The Pirabas Formation (Early Miocene from Brazil) and the Tropical Western Central Atlantic Subprovince

A Formação Pirabas do Brasil (Mioceno inferior) e a subprovíncia tropical do Atlântico Noroeste Central

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Abstract: The Neogene Tropical Western Central Atlantic-South American faunal assemblage from the Pirabas Formation (Early Miocene) has specific and unique features, which distinguishes it from the rest of the Proto-Caribbean Subprovince in diversity, paleoceanographic condition and ecosystems. Principal component analysis (PCA) distinguished three groups of localities with similar faunas (Group A: Ilha de Fortaleza, Colônia Pedro Teixeira and Praia de Fortalezinha; Group B: Estação Agronômica, Ilha de Marajó, Turiacu, Baixo Parnaíba, Aricuru and Salinópolis; Group C: Capanema B-17 Mine) and five different depositional facies (surf zone, beach, lagoons, tidal channel and tidal delta), in agreement with previous geological studies showing heterogeneous paleoenvironments among the outcrops. These heterogeneous lithostratigraphic sequences suggest different members, and may be related to different ages along the Pirabas sequence. The Neogene Northwestern Atlantic Subprovince is erected to encompass this entire geographical area.

Keywords: Neogene. Pirabas. Paleoecology. Paleobiogeography. Proto-Caribbean.

Resumo: A assembleia da fauna Neógena Tropical Sul Americana da Formação Pirabas (Mioceno inferior) possui características específicas e únicas que a distinguem do resto das subprovíncias Proto-Caribenhas em diversidade, condições paleoceanográficas e ecossistemas. A análise de componentes principais distingue três grupos de localidades com faunas similares (Grupo A: ilha de Fortaleza, colônia Pedro Teixeira e praia de Fortalezinha; Grupo B: Estação Agronômica, ilha de Marajó, Turiaçu, baixo Parnaíba, Aricuru e Salinópolis; Grupo C: Mina B-17, Capanema) e cinco diferentes fácies deposicionais (zona de arrebentação, praia, lagoa, canal de maré e delta de maré), corroborando estudos geológicos prévios, que mostram uma série de paleoambientes heterogêneos nestes afloramentos. Essa sequência litológica heterogênea sugere a presença de vários membros, que poderiam ser correlacionados a diferentes idades ao longo da sequência da Formação Pirabas. A denominação de subprovíncia tropical do Atlântico Noroeste Central é proposta para o Neógeno dessa área geográfica.

Palavras-chave: Neógeno. Pirabas. Paleoecologia. Paleobiogeografia. Proto-Caribe.

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INTRODUCTION

Since the 19th century, the fossiliferous limestone studied by Ferreira Penna (1876) has yielded a high species diversity from the exclusively Cenozoic deposits (Figure 1) along the northern Atlantic coast of South America in Brazil (Pará, Maranhão and Piauí states).

The early contributions of White (1887) and Maury (1925) were the basal references on the Pirabas Formation (Early Miocene from Brazil), particularly in mollusk, bryozoan and coral research, followed by the contributions of Petri (1954, 1957) on foraminifera, Beurlen (1958), Brito (1971, 1972, 1977) and Martins-Neto (2001) on crustaceans, Santos (1958, 1967) on echinoids, Santos & Travassos (1960) and Santos & Salgado (1971) on fishes, Paula-Couto (1967) and Toledo & Domning (1989) on sirenians. Many other references, summarized in Rossetti & Góes (2004) and Távora *et al*. (2010) provide additional descriptions, records and/or reviews of different fossil taxa.

All of these authors suggest close relationships between the faunal assemblages from the Pirabas Formation and the Caribbean Neogene fauna, based on qualitative analysis, species co-occurrence and personal conclusions. However, based on fossil fish faunas, Aguilera *et al*. (2011 and in progress) conclude that the Pirabas Formation has a distant relationship with the Gatunian Province in the Caribbean region. This is true even when the Pirabas Formation is compared with the Early Miocene Husillo and Cojimar formations from Cuba, the Mao Formation from the Dominican Republic, the Cantaure and Castillo (lower section) formations from Venezuela, the Tuira Formation from Panama, the Brasso Formation from Trinidad, the Kendeace Formation from Grenada, and the Viche Formation from Ecuador.

The topics considered here are the faunal composition, the influence of the Tropical Atlantic water mass on the North Brazilian Current (Johns *et al*., 1998, 2002), the high tidal range (Beardsley *et al*., 1995; DHN, s. d.), the eustatic sea level changes (Haq *et al*., 1988; Carter, 1998; Kominz *et al*., 2008) and the sea level fluctuations in northern Brazil (Rossetti, 2001), the early Miocene age of the Pirabas Formation, and the geographic location of the Pirabas Basin previous to the present configuration of the Caribbean Sea.

The main lithostratigraphic and paleoenvironmental interpretation of the Pirabas Formation is that of Góes *et al*. (1990), Rossetti (2001) and Rossetti & Góes (2004). These authors present a representative vertical profile (Figure 2), synthesizing the depositional sequence and characterizing the Pirabas Formation as consisting of carbonate rocks from offshore platform deposits (grainstone and consolidated packstone, stratigraphic wackestone-packstone and laminated mudstone), littoral facies (shoreface/foreshore), marginal lagoons and restricted platform (gray to olive mudstone and conglomeratic sandstone), and mangrove estuarine lagoons (dark mudstone, massive or laminated). The Early Miocene age assignment of the Pirabas Formation follows Petri (1957), Fernandes (1984), Ferreira *et al*. (1978), Fernandes & Távora (1990) and Távora & Fernandes (1999).

Recent research (S. A. F. Costa, A. E. A. Santos Junior, H. M. Moraes-Santos & O. Aguilera, personal communication) described a heterogeneous lithostratigraphic sequence along a section in the Capanema B-17 Mine, and proposed five lithofacies: surf zone, beach, lagoons, tidal channel and tidal delta, which would describe an littoral system with wave and tidal influence.

These heterogeneous sequences and the faunal assemblages recorded in different outcrops suggest that different members should be recognized, and accurate geochronological research may reveal different ages within the Pirabas sequence.

Based on this heterogeneous lithostratigraphic profile and the diverse fossil record (which includes 214 invertebrates and vertebrates from 21 outcrop-localities), our objective is a quantitative analysis aimed at producing an appropriate interpretation to support future research on the context of geochronology, paleoenvironments, paleobiogeography and stratigraphic review for the Pirabas Formation.

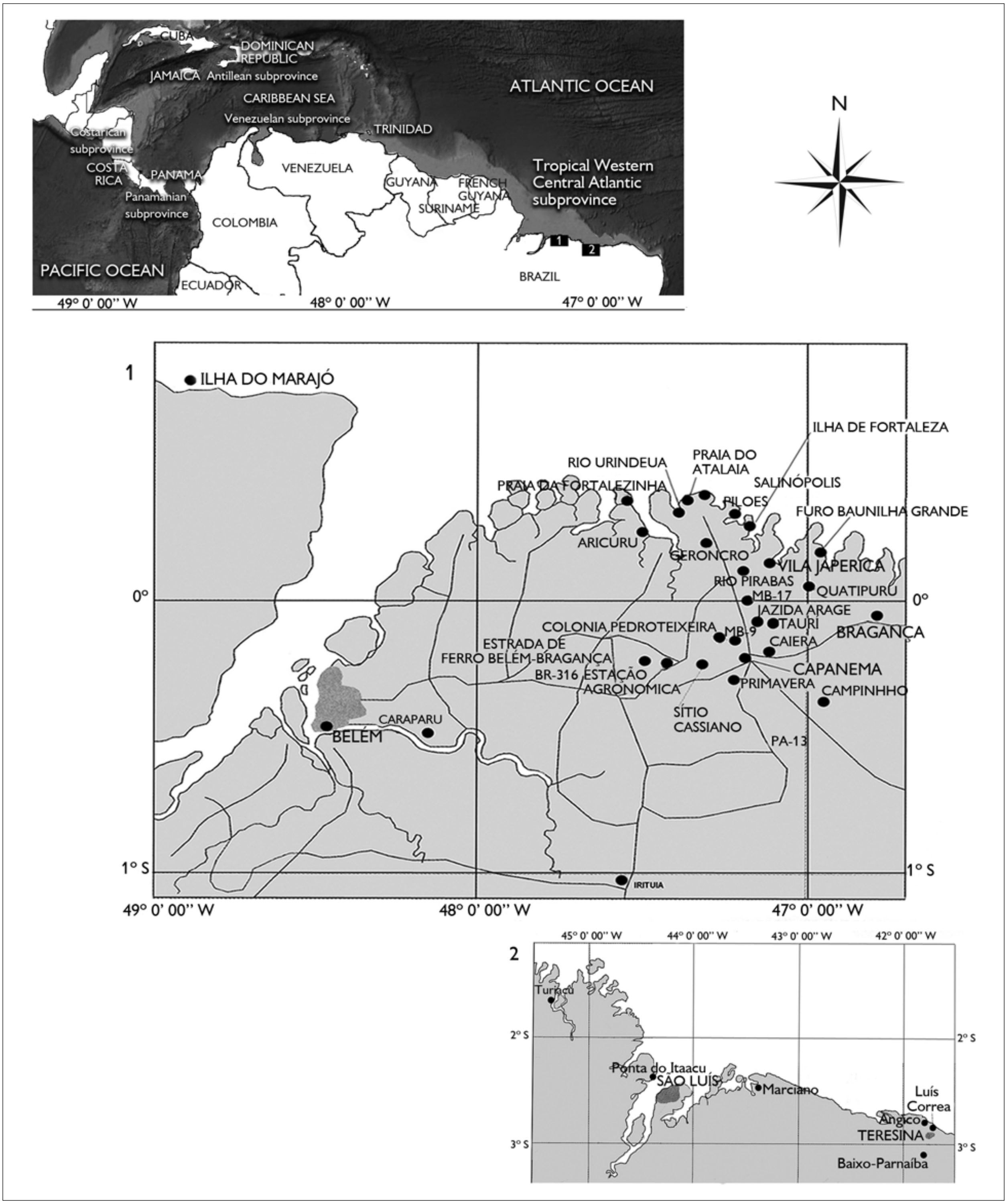

Figure 1. Map showing the Tropical American region and the Proto-Caribbean Pirabas Formation outcrops. 1. Outcrops in Pará state. 2. Outcrops in Maranhão and Piauí states (modified from Aguilera *et al*., 2011 and Távora *et al*., 2010).

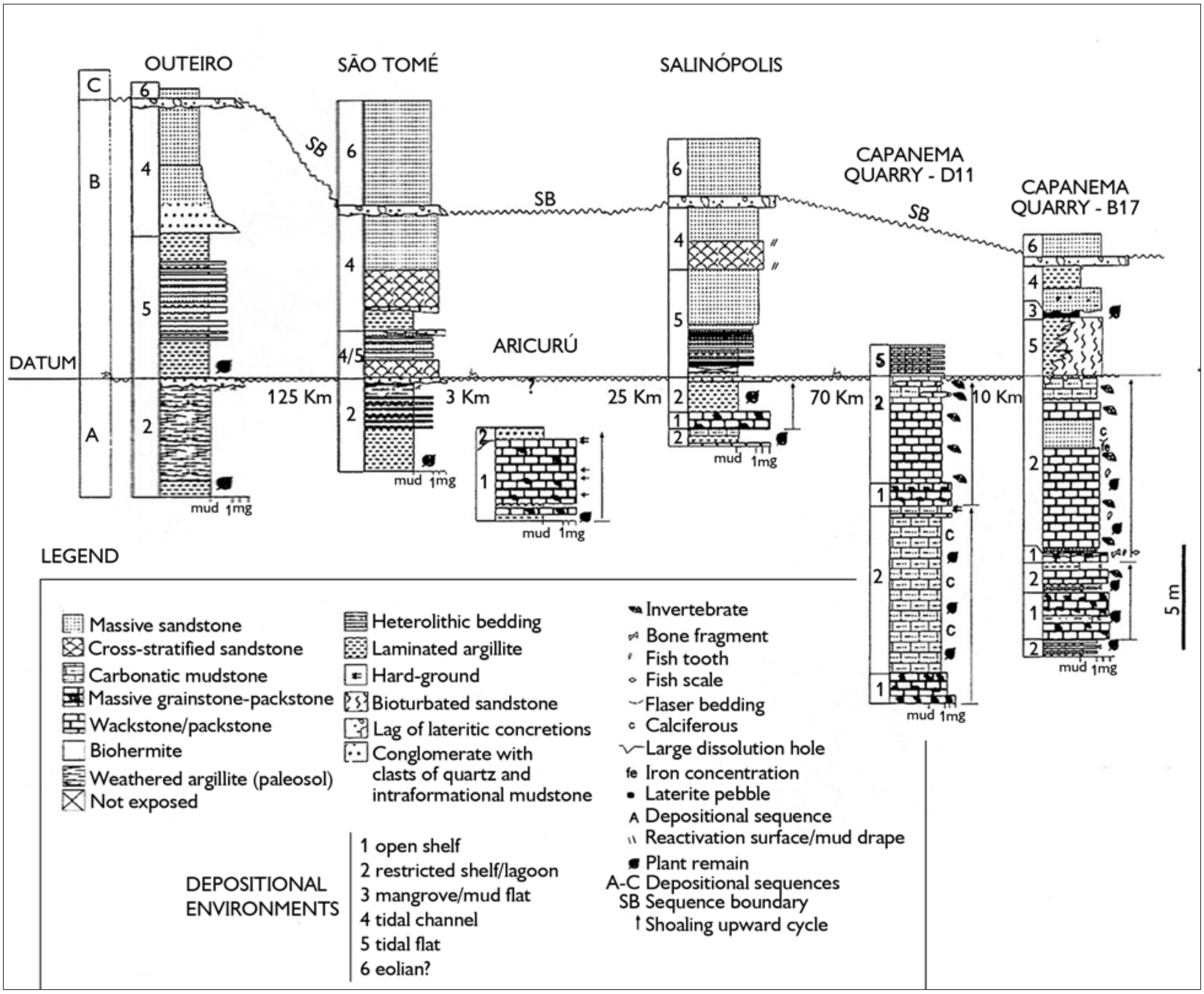

Figure 2. Stratigraphic correlation of the Pirabas Formation (Early Miocene) on the Bragantina and Pará platforms, northern Brazil (modified from Rossetti & Góes, 2004).

METHODS

The data presented were taken from published literature (White, 1887; Maury, 1925; Petri, 1954, 1957; Beurlen, 1958; Santos, 1958, 1967; Santos & Travassos, 1960; Paula-Couto, 1967; Santos & Salgado, 1971; Brito, 1971, 1972, 1977; Fernandes, 1981; Toledo & Domning, 1989; Martins-Neto, 2001), including a variety of invertebrates (bryozoans, echinoids, mollusks and crustaceans) and vertebrates (sirenians and fishes), recompiled in a recent paper by Távora *et al*. (2010), and consulted during a general overview of the fossil collection in the Museu Paraense Emílio Goeldi (MPEG) repository. Some original taxonomic names listed by Távora *et al*. (2010) may need to be revised. However, the genus-level data can be used with confidence in the present analysis. The description of the local geology and stratigraphy follows Góes *et al*. (1990), Rossetti (2001) and Rossetti & Góes (2004). Field study of the main sections at Atalaia beach, Ponta do Castelo, Fazenda, Fortalezinha and the Capanema B-17 Mine was conducted as part of the Museu Emílio Goeldi Vertebrate

Paleontology Project. The data were standardized at the generic level, as is common in this kind of study (Foote & Miller, 2007). This procedure served also to diminish distortions caused by preservation and sampling biases, endemic groups, and nomenclatural uncertainties.

We grouped localities according to the outcrops studied, which are deemed good geographic and paleoenvironmental representatives of the early Miocene Pirabas Formation sections. A few samples of taxa in certain localities are biased or absent due to lack of preservation or study. The binary data matrix includes 214 fossil invertebrates and vertebrates from 21 outcrop-localities (Table 1).

One of the most important multivariate methods of data analysis is PCA (Ferreira *et al*., 1999; Malinowski, 1991) based on the correlation between variables. It aims to group these correlated variables, generating a new set of variables called principal components (PC) onto which the data is projected. These PC are built as linear combination of original variables and have the important property of being completely uncorrelated. The first new axis is chosen in such a direction that it maximizes the variance along the axis, the second must be chosen orthogonal to the first one and the direction to describe as much variance left as possible so on.

The Principal Components Analysis (PCA) uses the calculated covariance and variance between localities; for this reason this is a Q-PCA according to Fasham (1977). The Q-PCA analysis was run using the free software PAST (Hammer *et al*., 2001), and the taxonomic groups was expressed in the PCA's planes using the concentration ellipse level of 30%. Following Jackson *et al*. (1989), the size effect of the linear relationship between the PCA axis 1 and the relative frequency of species occurrence were established with the largest occurrence. The coefficient from each PCA are present in the Table 2.

The confidence ellipses of genera groups were formed by computing the three following quantities using the PAST software (Hammer *et al*., 2001), as proposed by Abdi *et al*. (2009): (1) the coordinates of the center of the ellipse of each group in the factorial plane (Axis II and Axis III), (2) the angle between the major axis of the ellipse and the first dimension of the plane, and (3) the relative size of the minor axis compared to the major axis of the ellipse. To perform these procedures one must set the center of the ellipse at the center of mass of the points. Thereafter, the ratio between the minor axis and the major axis is calculated as the ratio of the second eigenvalue to the first eigenvalue. Finally, the angle of rotation is given by the first eigenvector. For a 30% confidence interval, the lengths of the axes of the ellipse are set to ensure that the ellipse comprehends 30% of the points. The value of 30% was chosen for visual clarification so as to avoid overlapping the ellipses and better identify the centroids of taxonomic groups in factorial plane.

RESULTS AND DISCUSSION

The Early Miocene faunal assemblage identified in northern Brazil is called here the Proto-Caribbean Pirabas fauna (not Caribbean), based on the nature of this fauna and because the Caribbean Sea proper was only formed after the Pacific and Atlantic were completely isolated in the Pliocene (Coates *et al*., 1992, 2004; Coates & Obando, 1996). The paleobiogeographic model for the southern Caribbean comprises the lower Miocene-lower Pleistocene Gatunian Province and the middle Pleistocene-upper Pleistocene Caribbean Province (Landau *et al*., 2008). According to this system the Neogene Tropical Western Central Atlantic Subprovince can be erected to encompass this entire geographical area.

In our assessment, the Proto-Caribbean Pirabas fauna is arranged in three faunal groups and five different facies. Faunal group A, includes the isolated vector of Ilha de Fortaleza (IFOR), Colônia Pedro Teixeira (CTEI), and Praia de Fortalezinha (PFORT). This group exhibits a pattern of co-occurrence and singularity of fossil faunas indicated by the assemblages of gastropods, echinoids, crustaceans and vertebrates (Figure 3, left projection). Group B includes vector from Estação Agronômica (ESTA), Salinópolis (SALI), Ilha de Marajó (IMAR), Turiacu (TURI), Baixo Parnaíba

Table 1. Functional groups organized by genera and localities. Abbreviations: ANGI - Angico; ARIC - Aricuru; BAUG - Furo Baunilha Grande; BPAR - Baixo Parnaíba; CAIE - Caieira; CASS - Sítio Cassiano; CTEI - Colônia Pedro Teixeira; ESTA - Estação Agronômica; GERO - Gerôncio; ID - corresponding genera name abbreviations; IFOR - Ilha de Fortaleza; IMAR - Ilha de Marajó; IGMA - Igarapé Marciano; LCOR - Luís Correa; MB17 - Capanema B-17 Mine; PFORT - Praia de Fortalezinha; PITA - Ponta do Itaaçu; RURI - Rio Urindeua; SALI - Salinópolis; TAUA - Tauari; TURI - Turiacu; VJAP - Vila de Japarica.

(Continued)

Genera	ID	ARIC	CAIE	CTEI	ESTA	BAUG	GERO	IFOR	IMAR	MB17	PFORT	RURI	SALI	CASS	TAUA	VJAP	IGMA	PITA	TURI	ANGI	LCOR	BPAR
Bryozoans																						
Biselenaria	BISEL	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Crisia	CRISI	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cupuladria	CUPUL	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Fustra	FUSTR	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Idmonea	IDMON	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lichenopora	LICHE	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Metrarabdotos	METRA	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nelia	NELIA	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pasythea	PASYT	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Steginoporella	STEGI	1	0	1	1	0	0	1	0	0	0	0	1	1	0	0	1	0	0	0	0	0
Vincularia	VINCU	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Vittaticella	VITTA	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lunulites	LUNUL	0	0	0	1	1	0	1	0	0	0	0	1	0	0	0	1	0	1	0	0	0
Trigonopora	TRIGO	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Echinoids																						
Abertella	ABART	0	0	1	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Anisopetalus	ANISO	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Agassizia	AGASS	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Classidulus	CLASS	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Clypeaster	CLYPE	0	0	1	1	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Echinolampas	ECHIN	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Histocidaris	HISTO	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plagiobrissus	PLAGI	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Phyllacanthus	PHYLL	1	0	1	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Prionocidaris	PRION	1	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0

Table 1. (Continued)

Genera	ID	ARIC	CAIE	CTEI	ESTA	BAUG	GERO	IFOR	IMAR	MB17	PFORT	RURI	SALI	CASS	TAUA	VJAP	IGMA	PITA	TURI	ANGI	LCOR	BPAR
Rhyncho-lampas	RHYNC	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Schizaster	SCHIZ	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cirripeds																						
Balanus	BALA	0	0	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0
Megabalanus	MEGAB	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0
Decapods																						
Achantocarpus	ACHAN	0	0	1	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Arenaeus	ARENA	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Calappa	CALLA	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	1	0	0	0	0	0
Calappilla	CALAP	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Callinectes	CALLI	0	0	1	0	1	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Cyclocancer	CYCLO	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Euphylax	EUPHR	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Hepatella	HEPAT	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Necronectes	NECRO	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Nepturus	NEPTU	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Panopaeus	PANOP	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Paratumido-carcinus	PARAT	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Parthenope	PARTH	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Portunus	PORTU	0	0	1	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Randallia	RANDA	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Scylla	SCYLL	0	0	1	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Sesarma	SESAR	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tasadia	TASAD	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tetraxanthus	TETRA	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Typilobus	TYPIL	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Uca	UCA	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 1. (Continued)

Genera	ID	ARIC	CAIE	CTEI	ESTA	BAUG	GERO	IFOR	IMAR	MB17	PFORT	RURI	SALI	CASS	TAUA	VJAP	IGMA	PITA	TURI	ANGI	LCOR	BPAR
Elasmobranchs																						
Megaselachus	MEGAS	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Carcharhinus	CARCH	0	1	1	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Galeocerdo	GALEO	0	0	1	0	0	0	1	0	1	1	0	1	0	0	0	0	0	0	0	0	0
Ginglymostoma	GYNGL	0	0	1	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Hemipristis	HEMIP	0	0	1	0	0	0	1	0	1	1	0	1	0	0	0	0	0	0	0	0	0
Hypoprion	HYPOP	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Isurus	ISURS	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Myliobatis	MYLIO	0	0	1	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0
Nebrius	NEBRI	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Paleomyliobatis	PALEO	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Rhinoptera	RHINO	0	1	1	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Scoliodon	SCOLI	0	0	1	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Sphyrna	SPHYR	0	1	1	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Teleost																						
Sciades	SCIAD	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Diodon	DIODO	0	0	1	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Sphyraena	SPHYN	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bivals																						
Adrana	ADRAN	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Amusium	AMUSI	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Anadara	ANADA	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	1	0	0	0	1	1
Anomia	ANOMI	1	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Antigonia	ANTIG	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Apolymetis	APOLY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Arca	ARCA	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	1	0
Arcinella	ARCIN	0	0	0	1	0	0	1	0	1	0	1	1	0	0	0	0	0	0	0	0	0
Barbatia	BARBA	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Callista	CALLIS	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 1. (Continued)

Genera	ID	ARIC	CAIE	CTEI	ESTA	BAUG	GERO	IFOR	IMAR	MB17	PFORT	RURI	SALI	CASS	TAUA	VJAP	IGMA	PITA	TURI	ANGI	LCOR	BPAR
Cardita	CARDI	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	1	0	0	0	0	0
Cardium	CARDM	0	0	0	1	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Cerithium	CERRIT	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
Chama	CHAMA	0	0	0	1	0	0	1	0	1	0	0	1	0	0	0	1	0	0	0	0	0
Chione	CHION	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	1	0	1	1
Chlamys	CHLAM	0	1	1	1	0	0	0	0	1	0	0	1	0	0	1	1	0	1	0	1	1
Clementia	CLEME	0	1	0	1	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Corbula	CORBU	0	0	0	1	0	0	1	0	1	0	0	1	0	0	0	1	1	0	0	0	0
Crassinella	CRASI	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Crassostrea	CRASS	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	1
Cubitostrea	CUBIT	0	0	1	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Cultellus	CULTE	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Divaricella	DIVAR	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dosinia	DOSIN	0	0	0	0	0	1	1	0	1	0	0	1	0	0	0	1	0	1	0	0	0
Ficus	FICUS	0	0	0	0	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0
Fragum	FRAGU	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Glycemeris	GLYCE	0	0	0	1	0	0	1	0	1	0	1	1	0	0	0	1	0	0	0	0	0
Iphig	IPHIG	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Laevicardium	LAEVC	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	1	0	0	0
Laevigatum	LAEVG	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Leda	LEDA	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lima	LIMA	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Linga	LINGA	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	1	0	0	0	0	0
Lucina	LUCIN	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Macoma	MACOM	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Macrocalista	MACRO	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Mactra	MACTR	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Mercenaria	MERCE	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Metis	METIS	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 1. (Continued)

Genera	ID	ARIC	CAIE	CTEI	ESTA	BAUG	GERO	IFOR	IMAR	MB17	PFORT	RURI	SALI	CASS	TAUA	VJAP	IGMA	PITA	TURI	ANGI	LCOR	BPAR
Microcardium	MICRO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Miltha	MILTA	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Modiolus	MODIO	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mytilus	MYTIL	0	0	1	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Neopycnodonta	NEOPY	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Noetia	NOETI	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Pecten	PECTE	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Periglypta	PERIG	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Phacoides	PHACO	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pitar	PITAR	0	1	1	1	0	0	1	0	1	0	0	1	0	0	0	1	1	1	0	1	0
Pycnodonte	PYCNO	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Plicatula	PLICA	1	0	0	1	0	0	1	0	1	0	0	1	0	0	0	1	0	0	0	0	0
Pteria	PTERI	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0
Scapharca	SCAPH	0	0	0	1	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Semele	SEMEL	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Solena	SOLEN	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Solecurtus	SOLEC	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Spondylus	SPOMD	0	0	0	1	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Tagelus	TAGEL	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tellina	TELLI	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Teredo	TERED	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tivela	TIVEL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Trachycardium	TRACH	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Venericardia	VENER	0	0	0	1	0	1	1	0	1	0	0	1	0	0	0	1	0	1	0	0	0
Ventricolaria	VENTR	0	0	0	1	0	0	0	0	1	0	0	1	0	0	0	1	0	1	0	0	0
Gasteropods																						
Alabina	ALABI	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Alectrion	ALECT	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Amauropsis	AMAUR	1	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0

Table 1. (Continued)

Genera	ID	ARIC	CAIE	CTEI	ESTA	BAUG	GERO	IFOR	IMAR	MB17	PFORT	RURI	SALI	CASS	TAUA	VJAP	IGMA	PITA	TURI	ANGI	LCOR	BPAR
Ancilla	ANCLA	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ancillaria	ANCIA	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Architectonica	ARCHI	0	0	0	1	0	1	1	0	1	0	0	1	0	0	0	1	0	0	0	0	0
Astraca	ASTRA	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bittium	BITTI	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Calliostoma	CALLI	0	0	0	1	0	0	1	0	1	0	0	1	0	0	0	1	0	1	0	0	0
Calyptraea	CALYP	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cancellaria	CANCE	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Cerithium	CERIT	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	1	0	0	0	0
Clava	CLAVA	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Colubraria	COLUB	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Conus	CONUS	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0
Crassispira	CRASI	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Crucibulum	CRUCI	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cylindritella	CYLIN	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Cypraea	CLYPT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Cypraeacteon	CYPRA	1	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0	0	1	0	0	0
Diodora	CYPRN	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Drillia	DIODR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
Fasciolaria	DRILL	0	0	0	1	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Ficus	FASCI	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fissurela	FISSU	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fissuridea	FISSA	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Fusinus	FUSIN	0	0	0	0	0	1	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Fusus	FUSUS	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Littorina	LITTOR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Lunatia	LUNAT	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Lyria	LYRIA	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Marginella	MARGI	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 1. (Continued)

Genera	ID	ARIC	CAIE	CTEI	ESTA	BAUG	GERO	IFOR	IMAR	MB17	PFORT	RURI	SALI	CASS	TAUA	VJAP	IGMA	PITA	TURI	ANGI	LCOR	BPAR
Melongena	MELON	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Mesalia	MESAL	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	1	0	0	1
Metula	METUL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Mitra	MITRA	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	1	0	1
Morum	MORUM	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Murex	MUREX	0	0	1	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Natica	NATIC	1	1	0	1	0	0	1	0	1	0	0	1	1	0	0	0	1	1	1	1	1
Oliva	OLIVA	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Olivella	OLIVE	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Orthaulax	ORTHA	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	1	0	0	0	0	0
Pachycrommium	PACHY	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	1	0	0	0	0
Petaloconchus	PETAL	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0
Phalium	PHALI	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Phosfictilis	PHOSF	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pleuroliria	PLEUR	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pycnodonte	PYCTE	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pyrula	PYRUL	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Polinices	POLYN	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Polystira	POLYS	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Potamides	POTAM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1
Retusa	RETUS	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Rhicl	RHICL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Serpulorbis	SERPU	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Scaphander	SCPHA	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Simpulum	SIMPU	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sinum	SINUM	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0
Siphocypraea	SIPHC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Siphonalia	SIPHA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sconsia	SCONS	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0

Table 1. (Conclusion)

Genera	ID	ARIC	CAIE	CTEI	ESTA	BAUG	GERO	IFOR	IMAR	MB17	PFORT	RURI	SALI	CASS	TAUA	VJAP	IGMA	PITA	TURI	ANGI	LCOR	BPAR
Solarium	SOLAR	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Stigmaulax	STIGM	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Strombus	STROM	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Surcula	SURCU	0	0	0	1	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Tectonica	TECTO	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Terebra	TEREB	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Trita	TRITA	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Tritonidea	TRITO	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Trochus	TROCH	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Trophon	TROPH	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Turbinella	TURBI	0	0	1	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Turbo	TURBO	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Turritella	TURRI	0	0	1	0	0	0	1	0	1	0	0	1	0	0	0	1	0	1	0	1	1
Umbrella	UMBRE	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Vasum	VASUM	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Vermetus	VERME	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Vexil	VEXIL	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Xancus	XANCU	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Xenophora	XENOP	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Cephalopods																						
Aturia	ATURI	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Scaphopods																						
Denthalium	DENTA	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Manmals																						
Dioplotherium	DIOPL	1	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Metaxitherium	METAX	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0
Rytiodus	RYTIO	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0	0

Table 2. PCA coefficient.

PC	Eigenvalue	% Variance	% Variance acumulated
1	0,487	30,001	30,001
2	0,226	13,913	43,914
3	0,158	9,724	53,638
4	0,138	8,489	62,127
5	0,095	5,851	67,978
6	0,080	4,942	72,920

(BPAR) and Aricuru (ARIC). All of these exhibit a pattern of co-occurrence of bryozoans, bivalves, and gastropods in lesser proportion (Figure 3, right projection). An independent vector from the Capanema B-17 Mine (MB17), without a significant relationship with Groups A and B, forms Group C.

The close relationship among the bryozoans in Group B is clear. However, the condition in Group A is closely related to the co-occurrence of echinoids, crustaceans and vertebrates.

The facies, called previously by Petri (1957) Castelo (shallow coastal marine, reaching 30 m deep), Caneco (littoral coastal marine to transitional basin border, reaching 10 m deep) and Baunilha Grande (mangrove marginal lagoons), are the basis for review and proposing the subdivision of the Pirabas Formation according to the isolated vector or vector complex into the following five facies: Ilha de Fortaleza (IFOR), Estação Agronômica (ESTA), Aricuru (ARIC), Capanema (MB17) and Colônia Pedro Teixeira (CTEI) (Figure 3).

CONCLUSION

The Neogene Tropical Western Central Atlantic-South American faunal assemblage from the Early Miocene Pirabas Formation has specific and unique features,

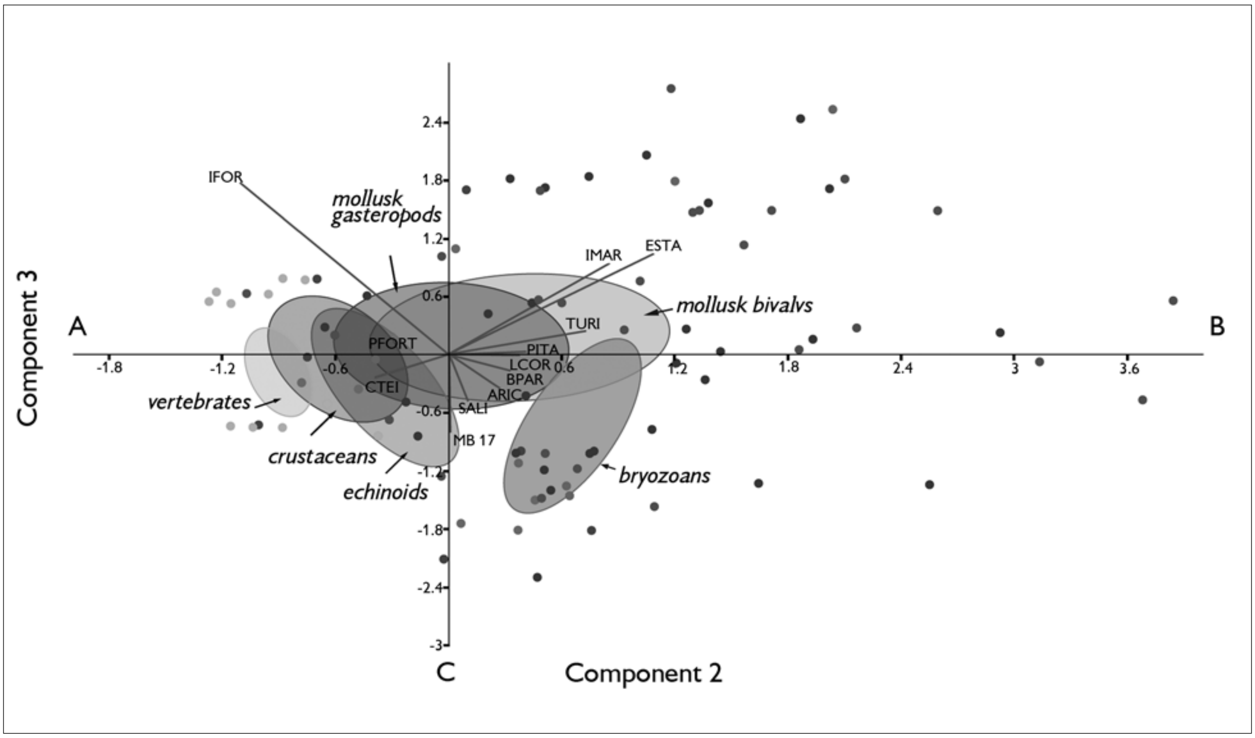

Figure 3. Principal components analysis arranged by genera and Pirabas Formation outcrops, and ovoid area of fossil assemblage (axis II versus axis III). Abbreviations: ARIC - Aricuru; BPAR - Baixo Parnaíba; CTEI - Colônia Pedro Teixeira; ESTA - Estação Agronômica; IFOR - Ilha de Fortaleza; IMAR - Ilha de Marajó; LCOR - Luís Correa; MB 17 - Capanema B-17 Mine; PFORT - Praia de Fortalezinha; SALI - Salinópolis; TURI - Turiacu; PITA - Ponta do Itaaçu.

which distinguish it from the rest of the Proto-Caribbean Subprovince in diversity, paleoceanographic condition and ecosystems.

The proposed Tropical Western Central Atlantic Subprovince is supported by the faunal assemblage analysis for the Proto-Caribbean Pirabas Formation, which is an exclusively Cenozoic unit cropping out along the northern Atlantic coast of Brazil in South America.

As a result of the PCA analysis, three faunal groups and five different facies were observed, in agreement with previous geological studies that indicated heterogeneous paleoenvironments along the section. These heterogeneous sequences in this lithostratigraphic unit could support a division into different formal or informal members, and/or indicate different ages of parts of the Pirabas Formation.

This study showed the diagnostic faunal assemblages and priority areas for future research in taxonomy, taphonomy, geochemistry, stratigraphy needed to establish detailed relationships between the different outcrops assigned to the Pirabas Formation. The paleoenvironments and paleobiogeography must be combined with complementary geochronologic research to provide absolute age determinations.

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