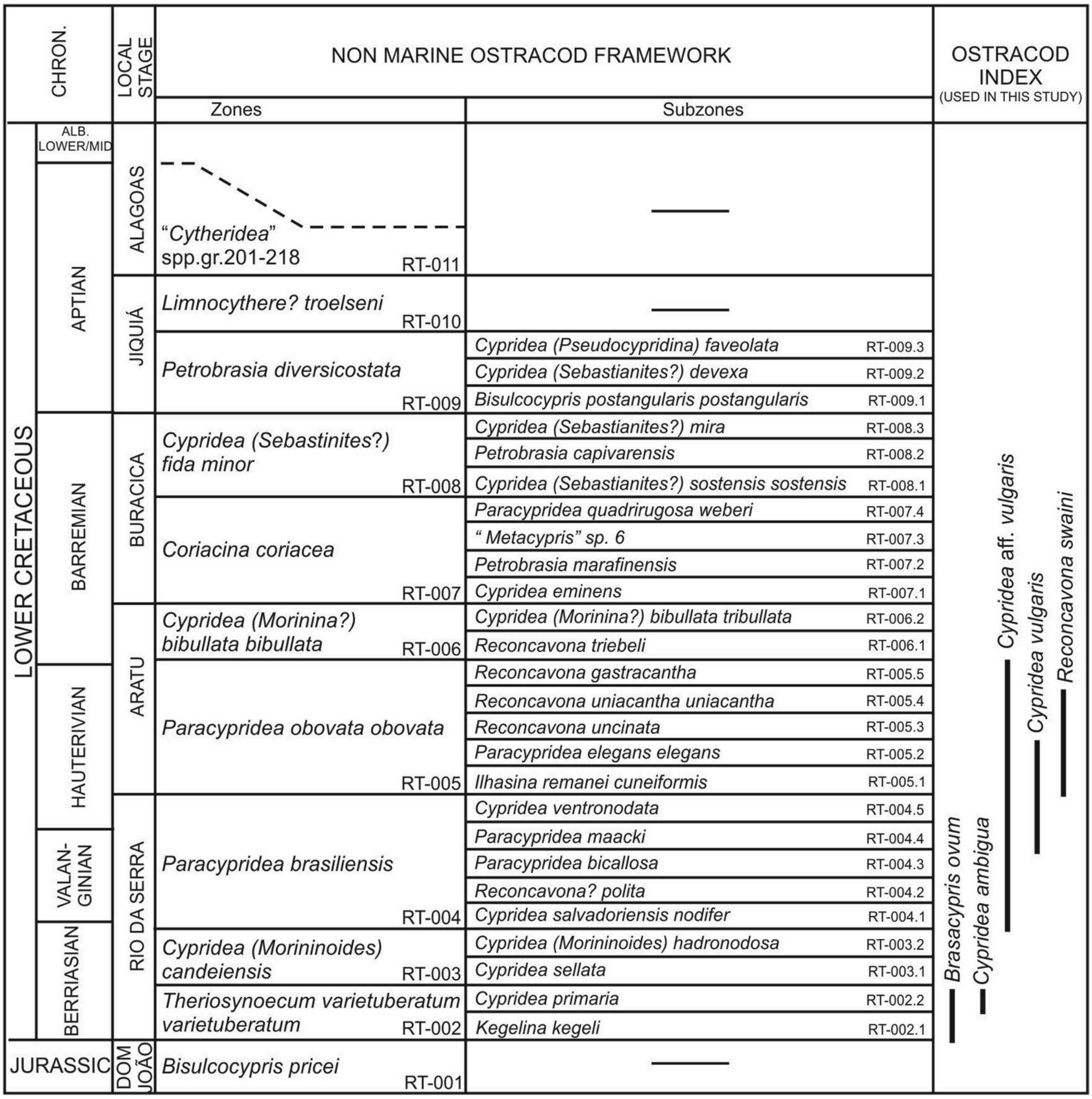

Fig. 4. Biostratigraphic framework based on non-marine ostracods (after Moura, 1972) and other ostracod index, stratigraphic range of Brasacypris ovum (Krömmelbein, 1965); Cypridea vulgaris e C. aff. vulgaris (Coimbra et al., 2002); C. *ambigua* e *Reconcavona swaini* (Moura, 1972). RT = Recôncavo-Tucano basin ostracod zonation by Viana (1966a).

Arai et al. (1989) (Fig. 4).

Some non-index ostracods (Fig. 4) are important for chronostratigraphic positioning because of their restricted range, which is limited to certain zones. *Cypridea ambigua* Krömmelbein (1962), and *Reconcavona swaini* Krömmelbein (1962) were recorded in the Recôncavo and Tucano basins (Viana, 1966a; Viana et al., 1971; Moura, 1972), and *Brasacypris ovum* Krömmelbein (1965) is restricted to the Itaparica Formation and the lower portion of the Candeias Formation, both in the Tucano Basin (Krömmelbein, 1966, 1965). The taxonomy of *Cypridea vulgaris* Krömmelbein (1962) is controversial as it is difficult to differentiate at species level, being sometimes treated as *Cypridea* aff. *vulgaris* (Braun, 1969; Grosdidier et al., 1996; Viana, 1966b; Bate, 1999). Coimbra et al. (2002) sustain that *C. vulgaris* and *C.* aff. *vulgaris* are different species, with *C.* aff. *vulgaris* having a stratigraphic range that spans zones RT-005 and RT-004, while *C. vulgaris* is limited to the RT-004.4 to RT-005.2 subzone range.

4. Results

4.1. Ostracod assemblages

Ostracod carapaces in varying states of preservation, from bad to good, were found in 40 of the 198 sample collected (Fig. 3). The assemblages revealed variations in abundance and diversity among the samples, with the highest rate of recovery in calciferous shales. In all the fertile samples, the ostracod shells exhibit the same color as the sediments, resulting from diagenesis.

Non-marine ostracods of four podocopic families were recorded: species of the families Cyprideidae Martin 1940 emended Sames (2011), Cyprididae Baird 1845, Darwinulidae Brady and Norman 1889, and Ilyocyprididae Kaufmann 1900. Seven species were identified: *Alicenula leguminella* (Forbes, 1855 *in* Lyell, 1855) Martens et al. (2003), *Alicenula sousaensis* Sousa et al. (2018), *Brasacypris ovum* Krömmelbein (1965), *Cypridea ambigua* Krömmelbein (1962), *Cypridea paraibensis* Sousa et al. (2018), *Cypridea vianai* Sousa et al. (2018) and *Reconcavona swaini* Krömmelbein (1962). Five species were left in open nomenclature: *Alicenula* ex gr. *leguminella*, *Alicenula* sp. 1, *Cypridea* sp. 1,

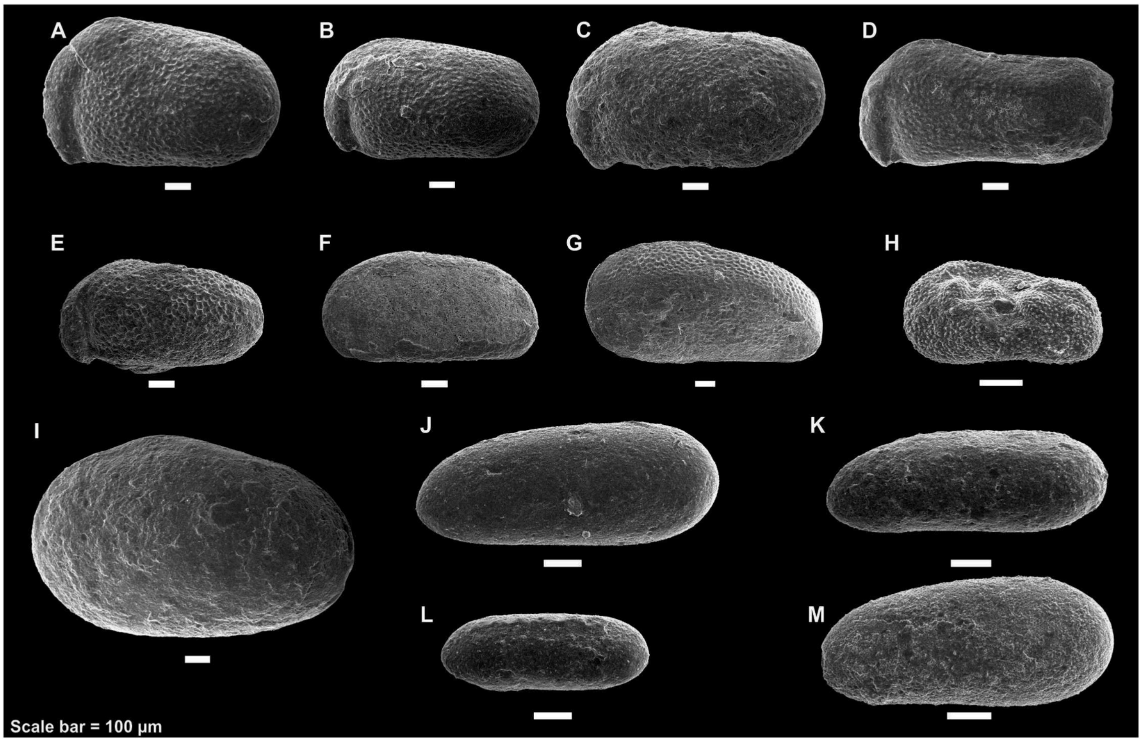

Fig. 5. Examples of non-marine ostracods from Core 2-FC-01-PB. All specimens are pictured in left lateral view. (A) *Cypridea vianai*, sample UFRJ-DG-LM180050, depth 160.33 m; (B) *Cypridea ambigua*, sample UFRJ-DG-LM180050, depth 160.33 m; (C) *Cypridea paraibensis*, sample UFRJ-DG-LM180053, depth 165.80 m; (D) *Cypridea* sp. RP3, sample UFRJ-DG-LM180050, depth 160.33 m; (E) *Cypridea* sp. 1, sample UFRJ-DG-LM180004, depth 22.90 m; (F) *Reconcavona swaini*, sample UFRJ-DG-LM180038, depth 129.76 m; (G) *Mantelliana* sp., sample UFRJ-DG-LM180018, depth 55.60 m; (H) *Ilyocypris* sp. 1, sample UFRJ-DG-LM180003, depth 14.30 m; (I) *Brasacypris ovum*, sample UFRJ-DG-LM180048, depth 159.62 m; (J) *Alicenula leguminella*, sample UFRJ-DG-LM180048, depth 159.62 m; (K) *Alicenula* ex gr. *leguminella*, sample UFRJ-DG-LM180048, depth 159.62 m; (L) *Alicenula sousaensis*, sample UFRJ-DG-LM180048, depth 159.62 m; (M) *Alicenula* sp. 1, sample UFRJ-DG-LM180003, depth 14.30 m.

Ilyocypris sp. 1, *Cypridea* sp. RP3. A brief description of these species were presents in Sousa et al. (2018), with exception of *Cypridea* sp. RP3.

Due to the poor preservation of some carapaces, six morphogroups received a general classification: *Cypridea* spp., *Alicenula* spp., *Mantelliana* spp., *Reconcavona* spp., and *Reconcavona*? spp. Others were indicated with a question mark after the name of the species (e.g., *Cypridea ambigua*?). Fragmented carapaces were present in most samples and treated as a group named Unidentified Ostracod. Fig. 5 shows the main non-marine ostracods identified in core 2-FC-01-PB.

4.2. Biostratigraphy of core 2-FC-01-PB

Cypridea ambigua, *Brasacypris ovum* and *Reconcavona swaini* are the species with biostratigraphic value in the ostracod assemblage from core 2-FC-01-PB (Fig. 6). The stratigraphic succession of these species in the core allowed the recognition of biozones RT-002.2, RT-005.4 and RT-005 (Fig. 4), indicating that the pelitic sediments of the Sousa Formation were deposited during the Berriasian (Rio da Serra local stage) to Hauterivian (Aratu local stage).

The results found from the core are presented in Fig. 6 (base to the top). The lower portion of the core (200.34–190.32 m) remained with an undetermined chronostratigraphy due to lack of ostracods. The species *Cypridea ambigua* and *Brasacypris ovum*, present in the 190.32–159.62 m range, indicate Biozone RT-002.2, from the Berriasian. In this portion, the ostracod fauna is abundant, with the ontogenetic series of *Brasacypris ovum* being recorded at depths 160.33 m and 159.62 m.

No biostratigraphically significant ostracods were recovered in interval 159.62–129.76 m, where the assemblages are poor and dominated by fragmented carapaces. *Cypridea vianai* was found near the top of the interval (131.15 m), and *Cypridea paraibensis* was recorded at the base of the interval (155.52, 153.43 and 148.29 m). Specimens of *Cypridea* genus were also detected. The record of *Reconcavona swaini* at a depth of 129.76 m designates a Berriasian–Hauterivian age (Rio da Serra to Aratu local stages). As *Cypridea paraibensis* is easy to identify and differentiate from other taxa, it is of potential biostratigraphic value to constrain the Berriasian–lowermost Hauterivian part of the section (Fig. 6). *Reconcavona swaini* occurs in a single sample (Biozone RT-005.4), being recorded as single occurrence. The last occurrence of *Alicenula sousaensis* together with the occurrence of *Reconcavona swaini* indicates that the former species is potentially a marker for the Rio da Serra and Aratu local stages.

Cypridea vianai was documented in samples from the 190.32–13.40 m range, that is, above the occurrence of *R. swaini* (Fig. 6). *C. vianai* is one of the species previously treated as *Cypridea* aff. *vulgaris* (Coimbra et al., 2002; Sousa et al., 2018). In the present study, the last occurrence of *C. vianai* is recorded at the top of Biozone RT-005, similar to that of *C.* aff. *vulgaris* (Figs. 4 and 6). Based on these data, the Hauterivian age (Aratu local stage) is suggested for the upper portion of the core, (129.46–13.40 m) (Fig. 6), but more studies are necessary to investigate the real range of *C. vianai*.

Non-marine ostracods were not recovered in the top of the core (13.40–0 m), probably because of weathering active in the near-surface layers and/or related to facies/lithology.

5. Discussion

5.1. Taxonomic issues and implications for biochronostratigraphy

The data obtained for the Sousa Formation from core 2-FC-01-PB are relevant to the reconstruction of the succession of ostracod bioevents and to the biochronostratigraphy. Previously, taxonomic

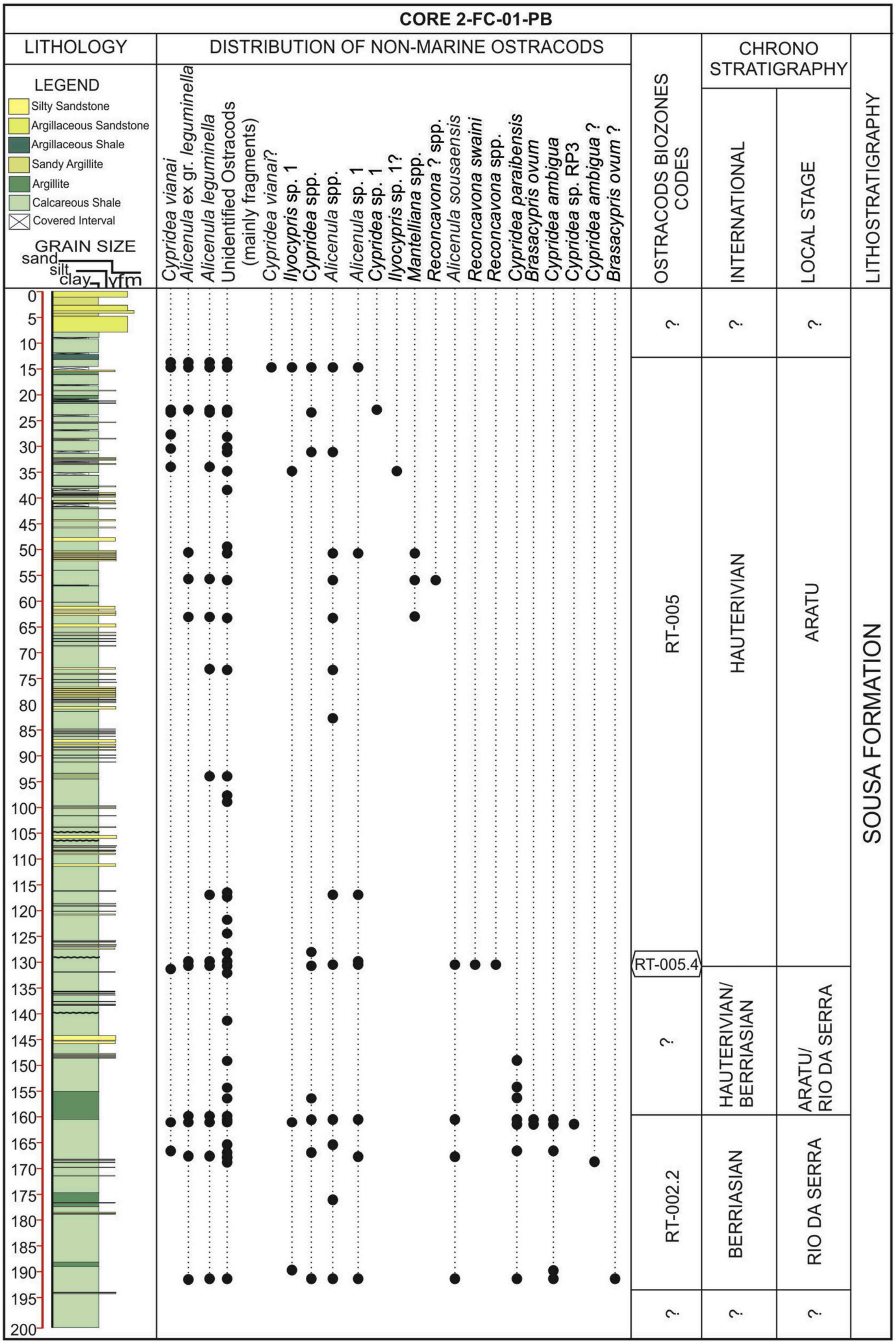

Fig. 6. Stratigraphic distribution chart of non-marine ostracods in core 2-FC-01-PB (Sousa Formation), relation among lithology, ostracods biozones codes, local and international ages.

incoherences, detected when we compared these data with other ostracod biostratigraphic information from the Rio do Peixe Basins, led to incorrect biostratigraphic allocation of the deposits of the Sousa Formation in the previous works of Braun (1969) and Mabesoone and Campanha (1974). The previously reported ostracod specimens had neither been formally taxonomically described nor photographically documentated. In Braun (1969), some ostracod genera were reported, but the levels where they were sampled and the geographic coordinates are not mentioned, preventing any correlation options.

Mabesoone and Campanha (1974) presented a biostratigraphic framework for the Sousa Basin based on the previous paleontological data from Braun (1969), in which several of the species used as biostratigraphic markers identified with some degree of uncertainty (with ‘cf.’). Besides taxonomic problems, Mabesoone and Campanha 1974 paper also contains issues related to biostratigraphic concepts. The authors restricted the ranges of species of the genus *Darwinula* (recte *Alicenula*, Martens et al., 2003; Sousa et al., 2018), specifically *A.* cf. *oblonga* and *A.* cf. *leguminella*, to the Jurassic, which is correct for *A. oblonga*. However, the restriction of *A.* cf. *leguminella* to Biozone RT-001 (Upper Jurassic) is questionable, given the reports of this species in younger strata in the Sousa and Araripe basins as follows: In the review of the fossiliferous content of the Rio do Peixe Basins, Hessel et al. (1994) classified *A.* cf. *leguminella* and *A.* cf. *oblonga* with uncertainty and restricted their stratigraphic range to the Rio da Serra local stage, from biozones RT-002 to RT-004 (Berriasian/Hauterivian). In the Araripe Basin, *A. leguminella* (= *D. leguminella*) is recognized in the Dom João (Upper Jurassic) (Coimbra et al., 2002) and Alagoas (Aptian) local stages (Tomé et al., 2014). In the present study, *A. leguminella* and *A.* ex gr. *leguminella* occur together with species from the RT-002 and RT-005 biozones (Berriasian–Hauterivian). This wide stratigraphic range, together with the lack of taxonomic features and slow evolutionary rates in Darwinulidae (Rossetti and Martens, 1998; Martens et al., 2005, 2003), leads to inaccurate biozone identification. Considering the time interval of about 15–20 Ma (Berriasian to Barremian) dealt with here, the general question if the described taxa really belong to a unique species should be taken into consideration. In the studied material Sousa et al. (2018) observed minor morphological variations in *A. leguminella* and clustered these specimens in *A.* ex gr. *leguminella*. However, without observing the internal carapace characters, it was not possible to determine whether the observed variations are intraspecific (such as sexual dimorphism) or sufficient to determine other species.

Some considerations can be made about *Brasacypris ovum*'s stratigraphic range, represented by a well-preserved ontogenetic series (Sousa et al., 2018). The frequent association of *B. ovum* and *Cypridea ambigua* recorded in the Recôncavo (Krömmelbein, 1966, 1965, 1962) and Sousa basins (this study), points to the possibility that *B. ovum*'s stratigraphic range is restricted to Biozone RT-002.

Nevertheless, the identification of *B. ovum* in the Aptian section of the São Franscico Basin by Leite et al. (2018) led these authors to propose a new diagnosis for this species that does neither match the holotype's original description nor the morphologic features present in the photographic record of Krömmelbein (1965, Tafel 15, 19a–c). Leite et al. (2018) emended the original diagnosis, indicating that the maximum width of the carapace is located in the posterior third, whereas in the holotype this feature is just slightly displaced to the posterior region, almost coinciding with the medium region of the carapace (Krömmelbein, 1965, Tafel 15, 19a–c). This was observed in the variation of the maximum width position illustrated by Leite et al. (2018, p. 8, fig. 4.3 and 4.6). Also in the new diagnosis, Leite et al. (2018) state that the posterior cardinal angle is slightly rounded, while in the holotype description and illustration the angle is clearly rounded, as also observed in Sousa et al. (2018). In relation to the description of the species given by Leite et al. (2018), several incongruities are found: only two poorly preserved specimens were photographed (fig. 4.1–4.6 of Leite et al., 2018) for the elaboration of the emend; sexual dimorphism does not seem consistent, since the female is smaller (fig. 4.1–4.3 of Leite et al., 2018) than the male, and the difference in carapace thickness is not as pronounced as expected in cases of dimorphism; ventral and dorsal margins are indicated as slightly convex, but these characteristics are not observed in the specimens of fig. 4.1–4.6 of Leite et al. (2018). The emend proposed by Leite et al. (2018) describes the cardinal angles as slightly curved, while the holotype is described with pronounced cardinal angles; posterior margin is indicated as sub-rounded by Leite et al. (2018), whereas in the holotype the margin is rounded and the carapace is described as oviform; and the inclination of the hinge margin (6–9°) in Leite et al. (2018) is totally different from the holotype (14°) from Krömmelbein (1965) and the ontogenetic series documented in Sousa et al. (2018) (12–16°), with angle measurement following the criteria established in Sames (2011).

Here we reject the modifications in *B. ovum*'s stratigraphic range proposed by Leite et al. (2018), due to the misidentification of *B. ovum* in Aptian strata of the São Franscico Basin. *B. ovum* remains both restricted to the Berriasian and an important and easily recognizable fossil index for this time interval. We adopt and emphasize the stratigraphic range for *B. ovum* as given by Krömmelbein (1966), who restricted the species to the *Theriosinoecum variotuberatum variotuberatum* Biozone (RT-002).

The scarce number of morphological characters of *Cypridea vulgaris* hamper its unambiguous identification and differentiation. Respective species are sometimes referred to as *Cypridea* aff. *vulgaris* or *Cypridea* cf. *vulgaris* (Bate, 1999; Braun, 1969; Grosdidier et al., 1996; Viana, 1966b). Coimbra et al. (2002) argued that *Cypridea vulgaris* and *Cypridea* aff. *vulgaris* are distinct species, pointing out that *Cypridea* aff. *vulgaris* is a group containing more than one taxon (Viana, 1966b; Braun, 1969; Grosdidier et al., 1996; Bate, 1999). These species have different stratigraphic ranges, with *C.* aff. *vulgaris*' range being larger (biozones RT-005 to RT-004) than that of *C. vulgaris* (limited to subzones RT-004.4 to RT-005.2) (Fig. 4). Sousa et al. (2018) removed *Cypridea vianai* from the *C.* aff. *vulgaris* group, but retained the same stratigraphic range.

5.2. Previous age interpretations for the Sousa Formation

The Sousa Formation interval (799.75 m) drilled by the Lagoa do Forno core (LFst-1-Pa, Fig. 1A), in southeastern Sousa Basin, was dated to the Aratu Stage by Lima and Coelho (1987), due to the record of *Dicheiropollis etruscus* Trevisan (1971) and the absence of *Tucanopollis crisopolensis* (Regali et al., 1974) Regali (1989). *D. etruscus* is an important gymnosperm pollen grain that first occurs in early Berriasian, with the last occurrence at the late Barremian (Trevisan, 1971). In the Cretaceous strata of Brazil, the extinction level of *D. etruscos* is used to define one biozone of Barremian age (Regali et al., 1974; Regali and Viana, 1989). In view of these facts, the age interpreted by Lima and Coelho (1987) does not preclude these sediments to be deposited exclusively during the Barremian, with older ages being admissible (Fig. 7).

Other palynological dating was proposed for the Rio do Peixe Group, using chronostratigraphic correlation with strata of the Araripe Basin. Regali (1990) included the group deposits in the upper portion of Rio da Serra local stage (Berriasian to Hauterivian). In the review of the biostratigraphic data from the northeastern Brazil interior basins, Arai (2006) positioned the Rio do Peixe Group in the Rio da Serra local stage and in the basal portion of the Aratu local stage (Berriasian-Hauterivian), based on the reinterpretation of the palynological assemblages obtained by Lima and Coelho (1987) (Fig. 7).

In previous studies based on ostracods, the Sousa Formation was dated as Upper Jurassic (Dom João local stage) and Lower Cretaceous (Rio da Serra local stage) (Mabesoone and Campanha, 1974), and similar ages were indicated by ‘conchostracans’ (Tinoco and Katoo, 1975). Later, the biostratigraphic data of ostracods and palynomorphs were revised and the Sousa Formation was repositioned in the Rio da Serra–Aratu local stage (Berriasian–Hauterivian) (Hessel et al., 1994).

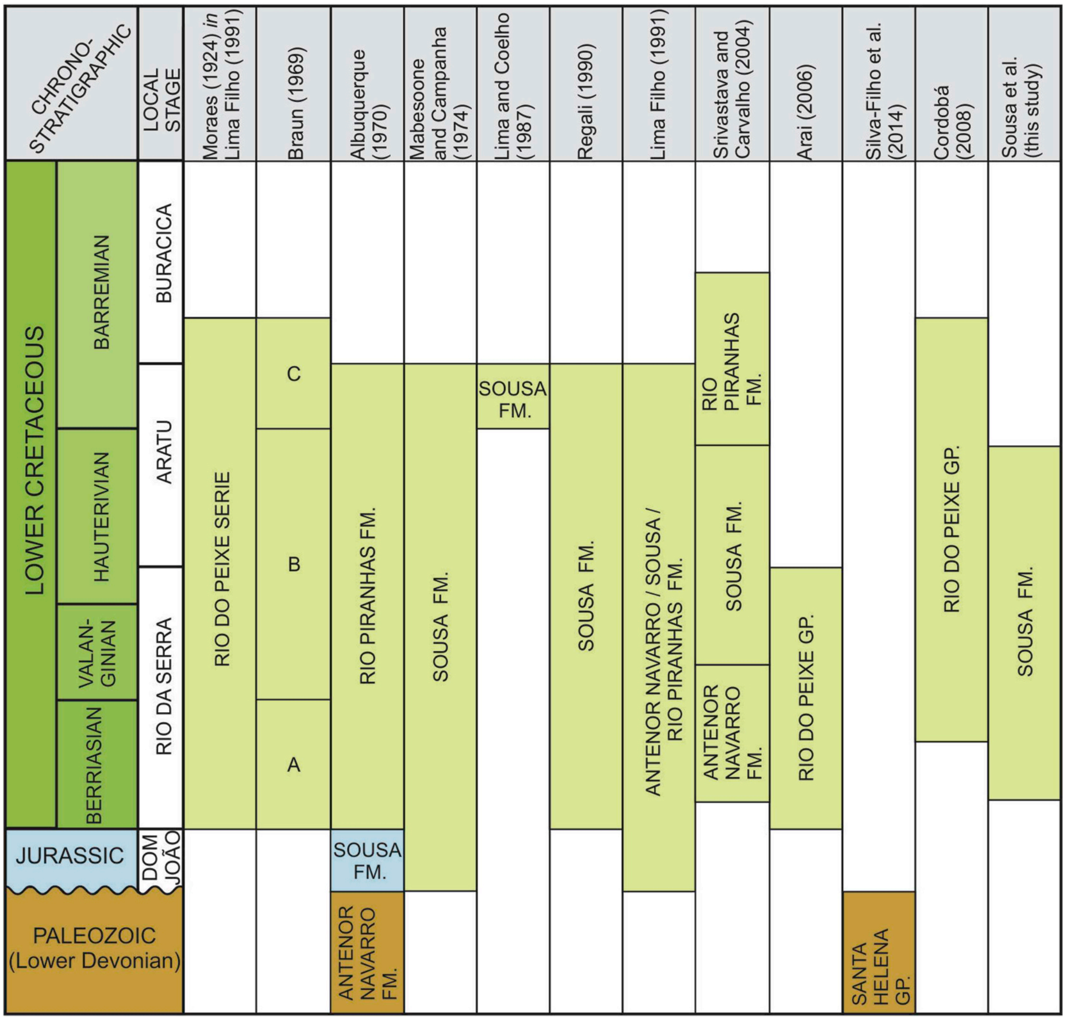

Fig. 7. Chronostratigraphic variation of the Rio do Peixe Group units based on microfossils (FM. = Formation; GP. = Group).

This age is compatible with the Berriasian–Hauterivian range suggested by non-marine ostracods obtained in the present study, refuting the presence of a Jurassic deposit in the Sousa Basin, and corroborating the interpretations of Regali (1990) and Arai (2006) (Fig. 7).

5.3. Correlation with other Gondwana basins

New efforts (Sousa et al., 2018; and this paper) in taxonomic and systematic revision of Lower Cretaceous non-marine ostracods shed new light on their paleobiogeographical and temporal distribution. Several ostracod species found in the Sousa Formation are also recorded in other Gondwana basins. The most widespread ostracod found in the Sousa Basin is *Alicenula leguminella*, which occurs between middle and low latitudes (*circa* 30°S to 30°N) and has a global distribution (Martens et al., 2003). The stratigraphic distribution of *A. leguminella* ranges from the Tithonian (Anderson, 1985; Coimbra et al., 2002) to the Aptian (Tomé et al., 2014), which makes it a poor index fossil for an accurate age constraint and biostratigraphic correlations, despite its wide geographic distribution (Anderson, 1985; Pei-ji, 1983; Wightman, 1990; Swain, 1999; Coimbra et al., 2002; Néraudeau et al., 2012; Tomé et al., 2014).

On the other hand, *Brasacypris ovum*, *Cypridea ambigua*, *C. paraibensis*, *C. vianai* and *Reconcavona swaini* have short temporal ranges, qualifying them as good index fossils (Fig. 4). The paleogeographic distribution of these species are plotted in the Lower Cretaceous Gondwana map (Fig. 8A), showing they occur in low-latitude deposits (circa 0–20°S) and are clustered in the central portion of West Gondwana.

The Berriasian species, *Brasacypris ovum* and *Cypridea ambigua*, were originally described in the Itaparica Formation and in the lower portion of the Candeias Formation in the Recôncavo and Tucano basins (Krömmelbein, 1966, 1965, 1962). As a result of the present study, *Brasacypris ovum's* geographic distribution is expanded from the Recôncavo and Tucano basins, now including the Sousa Basin. *C. ambigua* has a wider distribution than *B. ovum*, being documented from the Recôncavo (Krömmelbein, 1966, 1965, 1962), Tucano (Moura, 1972) and Sergipe (Krömmelbein, 1966) basins, as well as from the African basins of Gabon (Grosdidier et al., 1996; Viana, 1966b) and Congo (Grosdidier et al., 1996). The Sousa Formation lacustrine deposits correlate to the Itaparica and Candeias formations, of the Recôncavo and Tucano basins; and the Kissenda (Gabon Basin) and Sialivakou (Congo Basin) formations (Fig. 8B and C).

Reconcavona swaini was first described in the deposits of the Ilhas Group, from the Recôncavo (Krömmelbein, 1962) and Tucano (Moura, 1972) basins (Fig. 4). In the Gabon Basin, *R. swaini* is recorded in biozones AS6 and AS7, the Lower Cretaceous age, corresponding to the Melania Formation (Grosdidier and Bignoumba, 1984; Grosdidier et al., 1996; Bate, 1999; Poropat and Colin, 2012). *Cypridea vianai* was recovered from almost every sample of our core and, assuming its chronostratigraphic equivalence with *C.* aff. *vulgaris*, a correlation with the Candeias Formation and the Ilhas Group in the Recôncavo Basin is suggested. *C.* aff. *vulgaris* is present in the AS4 to AS5 biozone range of

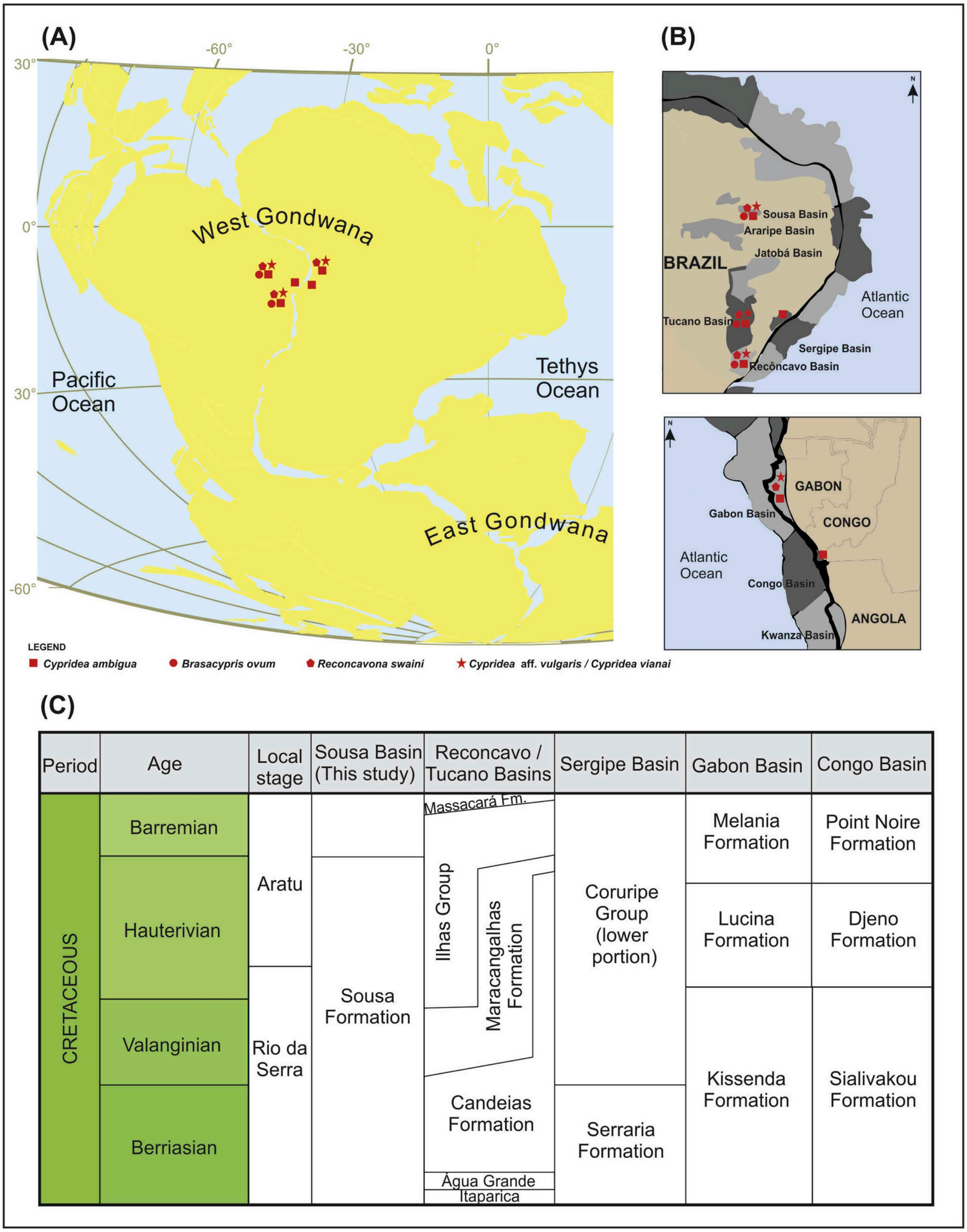

Fig. 8. (A) Paleogeographic map for the Berriasian-Hauterivian (mod. http://www.odsn.de/cgi-bin) showing the distribution of the non-marine ostracods recorded in the present study and in other Gondwana basins. (B) Ostracods occurrence in Brazilian and African sedimentary basins. (C) Chronocorrelation among lithostratigraphic units based on non-marine ostracods (Krömmelbein, 1966; Viana, 1966b; Grosdidier and Bignoumba, 1984; Grosdidier et al., 1996; Bate, 1999; Poropat and Colin, 2012).

the Gabon Basin, allowing for correlation with the Sousa Formation (Tucano and Recôncavo basins), and the Kissenda and Melania formations (Gabon Basin), all three of the Berriasian–Hauterivian age (Viana, 1966b; Grosdidier et al., 1996; Bate, 1999). *Reconcavona swaini* and *C. vianai* from the lacustrine strata of the upper part of the core suggest a stratigraphical relation to the deltaic deposits of the Ilhas Group (Recôncavo Basin) and the Melania and Kissenda formations (Gabon Basin) (Fig. 8B and C).

6. Conclusions

The investigation based on non-marine ostracods in the pelitic rocks of the Sousa Formation (Sousa Basin), from rift-lakes formed during the beginning of the rift process through the Early Cretaceous in West Gondwana, indicated lacustrine environments. The non-marine ostracods revealed rich to poor assemblages, with varying states of preservation and biomarker occurrence. *Alicenula leguminella*, *Brasacypris ovum*, *Cyprideа ambigua* and *Reconcavona swaini* indicate the Berriasian and Hauterivian age (Rio da Serra/Aratu local stages), evidenced by biozones RT-002 to RT-005. This study also expands the geographic distribution of the mentioned species, especially of *B. ovum*, previously mentioned only in the Recôncavo and Tucano basins. The integration of the biostratigraphic data from core 2-FC-01-PB constrains the age of the Sousa Formation to Berriasian–Hauterivian, refuting previously given Late Jurassic ages for it oldest deposits. Based on ostracod biostratigraphy, the deposits of the Sousa Formation are correlated with non-marine strata of the Brazilian and African sedimentary basins of West Gondwana. These data also show that the respective ostracod's paleogeographic distribution is limited to low latitudes.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsames.2019.102345.

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