

Aptian/Albian (Early Cretaceous) paleogeography of the South Atlantic: a paleontological perspective

*Paleogeografia do Atlântico Sul no Aptiano/Albiano (Eocretáceo):
perspectiva paleontológica*

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ABSTRACT: Paleontological data obtained in recent years reinforce the hypothesis that Aptian marine sedimentation in the sedimentary basins of the Brazilian continental margin – except the Pelotas basin, the southernmost Brazilian basin – took place under the domain of waters coming from the north through the Tethys Sea (Central Atlantic). Tethyan waters could reach the basins of the Brazilian continental margin via the seaway then existing in the present-day region of northeastern Brazil. Here there are records in several basins, notably in the São Luís (Codó Formation), Parnaíba (Codó Formation), Araripe (Santana Formation), Tucano (Marizal Formation), Sergipe (Riachuelo Formation) and Camamu (Algodões Formation) basins. Despite irrefutable marine evidence — e.g., dinoflagellates, echinoids, foraminifera, molluscs and fishes, conspicuously present in the Araripe Basin — there are very few paleogeographic reconstructions that include the seaway which is totally ignored in the international literature. The skepticism is even greater in relation to the Tethyan affinity although the evidence has been well documented by molluscs and dinoflagellates, together with ammonoids in the Sergipe Basin. That skepticism may be due to the fact that, in tectonic and geodynamic terms, the opening of the South Atlantic indeed proceeded from south to north, at least in the part that extends from Argentina to the northeastern Brazilian state of Paraíba.

KEYWORDS: Aptian; Albian; Brazil; Tethys.

RESUMO: Dados paleontológicos levantados nos últimos anos vêm reforçando cada vez mais a hipótese de que a sedimentação marinha aptiana nas bacias sedimentares da margem continental brasileira – com exceção da Bacia de Pelotas, a mais meridional delas – tenha ocorrido sob o domínio de águas oriundas do norte, via Mar de Têtis (Atlântico Central). As águas tethianas teriam chegado às bacias da margem continental através do “seaway” que atravessava a atual região Nordeste do Brasil, deixando seu registro nas bacias de São Luís (Formação Codó), Parnaíba (Formação Codó), Araripe (Formação Santana), Tucano (Formação Marizal), Sergipe (Formação Riachuelo) e Camamu (Formação Algodões). Apesar da prova irrefutável fornecida por diversos grupos de organismos marinhos fósseis (e.g., dinoflagelados, equinóides, foraminíferos, moluscos e peixes) conspicuamente presentes na Bacia do Araripe, são poucas as reconstituições paleogeográficas que representam explicitamente esse “seaway” que, até hoje, se encontra totalmente ignorado em publicações internacionais. O ceticismo é ainda maior com relação à afinidade tethiana, apesar de sua prova paleobiogeográfica estar bem evidenciada por moluscos e dinoflagelados e adicionalmente reforçada por amonóides da Bacia de Sergipe. Esse ceticismo é justificado, em parte, pelo fato de que, em termos tectônicos e geodinâmicos, a abertura do Atlântico Sul ocorreu do sul para o norte, pelo menos no trecho que vai da Argentina até o atual estado da Paraíba (Nordeste do Brasil).

PALAVRAS-CHAVE: Aptiano; Albiano; Brasil; Têtis.

INTRODUCTION

Contrary to the paleogeographic reconstruction based on the configuration of tectonic plates, the initial Mesozoic entrance of sea water into the BCMBs (Brazilian Continental Margin Basins, Fig. 1) resulted from the incursion of oceanic waters from the northern hemisphere, i.e., from the Tethys Sea. The traditional model, advocating the progressive advance of the primitive South Atlantic from south to north, is disbelieved, having been induced by the fact that the tectonic opening of the South Atlantic had occurred from south to north. However, the majority of BCMBs contain marine biotas of

Aptian/Albian age — the timing of the earlier marine incursion — which indicate their Tethyan origin. The evidence for this, accrued over recent decades, effectively renders irrefutable the early Tethyan influence model.

For the Albian (113 – 100 Ma), a similar model, proposed by Dias-Brito (1992, 2000), was based on the geographic distribution of pithonellids (pelagic calcispheres); he considered the Tethyan Realm as having a greater extension, reaching all the BCMBs, excepting the southernmost one (the Pelotas Basin) (Fig. 1).

Arai (2005, 2007, 2011), based on studies of organic-walled dinoflagellate cysts, recognized the presence of



Figure 1. Brazilian sedimentary basins (modified from Milani *et al.*, 2007). The Brazilian Continental Margin Basins (BCMBs) are indicated by italics, and the basins discussed in this paper are indicated by bold characters.

the Tethyan Realm in the BCMBs even in the Aptian (125 – 113 Ma) and confirmed that Tethyan waters emanating from the north reached as far as the Santos Basin, which represents the southernmost Tethyan-influenced site in the South Atlantic.

The present paper aimed to substantiate that model by means of an inventory of fossil biotic elements that confirm Tethyan characters in the Aptian – Albian interval (125 – 100 Ma).

Geological context

The dinoflagellates, which comprise the main basis of the present work, appeared worldwide in the Middle Triassic (ca. 247 – 237 Ma). However, Western Gondwana, of which present-day Brazil occupies a part, was undergoing an erosional phase during Triassic-Jurassic time (252 – 145 Ma). The sediments deposited in these periods were accordingly of continental (non-marine) derivation, some even subaerial (non-aqueous, mostly eolian). Thus, the pre-rift stage is represented mainly by oxidized, reddish sediments (Souza-Lima & Hamsi Jr. 2003).

Through the Early Cretaceous, most of the BCMBs experienced a rift phase. Along the extensional continental margin and in the Recôncavo, Tucano, Jatobá, Araripe and Potiguar basins, rift lakes were formed during the Neocomian. In the equatorial-marginal basins west of the Potiguar Basin, rift sedimentation occurred mostly during the Aptian-Albian. In the Aptian, independently of their tectonic constitution, all of these basins received synchronous sedimentation due to an eustatic rise, which was responsible for the earliest conspicuous occurrence of Mesozoic marine organisms in Brazilian sedimentary basins.

At the maximum of the Aptian transgression, the Brazilian interior sea connected temporarily the North Atlantic and the South Atlantic that were hitherto discrete (Arai 1999, 2000) and resulted in the deposition of an extensive megasequence (Megasequence Zuni). In several Brazilian interior basins (e.g., Parecis, Parnaíba and São Francisco basins), Zuni represents their only Cretaceous succession (Arai 2002). These basins were affected by uplifting after the Cretaceous deposition and became “chapadas” (mesa-type elevated terrains). Contrastingly, the BCMBs were not uplifted, due to continued subsidence; all BCMBs received open marine sediments from the Albian and that process continued thereafter (to the present day).

In the Aptian, except for the Pelotas Basin, the waters of the southern South Atlantic had still not effectively entered the BCMBs. However, due to the great Aptian transgression, which caused intermittent entrance of water from the Central Atlantic, a generalized deposition took place

under marine influence in the BCMB and interior basins. The intermittent introduction of sea water was responsible for the deposition of the evaporites of the Alagoas local stage (equivalent, *grosso modo*, to Aptian) in most of the basins. The Aptian transgression was sufficiently extensive to produce evaporites even in basins situated in the interior of the continent (e.g., Codó Formation, Parnaíba Basin; and Ipubi Member of the Santana Formation, Araripe Basin), including those toward Africa (Avocat *et al.* 1992). In the Pelotas Basin, evaporites are practically absent, because it was open-marine in the Aptian, when the drift phase had already commenced (Dias *et al.* 1995, Souza-Lima & Hamsi Jr. 2003).

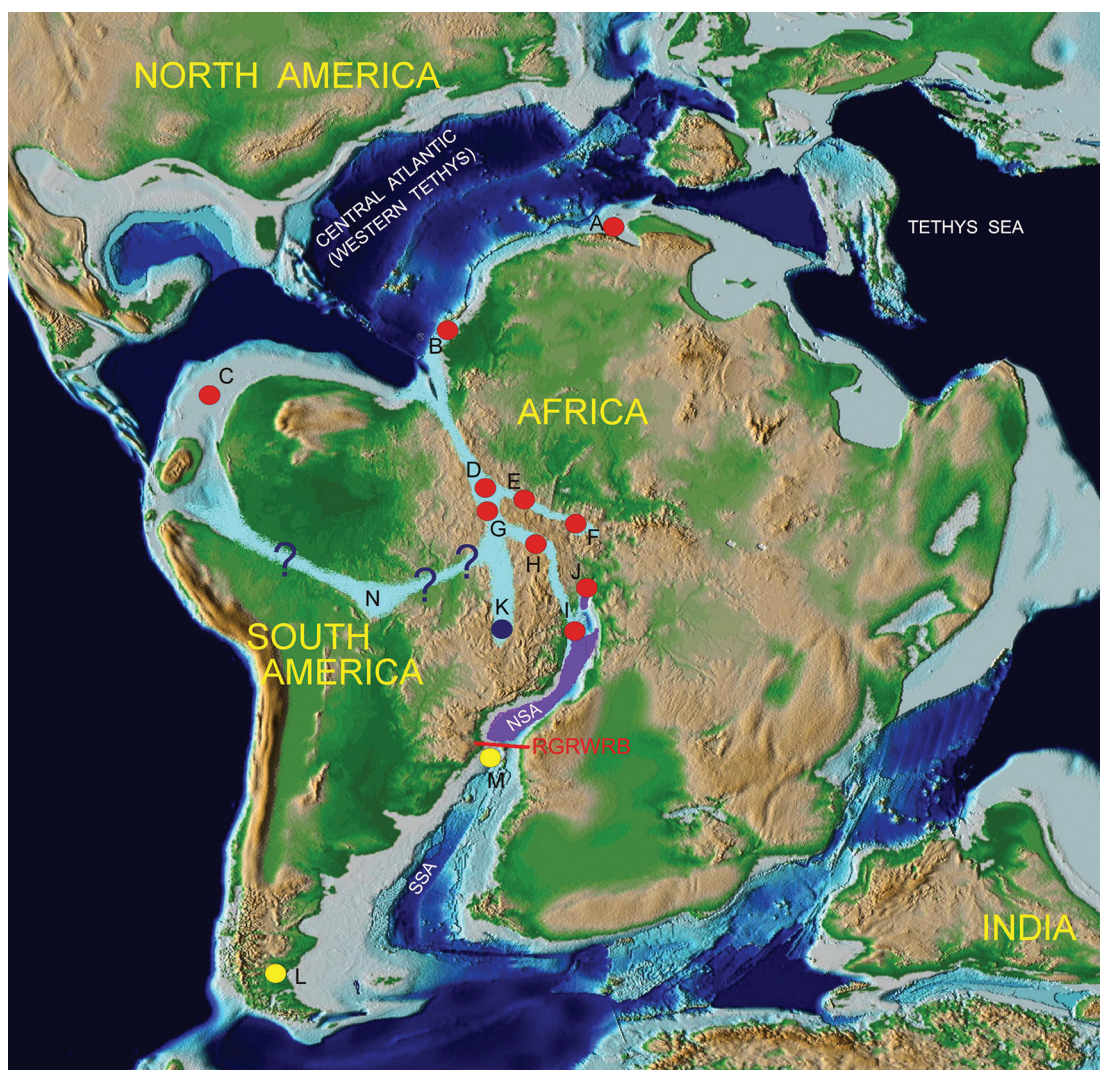
Seaway of Northeastern Brazil

Tethyan water arrived in the BCMBs via the seaway existing in the present-day region of northeastern Brazil, passing through the São Luís, Parnaíba, Araripe, Tucano and Sergipe basins. The most convincing evidence is the presence of marine fossils in the Santana Formation [Araripe Basin; e.g., fishes (Martill 1988, Maisey 1991, 2000, 2011, Silva Santos 1991, Saraiva 2008), dinoflagellates (Arai & Coimbra 1990), molluscs (Beurlen 1964), palynoforaminifera (Arai & Coimbra 1990), echinoids (Beurlen 1966, Manso & Hessel 2007, 2012) and marine turtles (Price 1973, Hirayama 1998)] and in the Codó Formation [Parnaíba and São Luís basins; e.g., fishes (Silva-Santos 1985, Lindoso *et al.* 2013b), dinoflagellates (Antonioli 2001, Antonioli & Arai 2002) and isopod crustaceans (Lindoso *et al.* 2013a)]. However, the route of the marine ingression has been conjectural. Three options and their possible combinations have been hypothesized: (1) via the Parnaíba Basin (Beurlen 1963, 1966, Beurlen 1971 apud Lima 1978, Braun 1966 apud Lima 1978, Arai *et al.* 1994); (2) via the Sergipe Basin (Beurlen 1971 apud Lima 1978, Tinoco & Mabesoone 1973 apud Lima 1978, Brito 1976 apud Lima 1978, Silva Santos 1991); and (3) via the Potiguar Basin (Lima 1978, Viana 1998). For some authors (e.g., Silva Santos 1991, Arai 1999), the Araripe Basin would occupy the middle of the route of an extensive seaway having a NW-SE orientation (Fig. 2). Others have considered that the Araripe Basin represents a junction of three seaways that effectively connected the Sergipe, Parnaíba and Potiguar basins (e.g., Mabesoone *et al.* 1999, Valença *et al.* 2003). However, the complete absence of marine sediments coeval to the Santana Formation in the interior basins situated between the Araripe and Potiguar basins (e.g., Icó, Iguatu, Lima Campos, Malhada Vermelha, Lavras da Mangabeira and Rio do Peixe basins) nullifies this possibility (Arai 2006) (Fig. 3).

MATERIALS AND METHODOLOGY

The basic paleobiogeographic model for this paper is based on a comprehensive survey of fossil dinoflagellate assemblages (i.e., protistan algae belonging to the Division Dinoflagellata, Class Dinophyceae) from

Cretaceous strata of Brazil. These reveal a consistent paleobiogeographic pattern for the primitive South Atlantic (Arai 2007, 2011). Moreover, the model has been strengthened by the inventory of other marine organisms which confirm Tethyan influence during Aptian/Albian time (see Appendix).



Occurrences of the *Subtilisphaera* Ecozone: (A) Morocco (Below 1981); (B) Senegal (Jain & Millepieid 1975); (C) Maracaibo Basin, Venezuela (Colmenares 1994); (D) São Luís Basin, Brazil (Arai et al. 1994); (E) Ceará Basin, Brazil (*locus typicus*, Regali 1989); (F) Potiguar Basin, Brazil (Arai et al. 1994); (G) Parnaíba Basin, Brazil (Antonlioli 2001, Antonlioli & Arai 2002); (H) Araripe Basin, Brazil (Arai et al., 1994); (I) Almada Basin, Brazil (Pedrão & Lana 2000); (J) Sergipe Basin, Brazil (Carvalho 2001). Occurrences of *Occiscyusta victorii*: (M) Pelotas Basin, Brazil (Arai 2005, 2007, 2011; Arai et al. 2006); (L) Río Fosiles, Provincia de Santa Cruz, Argentina (*locus typicus*, Pöthe de Baldis & Ramos 1983).

Figure 2. Aptian paleogeographic map as proposed by Arai (2005, 2007, 2011) and modified from Scotese's (2001) map for 120 Ma. Northeasternmost Brazil and West Africa were still joined, but waters coming from the Central Atlantic could reach the northern South Atlantic (NSA) via the seaway connecting the São Luís, Parnaíba, Araripe, Sergipe and Almada basins. The areas in violet color represent major evaporitic basins; the red line represents the barrier related to the structural high comprising the Rio Grande Rise and the Walvis Ridge (RGRWRB); the red circles (A - J) are occurrences of the *Subtilisphaera* Ecozone that suggest Tethyan influence; the yellow circles (L - M) are occurrences of typically Austral marine palynofloras; and the blue circle (K) is the radiolarian occurrence of Areado Formation. Note that Aptian marine strata are as yet unconfirmed in the Parecis Basin (N).

CHRONOSTRATIGRAFY		BASINS		NORTH OF PATOS LINEAMENT				SOUTH OF PERNAMBUCO LINEAMENT							
		STANDARD	LOCAL	POTIGUAR (ONSHORE)	IGUATU	RIO DO PEIXE	LAVRAS DA MANGABEIRA	BARRO	ARARIPE	CEDRO	MIRANDIBA	JATOBA	RECÔNCAVO/TUCANO	SERGIPE (DIVINA PASTORA LOW)	
LOWER CRETACEOUS	ALBIAN		AÇU											RIA	
	APTIAN	ALAGOAS	ALA					ARP	ARP		MAZ	MAZ	MAZ	MUR	
	BARREMIAN	JIQUEIÁ													
		BURACICA													
	HAUTERIVIAN	ARATU			?		?								
	VALANGINIAN														
BERRIASIAN	RIO DA SERRA		PEN	IGU	RDP	LDM		ABA				IS	IS	BIT	
JURASSIC	DOM JOÃO					?	MVL	MVL				SRG	SRG	SER	
							BST	BST			ALI	ALI	ALI	BAN	
PALEOZOIC?	PRE-D.JOÃO						MAU	MAU	MAU						
PERMO-CARBONIFEROUS												CUSB	AFL	IGN	
SILURO-DEVONIAN											TAC	TAC			

ABA = Abaiara Fm.; AÇU = Açú Fm.; AFL = Afligidos Fm.; ALA = Alagamar Fm.; ALI = Aliança Fm.; ARP = Araripe Gr. (Rio da Batateira, Santana, Arajara and Exu formations); BAN = Bananeiras Fm.; BIT = Barra de Itiúba Fm.; BST = Brejo Santo Fm.; CUSB = Curituba and Santa Brígida formations; IGN = Igreja Nova Gr.; IGU = Iguatu Gr.; IS = Ilhas Gr.; LDM = Lavras da Mangabeira Gr.; MAS = Massacará Gr.; MAU = Mauriti Fm.; MAZ = Marizal Fm.; MVL = Missão Velha Fm.; PEN = Pendência Fm.; RDP = Rio do Peixe Gr. (Antenor Navarro, Sousa and Rio Piranhas formations); RIA = Riachuelo Fm.; MUR = Muribeca Fm.; SAM = Santo Amaro Gr.; SER = Serraria Fm.; SRG = Sergi Fm.; TAC = Tacaratu Fm. The columns are roughly arranged from north (left) to south (right).

Figure 3. Correlation chart of lithostratigraphic units of the principal interior Mesozoic basins and major adjacent basins of northeastern Brazil (after Arai 2006).

RESULTS

Marine fossils in the interior basins

The following marine organisms have proven efficacious in the study of the Brazilian interior basins: dinoflagellates, foraminifera, radiolarians, molluscs, echinoids, crustaceans, fishes and reptiles (turtles).

Dinoflagellates

There is no doubt that the *Subtilisphaera* Ecozone, which represents a phytoplanktonic bloom, provides the most persuasive testimony of Tethyan affinity.

This ecozone, originally defined by Regali (1989), is characterized by an assemblage having high frequency and low diversity, and is constituted overwhelmingly by species belonging to the genus *Subtilisphaera*. Its occurrences can be diachronic on a worldwide scale, but in Brazil it is confined to strata of Aptian age. Its distribution is evidently restricted between the 20° paleolatitudes in both hemispheres (N and S). Its northernmost occurrence is in Morocco (Below 1981) and the southernmost one is in the Almada Basin, Brazil (Lana & Pedrão 2000a, b; Pedrão &

Lana 2000). In addition to these localities, typical occurrences of the Ecozone *Subtilisphaera* have been recorded in the following: Senegal (Jain & Millepied 1975); Maracaibo Basin, Venezuela (Colmenares 1994); São Luís Basin (Arai *et al.* 1994); Ceará Basin (*locus typicus*, Regali 1989); Potiguar Basin (Arai *et al.* 1994); Parnaíba Basin (Antonioli 2001, Antonioli & Arai 2002); and Araripe Basin (Arai *et al.* 1994).

This geographic distribution signifies the ecozone's Tethyan character. The ecozone is less conspicuous in the Potiguar Basin, thereby suggesting that the main route of the marine ingression was through the São Luís, Parnaíba and Araripe basins, where the ecozone is more prominent.

Paleoecologically, the *Subtilisphaera* Ecozone constitutes a fossil record of phytoplanktonic blooms, which were clearly favoured by an epicontinental marine environment (Arai *et al.* 1994).

In contrast to the virtually monospecific *Subtilisphaera* Ecozone, palynological analyses performed by Arai *et al.* (2006) in the lower Aptian of the Pelotas Basin have revealed a rich and highly diversified assemblage comprising spores, pollen grains, dinoflagellate cysts, acritarchs and palynoforaminifera. The following dinoflagellate-cyst (dinocyst) taxa were identified (Arai 2011): *Achomosphaera* spp., *Circulodinium*

distinctum, *Circulodinium* spp., *Cribroperidinium* cf. *parorhthoceras*, *Cribroperidinium* spp., *Exochosphaeridium* spp., *Florentinia mantellii*, *Impletosphaeridium* spp., *Occisucysta victorii*, *Odontochitina* spp., *Oligosphaeridium* complex, *O. tenuiprocessum*, *O. totum*, *Oligosphaeridium* spp., *Palaeoperidinium cretaceum*, *Pervosphaeridium cenomaniense*, *Pervosphaeridium* cf. *pseudohystrichodinium*, *Pervosphaeridium* spp., *Pseudoceratium anaphrissum*, *P. eisenackii*, *Spiniferites bejui*, *Spiniferites* spp., *Tenua americana*, *Trichodinium* spp. and *Wrevittia cassidata*. Components of other groups represented – appreciably less overall in both quantitative and qualitative terms – include the following significant occurrences: the pollen grains *Araucariacites* spp., *Callialasporites trilobatus*, *Classopollis* spp., *Equisetosporites* spp. and *Inaperturopollenites* spp.; spores, *Cicatricosisporites* spp., psilate and ornamented trilete spores; and acritarchs, *Cyclopsiella* spp. and *Micrhystridium* spp. Among the dinocysts identified, *Occisucysta victorii* and *Tenua americana* are particularly important, because their previously reported occurrence is their type locality (lower Aptian, Rio Fósiles, Província de Santa Cruz, Argentina), as designated by Pöthe de Baldis & Ramos (1983).

Foraminifera

Previous identifications of foraminiferal tests in interior basins of northeastern Brazil are scarce and are restricted to the Araripe Basin (e.g., Branner 1915, Carvalho & Carvalho 1974, Berthou *et al.* 1990, Bruno & Hessel 2006). On the other hand, palynoforaminifera (chitinous linings present in palynological preparations) are more common (Lima 1978, 1979, Arai & Coimbra 1990, Rios-Netto 2011 and Arai 2012). The latter paper is especially noteworthy in recording palynoforaminifera in infra-Ipubi strata (Crato Member, Santana Formation) of the Araripe Basin, thus indicating that a marine ingressão occurred there prior to the Aptian evaporitic deposition.

Radiolarians

The only records of radiolarians in Brazilian interior basins come from the Areado Formation (Aptian, São Francisco Basin). The first discovery was by Kattah (1991), followed by Dias-Brito *et al.* (1999).

Molluscs

The gastropod species, *Craginia araripensis* and *Gymmentone romualdoi*, instituted by Beurlen (1964) from the Santana Formation, are considered to be unquestionably marine.

Echinoids

Echinoids – typically marine organisms – are represented by four species in the Araripe Basin (Manso & Hessel 2007,

2012): *Bothryopneustes araripensis*, *Douvillaster benguelensis*, *Hemiaster proclivus* and *Pygurus tinocoi*.

Crustaceans

Codoisopus brejensis belongs to the crustacean Family Archaeoniscidae (Order Isopoda) and has been recorded from the Codó Formation. Although the species was endemic, it is considered to indicate Tethyan influence, because the Family Archaeoniscidae is exclusively Tethyan (Lindoso *et al.* 2013a).

From the Santana Formation, Maisey & Carvalho (1995) and Pinheiro *et al.* (2014) have reported respectively *Paleomattea deliciosa* and *Araripenaeus timidus* (both marine crustaceans belonging to the Superfamily Penaeoidea/Order Decapoda).

The Santana Formation also contains copepods (Subclass Copepoda). Well-preserved copepods, belonging to the Superfamily Dichelesthioidea, have been found in gills of the fish *Cladocyclus gardneri* (Cressey & Patterson 1973). On the other hand, it is possible that neither the copepod nor its host (*Cladocyclus gardneri*) is definitively marine in the Santana Formation (John G. Maisey, personal communication).

Fishes

Among classic fish species of the Santana Formation, *Araripichthys castilhoi* (Family Araripichthyidae) is surely Tethyan (Maisey & Moody 2001, Alvarado-Ortega & Brito 2011). *Cratoamia gondwanica* is a marine fish, of the Tribe Vidalamiini (Subfamily Vidalamiinae, Family Amiidae), described from the Crato Member (Santana Formation). Although instituted as a new species, it is considered indicative of Tethyan influence, because the Tribe Vidalamiini is unknown beyond the Tethyan Realm (Brito *et al.* 2008).

Nanaichthys longipinnus — a marine fish attributed to the Subfamily Rubiesichthyinae (Family Amiidae) — has been reported from the Marizal Formation (Tucano Basin). It was described as a new species, but is considered to connote Tethyan influence in view of the fact that the Subfamily Rubiesichthyinae is evidently exclusive to the Tethyan Realm (Amaral & Brito 2012).

Reptiles (Turtles)

Among fossil reptiles of the Santana Formation, there are two species of marine turtles: *Araripemys barretoii* and *Santanachelys gaffneyi*. The former was reported by Price (1973) from the Santana do Cariri region and considered to be representative of a group hitherto unrecorded outside the northern hemisphere. *Araripemys barretoii* was registered also from the Parnaíba Basin, in the Albian interval of the

Itapecuru Formation (Kischlat & Carvalho 2000, Batista & Carvalho 2007). These authors have considered *Araripemys barretoii* as freshwater turtle, but Oliveira (2007) admitted that it could inhabit also marine environments.

Tethyan fossils in the Sergipe Basin

Whereas in the interior basins marine deposition was interrupted in the Albian-Cenomanian, the continental-marginal basins continued to receive marine sediments. The situation of the Sergipe Basin is particularly notable for two reasons: (1) even after the disappearance of the seaway of northeastern Brazil, it continued to receive marine sedimentation due to the opening of Pernambuco-Paraíba gateway; (2) because of the regression and uplift, which began in Late Cretaceous, the basin has several exposures whence megafossils can be collected.

Pelagic Calcispheres

Most fossils called “calcispheres” are pithonellids (calcareous dinoflagellates), which are distinctly Tethyan (Dias-Brito 2002).

Foraminifera

According to Koutsoukos (1992), most foraminiferal assemblages, either planktonic or benthonic, suggest Tethyan affinity. Among planktonic species from Aptian/Albian strata, the following are especially important as Tethyan indicators: *Globigerinelloides aptiensis*, *G. barri*, *G. blowi*, *G. ferreolensis*, *G. maridalensis*, *Hedbergella labocaensis*, *H. maslakovae*, *H. semielongata* and *H. similis* (Bengtson & Koutsoukos 1992, Bengtson *et al.* 2007, Koutsoukos & Bengtson, 2007a, b).

Radiolarians

Radiolarians were recorded by Koutsoukos & Hart (1990) from the Albian (Riachuelo Formation) and the Cenomanian-Turonian (Cotinguiba Formation). Although the authors did not comment *vis-à-vis* the Tethyan character of these microfossils, they alluded to taxonomic and morphotypic affinities with coeval assemblages reported from the Caribbean region (Puerto Rico) and the North American western interior (Colorado, Kansas, Wyoming, Alberta).

Molluscs

Bivalves are the most traditional focus of paleontological studies of Aptian/Albian strata in the Sergipe Basin. One of the classic species is *Myophorella coqueiroensis*, which is marine (Hessel 2005). Andrade & Seeling (2000) and Seeling & Andrade (2000) emphasized the richness of marine bivalve faunas in the Sergipe Basin. Among bivalves of the Riachuelo Formation (Aptian-Albian), the genus

Neithea is very important in containing such Tethyan species as: *Neithea alpina*, *N. coquandi* and *N. hispanica*. The species *Neithea alpina* and *N. coquandi* are also present in the Algodões Formation (Albian-Cenomanian, Camamu Basin) (Andrade *et al.* 2004).

Gastropods are also very abundant in the Sergipe Basin; according to Cassab (2000), most of them have Tethyan affinity.

Ammonoids are the most important fossil group in the Sergipe Basin (Bengtson & Souza-Lima 2000). Among species from the Aptian-Albian interval, the following are considered typically Tethyan: *Epicheloniceras cf. martinoides*, *Vectisites simplex* and *V. cf. cruzi* (Bengtson & Koutsoukos 1992, Bengtson *et al.* 2007, Koutsoukos & Bengtson 2007a, b).

Echinoids

Echinoids (typically marine) are very common in the Aptian-Coniacian interval of the Sergipe Basin (Seeling *et al.* 2000, Manso 2003); and Manso & Souza-Lima (2012) described new taxa from the basin's Aptian-Albian strata. The last-mentioned authors did not affirm a Tethyan affinity, but previous records of taxa cited in their paper suggest that all of them are indeed Tethyan.

Fishes

Several fish species reported from the Santana Formation (Araripe Basin) also occur in the Riachuelo Formation of the Sergipe Basin, namely: *Cladocycclus gardneri*, *Neoproscinetes penalvai*, *Notelops brama*, *Rhacolepis buccalis*, *Tharrhias araripis* and *Vinctifer comptoni* (Silva-Santos 1991, Souza-Lima *et al.* 2002).

DISCUSSION

As demonstrated above, the paleontological data, involving several fossil groups, indicate the Tethyan origin of earlier marine waters that entered the primitive South Atlantic, even before the deposition of Aptian evaporites. The Tethyan influence persisted in all BCMBs (excepting the Pelotas Basin) until the latest Albian (Vraconian). For the Albian, the Tethyan influence is further evidenced by geochemical data (Azevedo 2001, 2004).

In northeastern Brazil, non-marine conditions were established in the interior basins in the Cenomanian, according to dating of the estuarine deposits of the Itapecuru Formation (Klein & Ferreira 1979) in the São Luís Basin. These represent the latest marine sedimentation on the NW-SE trend formed by the São Luís, Parnaíba and Araripe basins. In contrast to the interior basins, the basins of the continental margin

of northeastern Brazil continued to receive marine sediments, and the Tethyan influence persisted in the Potiguar and Sergipe basins until the Late Cretaceous.

Recent geological data confirm the model proposed herein; i.e., the Tethyan origin of earlier marine waters emanating from the north. Of particular relevance are the following factors: (1) recognition of Neocomian (ca. 140 Ma) marine sediments on the Romanche Fracture Zone, between northeastern Brazil and West Africa (Gasperini *et al.* 2001); and (2) recognition of granitic basement in the Rio Grande Rise (Carvalho 2013, Lisboa 2013a, b). The former point shows that the Tethyan waters reached the Brazilian equatorial margin as early as the beginning of the Cretaceous; the latter indicates that the physical barrier constituted by the “Microcontinent Rio Grande” and the Walvis Ridge effectively restrained free interchange of marine waters between the Pelotas and Santos basins. A similar model was proposed by Dingle (1999), who referred to the “proto-Walvis Ridge barrier”.

CONCLUSIONS

- Aptian marine sedimentation took place under the influence of Tethyan waters in all the BCMBs (Brazilian Continental-Margin Basins), except the Pelotas Basin, which was separated from them by the barrier constituted by the “Rio Grande Microcontinent”.
- The most probable route for the water entering the Northeastern Brazil seaway is through the São Luís, Parnaíba, Araripe and Sergipe basins, thus permitting

the ingress of Tethyan waters into the basins of eastern and southeastern Brazil.

- Considering the occurrences of marine fossils in the Areado Formation (São Francisco Basin), the total extent of the Aptian marine transgression into the continental interior could be much greater than has traditionally been postulated. That could be confirmed in the future by the possible discovery of Aptian marine strata in the Parecis Basin (Arai 1999).
- The classic modeling of the Barremian-Aptian marine transgression (e.g., Dias 1991, 2005, 2008) needs to be reviewed.
- Paleontological studies can provide important data in support of a paradigm revolution. For example, the continental-drift hypothesis, proposed by Wegener in the early 20th century, was originally underpinned by detailed paleontological observations and the fitting of the contours of South America and Africa.

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Appendix. Selected occurrences of marine megafossils in interior basins of northeastern Brazil.

Selected occurrences of marine megafossils in interior basins of northeastern Brazil.

Asterisks (*) indicate Tethyan indicators.

Sources of paleobiogeographic information are shown in bold characters.

[Co] = Codó Fm. (Parnaíba Basin); [Cr] = Crato Mb, Santana Fm. (Araripe Basin);

[It] = Itapecuru Fm. (Parnaíba Basin); [Ma] = Marizal Fm. (Tucano Basin);

[Sa] = Santana Fm. (Araripe Basin).

Echinoids

Bothryopneustes araripensis (Beurlen 1966) Manso & Hessel 2007 [Sa]

Douwillaster benguellensis (Loriol 1888) - **Manso & Hessel (2012)** [Sa]

Hemister proclivus Cotteau, Peron & Gauthier 1878 - **Manso & Hessel (2012)** [Sa]

Pygurus tinocoi Beurlen 1966 [Sa]

Molluscs

Legumen ellipticum Conrad 1858 (Veneridae) - **Santos & Melo (2009)** [Sa]

Craginia araripensis Beurlen 1964 [Sa]

Gymnentone romualdo Beurlen 1964 [Sa]

Crustaceans

**Codoisopus brejensis* Lindoso, Carvalho & Mendes 2013 (Isopoda) [Co]

Paleomattea deliciosa Maisey & Carvalho 1995 (Decapoda) [Sa]

Araripenaeus timidus Pinheiro, Saraiva & Santana 2014 (Decapoda) [Sa]

Fishes

Araripichthys castilhoi* Santos 1985 - **Brito & Yabumoto (2011) [Sa]

Cladocyclus gardneri Agassiz, 1841 - **Brito & Yabumoto (2011)** [Co, Cr, Sa]

**Cratoamia gondwanica* Brito, Yabumoto & Grande, 2008 [Cr]

Iansan beurleni (Silva-Santos 1968) [Sa]

**Nanaichthys longipinnus* Amaral & Brito 2012 [Ma]

Rhacolepis buccalis Agassiz 1841 - **Lindoso, Maisey & Carvalho (2013)** [Co, Sa]

Tharrhias araripis Jordan & Brenner 1908 - **Lindoso, Maisey & Carvalho (2013)** [Co, Cr, Sa]

Vinctifer comptoni (Agassiz 1841) - **Lindoso, Maisey & Carvalho (2013)** [Co, Sa]

Vinctifer longirostris Santos 1990 [Ma, Sa]

Reptiles (turtles)

Araripemys barreto* Price 1973 - **Oliveira (2007) [It, Sa]

Santanachelys gaffneyi Hirayama 1998 [Sa]