632 CLEAN VERSION

633 There *are* rudists in Brazil! Derived examples of
634 cf. *Amphitriscoelus* Harris and Hodson, 1922, in
635 the Araripe Basin, north-east Brazil: implications
636 for dating of the fossil Lagerstätten of the Santana
637 and Crato formations

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ABSTRACT

Internal moulds of rudist bivalves from the basal Exu Formation of the western Araripe Basin, northeastern Brazil, are identified as the Early Cretaceous (Barremian to Aptian) radiolitidin caprinuloideid genus cf. *Amphitriscoelus* Harris and Hodson. The rudists occur as part of a sparse assemblage of remané fossils in the Exu Formation, a fluvial sandstone resting disconformably on the Santana Formation of the Araripe Group and are likely to have been derived from the shallow marine upper parts of that formation. The presence of caprinuloideid rudists in the Exu Formation suggests that the underlying Santana Formation can be no younger than lower Aptian. These are the first rudist bivalves found in Brazil and are the furthest south occurrence of caprinuloideid rudists, confirming suspected faunal links for the Araripe Basin with the Caribbean province of the Tethyan realm.

Keywords: Bivalvia; Early Cretaceous; Aptian; Stratigraphy; remané fossils; Exu Formation

1. Introduction

The Santana Formation (Romualdo Formation of some authors. e.g. Arai and Assine, 2020; Sayão et al., 2020) of the Araripe Basin in north-east Brazil is extremely well known for a stratigraphic unit, the Romualdo Member, rich in early diagenetic concretions containing exceptionally well preserved vertebrate fossils (Martill, 1988; Maisey, 1991). The contained fossils are commonly fully articulated, often preserved in three-dimensions and frequently preserve soft tissues (Martill, 1988; Brito et al., 2010; Maldanis et al., 2016) and gut contents (Wilby and Martill, 1992). The fossil assemblages of the concretions of the Romualdo Member are dominated by osteichthyans (coelacanths and actinopterygians),

tetrapods (pterosaurs, crocodilians and rare theropod dinosaurs) and rare elasmobranchs (sharks and rays), and displays similarities with assemblages in the Kem Kem Group of North Africa (Maisey, 1993, 2000; Ibrahim et al., 2020). Invertebrate remains, excepting ostracods, are scarce in the concretions, but higher in the succession argillaceous strata within the Santana Formation lack concretions, instead containing (0 to ~600 mm thick) limestones rich in the gastropod *Paraglauconia* sp., small bivalves and, much rarer, the irregular echinoid *Bothryopneustes* (Beurlen, 1966; Martill, 1993; Manso and Hessel, 2007). These limestones are often lenticular but do occur intermittently throughout the Araripe Basin.

The precise age of these deposits has remained problematic for many years and the subject of considerable debate (Martill, 2007; Arai, 2014; Assine et al., 2016; Arai and Assine 2020; Melo et al., 2020). The entire Araripe Basin is intracontinental, separated from Brazil's Mesozoic coastal basins by several hundred kilometres of Precambrian basement. Significantly, the Araripe Basin lacks fully marine strata except for the higher parts of the Santana Formation, where even these short-lived events lack the shallow-water shelly faunas more typical of Brazil's coastal basins. Notably, there are no ammonites, or other exclusively stenohaline groups such as brachiopods, bryozoans and corals. There are, however, a few indications of brief marine incursions, where echinoids, marine molluscs, foraminifera and dinoflagellates (Beurlen, 1966; Mabesoone and Tinoco, 1973; Brito, 1997; dos Santos Bruno et al., 2006; Bengston et al., 2007) have been recorded at some levels, especially in the top ~ten metres of the Santana Formation.

The problem of correlating these strata was discussed in considerable detail by Martill (2007) who evaluated the various attempts to date them, concluding that the Santana Formation could be as young as Cenomanian and as old as Aptian. In particular, Martill (2007) noted that extreme caution should be applied to dates based on the use of the vertebrate fossils. There is a general consensus that the Santana Formation is somewhere in

the ‘mid’ Cretaceous and is commonly considered as being Aptian to Albian age (Lima, 1978, 1979a, b, 1980; Wellnhofer, 1991; Manso and Hessel, 2007). This implies an uncertainty of ~26 million years. Recently, Arai and Assine (2018) found the palynomorph *Sergipea variverrucata* Regali, Uesugui and Santos in the Romualdo Member of the Santana Formation, which is the only fossil marker that does not exceed the Aptian-Albian boundary, thus constraining the Aptian age of this unit. Further analyses by these authors on palynomorphs came to a similar conclusion (Arai and Assine, 2020).

Herein, we describe remains of rudist bivalves from a remané horizon at the contact between the Santana Formation and the overlying Exu Formation that provides a minimum age for the source horizon. These molluscs indicate the Santana Formation is likely older than lower Aptian and perhaps as old as Barremian, that is, considerably older than previously considered. The remains also represent the first rudist bivalves from Brazil and the southernmost occurrence of the Hippuritoidea.

2. Locality and geological occurrence

The material described herein comes from exposures of the Santana and Exu formations at the western extremity of the Chapada do Araripe, near the small town of Simões, in the state of Piauí (Fig. 1). The locality has been described by Martill (2008) and is close to Locality 23 of Martill and Wilby (1993, p. 129). It can be accessed by climbing down the steep bank on the west side of the PI-142 road from Marcolândia to Simões where it descends the Chapada (coordinates: 7°36′00.50″.S - 40°44′28.27″ W: altitude 636 m. Source, Google Earth; Fig. 1 herein). The Chapada do Araripe tableland dominates the Araripe Basin, and comprises a thick, mainly siliciclastic succession of fluvial and lacustrine

strata with thin marine/quasi-marine beds, of which the Crato and Santana formations are palaeontologically the most important. The succession also includes evaporites (da Silva, 1988; Martill and Wilby, 1993) and laminated limestones (Martill et al., 2007). The basin is fault-bounded, being a graben or half-graben depending on locale. The sedimentary succession rests with topographic unconformity on a metamorphic basement of Neoproterozoic meta-sediments and small granitic plutons of the Borborema massif (Corsini et al., 1991; Matos, 1992; Ponte, 1996).

2.1. Note on stratigraphic nomenclature.

The stratigraphic terminology used in the present paper is that of Martill and Wilby (1993). Alternative stratigraphic schemes have been proposed, with differences between schemes mostly reflecting conflicting opinions regarding the status of stratigraphic units as members or formations. Thus, the Santana Formation of the present paper is synonymous with the Romualdo Member of Beurlen (1962) and Romualdo Formation of Neumann and Cabrera (1999). Martill and Wilby (1993) restricted the use of the term Romualdo Member to that part of the succession with the fossiliferous concretions. Neumann and Cabrera (1999) adopted a slightly different approach elevating Beurlen's Romualdo Member to Romualdo Formation. The original, but informal, Formação de Sant'Ana of Small (1913) has been elevated to Santana Group by Neumann and Cabrera (1999). In the stratigraphic schemes of all authors, the thick sequence of fluvial sandstones at the top of the Chapada do Araripe have been called the Exu Formation. In some stratigraphic schemes an intervening Arajara Formation is recognised (Ponte and Appi, 1990). The Arajara Formation is prevalent in the northeastern part of the basin where it is dominated by pink and variegated clays. These may represent a highly oxidised upper part of the Santana Formation or a basal lacustrine deposit

of the Exu Formation.

The Santana Formation *sensu* Martill and Wilby (1993) is underlain by a thick sequence of evaporites, the Ipubi Formation, that in turn are underlain by a succession of laminated limestones and intercalated siliciclastics known as the Crato Formation. This is a Lagerstätte well known for its fossil insects, pterosaurs and palaeoflora (Martill et al., 2007). The Romualdo, Ipubi and Crato (descending order) stratigraphic units are commonly grouped together as a genetic sequence, not considering that there is a significant unconformity between the Ipubi and Santana units in which some tectonic deformation occurred (da Silva, 1986). This sequence is underlain by fluvial sandstones and some argillaceous red beds of the Missao Velha and Brejo Santana formations. Their internal stratigraphy has not been studied as yet. The fossils described here come from the very top of the stratigraphic unit called alternatively the Santana Formation (Martill and Wilby, 1993), Romualdo Formation (Neumann and Cabrera, 1999) or Romualdo Member (Beurlen, 1962).

The Santana Formation is exposed all around the Chapada do Araripe and in a few outcrops beyond the main escarpment, where it forms an aquiclude to the Exu Formation sandstones (Fig. 2). In a few places, the palaeotopography of the basement has significant relief such that the Exu Formation sandstones overlap the Santana Formation to rest on structurally higher basement rocks. In such places no Santana Formation is seen, but in no place does the Exu Formation base cut down into the Santana Formation to the level of the concretion horizon. This is particularly important, as it means that the fossils described here (Figs 3-4) cannot have been derived from strata older than that part of the Santana Formation containing the thin marine limestones.

3. Systematic palaeontology

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777 *Remarks.* The higher classification of the rudist bivalves used herein follows Skelton (2013)
 778 and updates from Stueber et al. (2016).

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780 Class Bivalvia Linnaeus, 1758

781 Subclass Heterodonta Neumayr, 1884

782 Order Hippuritida Newell, 1965

783 Suborder Hippuritidina Newell, 1965

784 Superfamily Caprinoidea d'Orbigny, 1847

785 Family Caprinuloideidae Damestoy, 1971

786 Subfamily Rethinae Yanin, 1990

787 Genus *Amphitriscoelus* Harris and Hodson, 1922

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789 *Type species.* *Amphitriscoelus waringi* Harris and Hodson, 1922, pp. 130-133, pls. 1-4, from
 790 the Aptian(?) of Trinidad, West Indies (Fig. 5 herein). Also recorded from Mexico and Cuba.

791 *Other species.* *Amphitriscoelus plurioculata* Alencaster and Pantoja-Alor, 1996 (Aptian,

792 Mexico); *Amphitriscoelus primaevus* Pantoja-Alor, Skelton and Masse, 2004 (Barremian,

793 Jamaica) (Mitchel and Green, 2011); *Amphitriscoelus* sp. (Barremian-?lower Aptian,

794 Jamaica; Texas),

795 *Diagnosis.* (After Dechaseaux et al., 1969, p. T790.) "Both valves elongate, incurved but not

796 coiled, small; [attached valve] tooth narrow, elongate in section, anterior socket large,

797 posterior socket small but joined to large accessory cavity which is undivided, pallial canals

798 more or less rectangular or rounded-triangular limited to anterior, dorsal and posterior

799 regions; [free valve] with small anterior accessory cavity, vertical wall joins anterior tooth

800 with anteroventral border of posterior muscle insertion forming cavity separate from shell

cavity, pallial canals same shape and arrangement as in [attached valve].”

Range. Late Barremian to early Aptian (Mitchell, 2013, p. 49); Brazil, Cuba, Jamaica, Mexico, Texas (USA) and Trinidad (Alencaster and Pantoja-Alor, 1992).

Amphitriscoleus sp. cf. *A. waringi* Harris and Hodson, 1922, Figs. 4-5.

Material. Two specimens comprising a right and left valve preserved as internal moulds in ferruginous, cemented, fine-grained sandstone (Figs. 3-5). Both specimens have been cut to reveal details of the internal vascularization; a thin section has been cut from UERJ-FI 32. Registered in the collection of the University Federal de Rio de Janeiro, Rio de Janeiro, Brazil, serial numbers UERJ-FI 32 and UERJ-FI 33; both preserved as internal moulds.

Locality. West slope of Chapada do Araripe, Piauí, north-east Brazil, 7°36'00.50".S - 40°44'28.27" W.

Horizon. Remané deposit at the base of the Exu Formation, Cretaceous, but precise age unknown (see below). Derived most probably from highest beds of Santana Formation, Araripe Group.

Remarks. These specimens are identified as rudist bivalves on account of their septate cross section (Fig. 5A,C), elongate-cone shaped outline (Fig. 3A,B), and the presence of a perimetral, incomplete circle of ectomyophoral canals on the left valve (Fig. 5C,D). However, both specimens are so incomplete and poorly preserved that it is impossible to make a formal description. Rather, we provide Figures 4-5, illustrating the better points of the available specimens and recommend comparison with one or more of the several published descriptions of *A. waringi* (in the first instance, compare Figs 3 and 4).

Both specimens are preserved as moulds within fine-grained, ferruginous sandstone. No original shell remains and voids within the valves have been filled with fine-grained sandstone in some instances. The filled voids are surrounded by cavities where the aragonitic shell has subsequently been dissolved. One specimen appears to be a complete internal mould with a rounded termination of the body cavity. A second specimen is more incomplete and may represent a specimen fractured prior to burial in the remané deposit.

Description: Specimen UERJ-FI 32 is an incomplete near straight cylindro-conical left valve tapering rapidly to a blunt point at its origin. The cross section reveals part of the sediment-filled body cavity, posterior myophore, anterior tooth and a partial perimeter with at least twelve ectomyophoral canals (Fig. 4C, 5C,D).

Taphonomy: Both specimens are preserved as moulds within fine ferruginous sandstone. No original shell remains, and voids within the valves have been filled with fine sand in some instances. The filled voids are surrounded by cavities where the aragonitic shell has subsequently been dissolved. One specimen appears to be a complete internal mould with a rounded termination of the body cavity. A second specimen, UERJ FI 33, is incomplete and may represent a specimen fractured prior to burial in the remané deposit.

4. Discussion

4.1. Origin of the Exu Formation rudists

The rudist bivalve specimens described herein are clearly reworked fossils: they were found in a remané conglomerate at the base of the Exu Formation; and are a marine fauna found in a fluvial sequence. The enclosing matrix of coarse-grained, gritty sandstone is also at odds with the preferred sediment requirements of rudist bivalves. Rudist bivalves have not previously been reported from the stratigraphic units underlying the Exu Formation. Indeed, these are the first invertebrate animal fossils to be recorded from this formation at all. The

underlying Santana Formation contains a restricted assemblage of shelly fossils in its upper part, including the echinoid *Bothriopneustes araripensis* (Manso and Hessel, 2007), small bivalves and an abundance of the cassiopid gastropod *Paraglauconia* sp. (Lima, 1979a; Martill, 2007).

Rudist bivalves are well known as reworked bioclasts in younger deposits. For example, Chubb (1971, p. 195, pl. 40, fig. 13) described *Bournonia sanctmariae* Chubb, 1967, from a unique and well-preserved specimen in the Eocene Richmond Formation of Jamaica. As noted by Chubb, this Eocene sequence is well-known for its diversity of remané rudists (see also Pickerill et al., 1995, pp. 194, 197).

4.2. Rudists in South America

Rudist occurrences are sporadic on continental South America except in Venezuela where numerous sites have yielded *Amphitriscoelus waringi* Harris and Hodson, 1922, *Amphitriscoelus* sp., *Caprina* sp. *Coalcomana ramosa* Boehm, 1898, and *Pseudocaprina plumensis* Harris and Hodson, 1922, from the Barremian to lower Albian (Imlay, 1944; Gonzalez de Juana, 1968; Masse and Rossi, 1987). The southernmost occurrence appears to be *Jerjesia chilensis* (d'Orbigny, 1842), from the Cordillera of Coquimbo of Chile (Gerth, 1928; Masse et al., 2015b) at ~30° south and examples of the Mexican monopleurid *Douvilleia skeltoni* Alencaster and Pantoja-Alor, 1998 reported by Masse et al. (2015a). In Peru, *Agriopleura blumenbachi* Studer, 1834, (Likely *Jerjesia* sp. [See Masse et al., 2015b; Sha et al., 2020]) has been recorded from Barremian – lower Aptian strata at Paita, Pan de Azucar, Estancia el Muerto (Gerth, 1928), and *Paraarrettia peruviana* (Gerth, 1928) (see Skelton, 1993, p. 21), was described from the Campanian - Maastrichtian of Cerro la Silla de Paita (Gerth, 1928), while Philip and Jaillard (2004) also reported on Upper Cretaceous rudist from Peru. The occurrence of *Amphitriscoelus* described here is the first record of rudists in

Brazil (see Granier and Dias-Brito, 2015, for refutation of claims for Brazilian rudists) and provides evidence of a link between the Araripe Basin and the central Atlantic Caribbean province. The Araripe locality is some 3200 km from the Venezuelan localities and between 500 to 600 km from the present coastline of northeastern Brazil, where Atlantic marginal basins contain marine Cretaceous deposits (for example, the Ceará/Potiguar basins to the north and Sergipe/Alagoas basin to the east).

Although rudist bivalves were previously reported to occur in Brazil (Falkenheim et al., 1981; Granier et al., 1991), Granier and Dias Brito (2015) have demonstrated that none of those accounts are reliable. It is probable that all so-called rudist bivalves reported from Brazil hitherto are, in fact, misidentified ostreids, shells of the grypheid *Pycnodonte* and possibly even large serpulid worm tubes (Granier and Dias Brito, 2015). These authors were resolute that there are no rudist bivalves in Brazil and made a well-reasoned argument for their absence in the Brazilian marginal basins of the South Atlantic. In particular, they noted that the absence of rudist bivalves in the northern segment of the young South Atlantic Ocean (NYSAO of their paper), including Africa as well as South America, can be attributed to a lack of connections between this region and the Tethys. As a consequence, a lack of suitable marine currents prevented the wider dispersal of the planktonic larval stages of rudists into the South Atlantic. Such a scenario seems extremely plausible and may well prove to be a satisfactory explanation for rudist absence in that province. However, the specimens described in the present paper are from the Araripe Basin which is situated within the hinterland of the South American continent. The Araripe Basin may have had connections with the marginal basins of the Central Atlantic Ocean, notably the Ceará and Potiguar basins to the north, or perhaps the extensive Parnaíba Basin to the west and northwest. Certainly, fish faunas of the Araripe Basin share affinities with Cretaceous sedimentary basins of Parnaíba, and even further west in Venezuela and Colombia (Moody and Maisey, 1994;

Schultze and Stohr, 1996; Brito, 1997, Lindoso et al., 2016). It has been posited that the Araripe Basin and the Sergipe Alagoas complex of basins may have provided intermittent links between the Tethyan and South Atlantic provinces (Maisey, 1991). Martill and Wilby (1993) postulated a Cariri Island at times of high sea stand when a complete, albeit narrow, seaway may have linked the two oceanic provinces via the Sergipe-Alagoas basins to the south and the newly formed rifts between South America and West Africa to the east and north, but reliable palaeontological evidence in support of this hypothesis is lacking.

4.3. Spatial and temporal range of *Amphitriscoelus*

Harris and Hodson (1922) first described *Amphitriscoelus* from the Aptian of Trinidad (Fig. 6). Subsequently, it was discovered in the lower Aptian of Michoacán Huetamo, Mexico, where two species occur: *A. waringi* and *A. pluriloculata* Alencaster and Pantoja-Alor, 1996. Both species also occur near Michoacán in the San Lucas Valley, Mexico (Pantoja Alor, 1999). A Barremian Cuban occurrence of *A. waringi* was reported by Mac Gillavry (1937) and also by Chartrouse and Masse (1998). *Amphitriscoelus* sp. occurs in the Barremian-?lower Aptian of Jamaica (Skelton and Masse, 1998), and was detected in Amoco No.1 Smoot, well borehole, Houston County, Texas (Scott, 1990). The limited geographical distribution of *Amphitriscoelus* supports the concept of a distinct endemic Caribbean – rudist bioprovince (Skelton, 1982; Rojas et al., 1992). Yet the occurrence of *Amphitriscoelus* in Brazil extends the range of this province significantly toward the South Atlantic Basin (Fig. 7).

Despite a concerted collecting effort, *Amphitriscoelus* has not been reported from strata younger than lower Aptian or older than Barremian, appearing to have a well-defined stratigraphic range (Alencaster and Pantoja-Alor, 1995, 1996, 1998; Pantoja-Alor et al., 1994; Skelton and Masse, 1998; Steuber et al., 2016). *Amphitriscoelus* thus proves potentially

useful as a biostratigraphic marker when other diagnostic fossils are lacking, as in the Araripe Basin.

5. Conclusions

The presence of the rudist bivalve *Amphitriscoelus* in the Araripe Basin is of considerable significance for dating the strata underlying the sandstones of the Exu Formation. Although the specimens are clearly derived from a preceding stratigraphic unit, beneath the disconformity at the boundary base of the Exu Formation, the relationship of the Exu Formation to the underlying units shows that nowhere in the basin does this boundary extend downwards to the concretion horizon of the Santana Formation. Thus, the Santana Formation must be at least as old as lower Aptian, the youngest age of the genus *Amphitriscoelus*. A lower Aptian age for the Santana Formation thus ‘pushes back’ ages attributed to other parts of the Araripe Group. Indeed, *Amphitriscoelus* first appeared in the record in strata as old as Barremian and ranges into the lower Aptian (Steuber et al., 2016). If the examples described herein would be Barremian, then the Araripe Group strata are considerably older than hitherto believed. F

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FIGURE CAPTIONS

Fig. 1. A rudist locality in the Cretaceous of north-east Brazil. (A) Outline map of the study area, to the east of Simões. Key: Star = rudist locality; Light grey shading = Exu Formation forming the tableland of the Chapada do Araripe; dark grey shading = Santana Formation beneath the escarpment formed by the Exu Formation at the chapada margins; white shading = metamorphic basement. (B) Outline map of Brazil showing the location of the study area.

Fig. 2. Measured section of the study area, with a star showing the stratigraphic position of the rudist horizon. Possibly some of the stratigraphic gaps are a consequence of slumping.

Fig. 3. *Amphitriscoelus* sp. UERJ-FI 33 from the Exu Formation, near Simões, Ceará, north east Brazil. Internal mould of right valve in A, anterior view, B, posterior view, C, apical view, D, transverse section. Scale bar = 10 mm.

Fig. 4. *Amphitriscoelus* sp. UERJ-FI 32 from the Exu Formation, near Simões, Ceará, north east Brazil. Internal mould of left valve in A, anterior view; B, posterior view, but most detail obscured by matrix, and C, transverse section. Scale bar = 10 mm.

Fig. 5. Cross sections of *Amphitriscoelus waringi* Harris and Hodson, 1922 and Exu rudists compared. A, cf. *Amphitriscoelus*, right valve, specimen UERJ-FI 33; B, simplified line drawing of A; C, cf. *Amphitriscoelus*, left valve, specimen UERJ-FI 32; D, simplified line drawing of C; E, right valve of *A. waringi* specimen IGM-6367 from Huetamo region, Michoacán, Mexico; F, simplified drawing of E; G,H, *Amphitriscoelus waringi* paralectotype from Lower Aptian of Trinidad; specimen no. 1539 in the Paleontological Research

1221 Institution, Ithaca, NY, USA. E, from Alencaster and Pantoja-Alor, 1996 fig. 3(8); G,H, from
1222 Skelton, 2013 fig. 13g. Abbreviations: bc, body chamber; pm, posterior myophore.

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1225 **Fig. 6.** Biogeography of rudist bivalve families in the Aptian. Based mainly on Sha et al.

1226 (2020); base map based on Scotese (2001). The new Brazilian occurrence is indicated by the

1227 black star. Note that the Brazilian specimens are the southern most occurrence rudist bivalves

1228 in the Caribbean province.

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1230 **Fig. 7.** Sedimentary basins of north east Brazil with strata crudely divided into fluvial Aptian,

1231 marine or transitional marine Aptian and younger than Aptian. The heavily dashed line

1232 represents the likely southernmost extension of the Caribbean rudist faunal province. Map

1233 based on Assini et al., (2016, Fig. 1).

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Figure 1

[Click here to access/download;Figure;Fig 1 Rudist locality map revised.jpg](#)

Figure 6

Figure 7 new figure

[Click here to access/download;Figure;Fig 7 Basins in Brazil.jpg](#)

There *are* rudists in Brazil! Derived examples of *Amphitriscoelus* Harris and Hodson, 1922 in the Araripe Basin, north-east Brazil: implications for dating of the fossil Lagerstätten of the Santana and Crato formations

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Conflict statement

There are no conflicting or competing interests.

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