Late Burdigalian (Miocene) age for pectinids (Mollusca-Bivalvia) from the Pirabas Formation (Northern Brazil) derived from Sr-isotope ($^{87}Sr/^{86}Sr$) data

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Abstract

The faunas of the highly fossiliferous Pirabas Formation belong to the southern part of the biogeographical unit (Province?) known as "Neogene Tropical America". This unit (Province?) a developed prior to the closure of the Central American Seaway by the Isthmus of Panama. Until now, the age of the Pirabas Fm was inferred only from biostratigraphy. The Sr-isotope ($^{87}Sr/^{86}$ Sr) values of pectinid shells - from the Paribas Fm show that some parts of this unit were deposited during the Late Burdigalian (about 16-17 ma). This result does not contradict biostratigraphic data and theyt constrains the age of the Pirabas Formation more tightly than do previous estimates of age, allowing for future, more precise biogeographical comparisons.

Key words: 87Sr/86Sr, strontium, SIS, ; Pectinoidea; Miocene; Pirabas Fm.; Brazil

Introduction

The Pirabas Formation is one of the most - fossiliferous lithostratigraphic units of Brazil. It contains a high number of taxa that represent mainly plants, microfossils, mollusks, echinoderms, bryozoans, fishes, crocodiles, and sirenians (see compilations of TÁVORA et al. 2004, ROSSETTI & GOES 2004). The formation occurs on the northern and northeastern coast of Brazil (Pará, Maranhão and Piauí states), and is overlain by siliciclastic deposits of the Barreiras Formation (ROSSETTI et al. 2013). The formation was deposited in environments typical of coastal deposits, such as shallow platform, tidal flat, lagoon and mangroves separated from the inner shelf by island barriers (FERREIRA 1977, GÓES et al. 1990). The formation comprises mainly of carbonates, intercalated with laminated siltstones, and, less commonly, fine-grained sandstones. The stratal architecture indicates an overall progradational pattern, but sedimentation was influenced by cyclical transgressive-regressive events that affected both lithology and biota (NOGUEIRA et al. 2011, ROSSETTI et al. 2013).

The location of the Pirabas Formation is significant because it occurs in the southernmost part of the Baitoan or Miocene Caribbean Province (WOODRING 1971, 1974, PETUCH 1982, 1988, 2003, VERMEIJ 2005), a biogeographical unit (province?) of "Neogene Tropical America", developed before the Central American Seaway was closed by growth of the Isthmus of Panama (WOODRING 1966, JACKSON et al.1993, AGUILERA et al. 2011, O'DEA et al.2016)(Fig. 1). The Brazilian fossil fauna of the Pirabas Fm are therefore related closely to Caribbean faunas and, consequently, the accurate determination of its age is of utmost importance in order to make appropriate correlations across central America in the Neogene.

As detailed below, the age of the Pirabas Formation has been established on paleontological grounds, and has been subject to one imprecise attempt at numerical dating (BELÚCIO & TÁVORA 2001). WHITE (1887) assigned a Cretaceous age to some beds of the Pirabas Formation. The dating was questioned by WOODRING (1926) and OLIVEIRA (1953) who noted that WHITE (1887) had mixed fossils and localities thus resulting in erroneous interpretations. In a brief note, MAURY (1919) proposed a Tertiary age for the Pirabas beds, and suggested preliminary correlations. Later, in her classic monograph, MAURY (1925), assigned an Early Miocene age to the Pirabas beds, mainly based on the presence of the gastropod *Orthaulax pugnax* (HEILPRIN 1887) (see also COOKE 1922). This age was overlooked for many years.

Discussions of the age range represented by the Pirabas Formation (Oligocene-Miocene or Early Miocene) have been influenced by whether or not outcrop or subsurface (borehole) information was interpreted. Studies of outcrops seem to assign a limited age range in the Early Miocene to the Formation, while studies of borehole material indicate a more extensive succession ranging in age from the Late Oligocene to Early Miocene. These studies are review below.

FERREIRA et al. (1981), based on a study of foraminifera from a core (Vila Mãe do Rio “48”, Irituia town, Pará state), considered that the lower and middle portion of the formation are Oligocene in age, due to the presence of *Globorotalia opima* (biozone N2, BLOW 1969), while the upper portion is characterised by a typical benthic Miocene assemblage. Later, FERNANDES (1984), FERREIRA et al. (1984) and FERNANDES & TÁVORA (1990) studying the foraminifera from cores from Capanema, Belém and Irituia towns, correlated the studied strata with the global biozones N4 and N5 (Aquitanian-Burdigalian, BLOW 1969), based on the presence of an assemblage consisting of *Globorotalia opima, G. rohri*, *Globigerinoides quadrilobatus altiaperturus, G. trilobus trilobus* (Early Miocene (Eomiocene) and *G. primordius* (base of Early Miocene). The presence, however, of *Globorotalia kugleri* and *Globoquadrina dehiscens* (Late Oligocene-Early Miocene), and the nannofossil *Triquetrorhabdulus carinatus* (Neooligocene-Eomiocene) (CONCHEYRO & TÁVORA (1992) allowed the base of the formation to be extended downward to the biozone N2 of BLOW (1969), dating the whole sequence as Late Oligocene-Early Miocene (N2–N5, Chattian-Burdigalian). Studies throughout the Bragantina Zone (Capanema and Maracanã) and Belém confirmed this age (FERNANDES & TÁVORA 1990, TÁVORA & FERNANDES 1999).

On the basis of palynological studies of material from diverse outcrops in Pará state, LEITE (2004) recognized the *Crototricolpites annemariae, Echitricolporites maristellae*, and *Polypodiaceoisporites potoniei* assemblage, compatible with HOORN’s (1993) concurrent range zone of *Psiladiporites–Crototricolpites* and *Crassoretitriletes* (Interval Zone sensu LORENTE 1986) from the Early-to-Middle Miocene. Later, studies on the Baunilha Grande Ecofacies indicated a late Early Miocene age (Zone T-13 of *Malvacipolloides maristellae* according to JARAMILLO et al. 2011) (ANTONIOLI et al. 2015).

The age of the Pirabas Formation can be constrained by numerical methods. BELÚCIO & TÁVORA (2001) made an early attempt to use $^{87}Sr/^{86}Sr$ values of pectinid shells to date the formation with Sr-isotope stratigraphy. Unfortunately, they encountered some methodological problems and only an abstract of their work was published. Nevertheless, some aspects of this abstract will be discussed later. Here three new $^{87}Sr/^{86}Sr$ values are presented and interpreted in terms of age to show that the studied sections of the Pirabas Formation are of Burdigalian (Early Miocene) age.

Material and methods

Sr-isotope stratigraphy is used to date three specimens of *Pectinidae* from the Paleontological collection of the Museu Paraense Emílio Goeldi *. They correspond to (nomenclature according to FERNANDES & TÁVORA, 1989): *Chlamys* (*Chlamys*) *thalera* (MAURY 1925), from Ilha de Fortaleza; *Chlamys* (*Argopecten*) *capanemensis* FERREIRA 1960, from Quarry B-11, Capanema; and *Chlamys (Leptopecten) latiaurata* (CONRAD 1837) from Quarry B5, Capanema. The geographical locations from which the samples were collected are shown in Figure 2, and the stratigraphy of the locations are given in Figure 3.

The samples were cleaned of adhering matrix by physical abrasion, and then broken into cm-sized pieces. The pieces were cleaned by brief immersion in 1% nitric acid, then washed with ultra-pure water, and finally were dried in a clean environment. From these pieces, the best preserved one were gently broken into sub-mm-sized pieces. From the fragments, about 10 mg of the best-preserved pieces were hand-picked under the microscope for later analysis. The diagnostic features of good preservation are fragmentation along the original layering to yield thin, sheet-like, fragments of transparent calcite, and an absence of Fe or Mn stains. In assessing alteration, we did not employ the common methods of trace-element anaysis, XRD, or stable-isotopic analysis as > 20 years experience with these methods has shown that they are less sensitive at revealing alteration than is visual examination under the microscope. Examination by CL is sometimes useful, but as some modern carbonate shells have luminescent portions (Barbin et al. 1991) it is not always diagnostic.

The picked samples were dissolved in nitric acid, evaporated to dryness, and Sr was separated from the residue using column chromatography with Sr-Spec resin. All analyses reported here have been adjusted to a value of 0.710248for NIST987, previously known as SRM987. Multiple replicates of the standard NIST987 run before, during, and after the isotopic analysis reported here gave an external precision of 0.000 009 (Table 1).

Numerical ages were derived from $^{87}Sr/^{86}Sr$ ratios using the LOWESS5 calibration curve of MCARTHUR et al. (2012). The uncertainties on the numerical ages are derived by compounding the uncertainty of measurement with the uncertainty on the calibration line.

3. Results and Discussion

Results are summarized in Table 1, along with the three dates obtained from different species and from different localities. The three ages span an age range of 1.2 myrs and indicate a late Burdigalian age (about 16–17 Ma) for the studied portion of Pirabas Formation. The Burdigalian comprises the lapse between 20.44 to 15.97 Ma (COHEN et al., 2013).

Previously, BELÚCIO & TÁVORA (2001) presented in an abstract the results of five $^{87}Sr/^{86}Sr$ analyses of valves of *Chlamys* from three localities in the Pirabas Formation. The values are reproduced here in Table 1. These ages are problematical because firstly, the authors do not provided

$^{87}Sr/^{86}Sr$ data for the standards that were measured at the time of their analysis, so the interlaboratory bias is not known; the values cannot therefore be directly compared to values presented here, nor can they be reliably converted into numerical ages using LOWESS 5, although this is done in the present study to provide tentative ages. Nevertheless, interlaboratory bias is unlikely to be more than 0.000040 (MCARTHUR1994), equivalent in the early Neogene to an age range of around 0.7 Ma, so these ages, although approximate, remain indicative and are accepted here. More problematically is the fact that the Sr-isotope ratios, for the most part, have large uncertainties (Table 1) which result in high uncertainties on derived age. . Nevertheless, as 87Sr/86Sr increases at a high rtae per myrs through the lower and middle Miocene (*sensu lato*) , the large uncertainties in $^{87}Sr/^{86}Sr$ introduce an age uncertainty of no more than 3.6 Ma(Table 1). Finally, the ages in BELÚCIO & TÁVORA (2001) were derived using an early Sr-isotope calibration (DEPAOLO & INGRAM 1985) rather than one of the more up-to-date calibrations available in 2001. Here we use the more recent calibration of MCARTHUR et al. (2012). Note that the ages of BELÚCIO & TÁVORA (2001) could not be adjusted for interlaboratory bias, so they are likely to be systematically in error by up to a putative 0.7 Ma.

BELÚCIO & TÁVORA (2001) attribute the differences between results from de Ilha de Fortaleza + Atalaia and B 17 to differences in sample preaparation, , the first two being cleaned by mechanical methods and the B 17 by acetic acid. Nevertheless, 4 of the 5 values gave numerical ages similar to those presented in this paper. The outlier may be an erratic rather than an altered sample, as alteration tends to decrease $^{87}Sr/^{86}Sr$ in samples from South America (see SCASSO et al. 2001, DEL RÍO et al. 2013), owing to the influence of a volcanic (mantle) component in the sediments that was derived from the high Andes volcanic chain.

The Burdigalian ages of 16.0 to 17.3 Ma indicated by our Sr-isotope stratigraphy agree with the biostratigraphic ages based on foraminifera and palynomorphs. The ages improves the stratigraphic resolution and constrains the age of the upper, thickest, part of the Pirabas Formation to the youngest part of the Burdigalian (20.44 to 15.97 Ma ;COHEN et al., 2013) rather than to the older part as stated , for example in AGUILERA et al. (2014). These results are biogeographically significant because since the first descriptions, the fauna has been related to other faunas from the Northern Hemisphere, particularly with those from the Caribbean and the southwestern coast of North America (e.g. MAURY 1925, WOODRING 1966, FERREIRA 1980). Several of these Caribbean and North American (?) faunas have been dated by Sr-istope stratigraphy. One of the units most frequently mentioned as correlative to the Pirabas Formation is the Chipola Formation (Florida). Dating by strontium isotope stratigraphy (BRYANT et al. 1992-, -) gave an estimated age of 18.3 – 18.9 Ma for the upper part of the Chipola Fm of northwestern Florida (17.5 to 18.3 Ma recalculated to NIST987 0.710248 and the LOWESS 5 calibration of McArthur et al. 2012). These recalculated ages are also Burdigalian but are slightly older than our ages for parts of the Pirabas Fm..

MORENO et al. (2015) and HENDY et al. (2015) presented $^{87}Sr/^{86}Sr$ ages from 17.45 to 17.51 Ma (Burdigalian) for the Jimol Fm. (Northern Colombia). The value for NIST987 was given only as 0.71024 (five significant figures) but independent evidence suggests that a value of 0.710246 might apply. Recalculated here to 0.710248 and LOWESS 5, these ages are between 16.8 ± 0.3 Ma at the top of the Jimol Fm and 17.3 ± 0.3 Ma at 60 m below the top. These ages are within the same within uncertainty as those presented here for the Pirabas Fm.

In Venezuela, ages obtained from biostratigraphy (planktonic foraminifera and calcareous nannoplankton) and Sr-isotope stratigraphy (GRIFFITHS et al. 2013) are coincident in assigning a Burdigalian age to the Cantaure Formation, with the latter method indicating an age range between 16.3 and 16.6 Ma (16.4 ± 0.2 and 16.6 ± 0.2 Ma converted to LOWESS5). The Culebra Formation in Panamá was also dated by strontium isotope stratigraphy by KIRBY et al. (2008), whose ages are 23.07-20.62 Ma (20.7 ± 0.5 recalculated here) for the basal and middle part of the unit, and 19.83 -19.12 (18.8 ± 0,2 recalculated here) for the upper part Therefore, this upper part is Burdigalian in age. Based on the new age results, it is now possible to compare the fauna of the Pirabas Formation with its temporal relatives in a more precise time frame, with the consequent improvement of biogeographical hypotheses.

Conclusions

The age range of 16.0 to 17.3 Ma for the studied sections and, by extension, of the outcropping part of the Pirabas Formation from northern Brazil (i.e. the upper and thicker portion of the unit) is constrained to the youngest part of the Burdigalian ., based on the $^{87}Sr/^{86}Sr$ rates obtained from *Chlamys* shells from three different localities. These datings refine previous age assignments obtained by biostratigraphy, and together with others recognized for different units of the "Neogene Tropical America", will allow for a more accurate history of faunistic changes related to the uplift of the isthmus of Panamá.

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Table 1. $^{87}Sr/^{86}Sr$ ages obtained in this work and from Belúcio & Távora (2001). During the period of measurement for this study, the long-term 2 s.d. of measurement for NIST987 was 0.000 009.

Locality	**Sample ID**	**Species**	$^{87}Sr/^{86}Sr$	±		**Age**		**Stage**
					Min	**Mean**	**Max**	
This Work								
Capanema, quarry B-11	Arg B-11	*C. capanemensis*	0.708 641	0.000 008	16.7	17.2	17.7	Burdigalian
Capanema, quarry B-5	Arg B-5	*C. latiaurata*	0.708 669	0.000 007	16.3	16.8	17.3	Burdigalian
Ilha de Fortaleza	Arg I de F	*C. thalera*	0.708 721	0.000 007	15.5	16.0	16.5	Burdigalian
Standard	NIST987		0.710 248	0.000 009				
Belúcio and Távora (2001)								
Bed B-17			0.708 506	0.000 058	18.1	18.8	19.6	
Bed B-17			0.708 453	0.000 199	17.0	19.5	23.1	
Atalaia			0.708 900	0.000 040	7.5	9.5	10.9	
Atalaia			0.708 669	0.000 065	15.9	16.8	17.6	
Ilha de Fortaleza			0.708 671	0.000 025	16.4	16.8	17.1	
No standard data given								

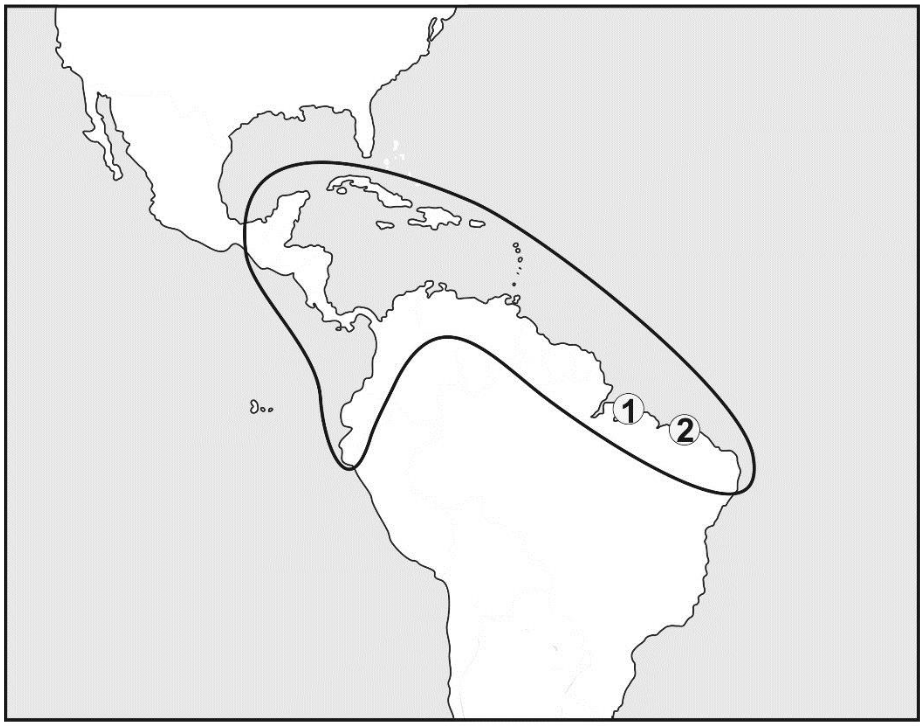

Figure 1. Schematic map of central America. The outline of the Baitoan or Miocene Caribbean Province, according to Woodring (1971, 1974), Petuch 1982, 1988, 2003) and Vermeij (2005) is indicated by a thick black line. 1. Location of the rich fossiliferous assemblages of the Pirabas Formation. 2. Southern limit of the fossiliferous assemblages (impoverished) (Ferreira 1970, Távora et al. 2010). No marine Miocene fossils are found further south.

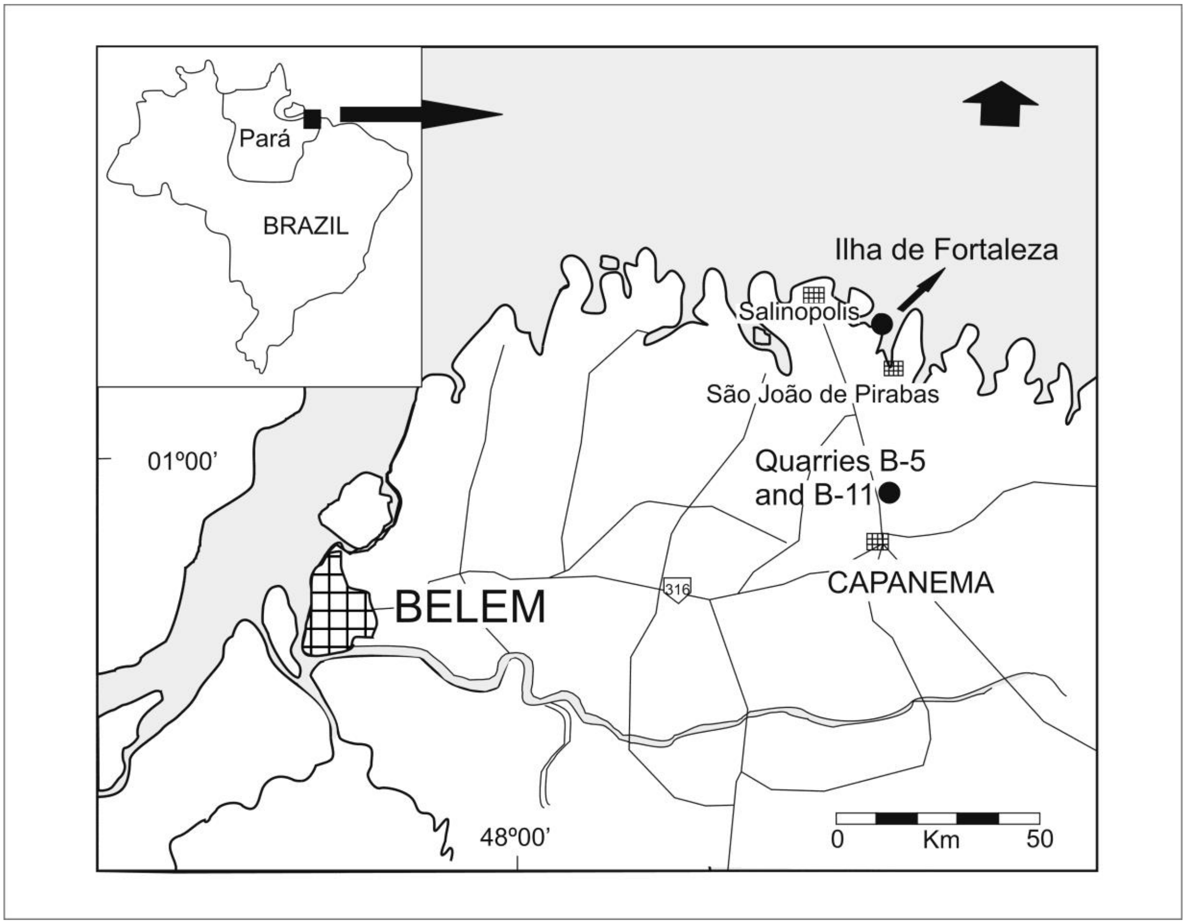

Figure. 2. Geographic positions of localities mentioned in the text (black circles).

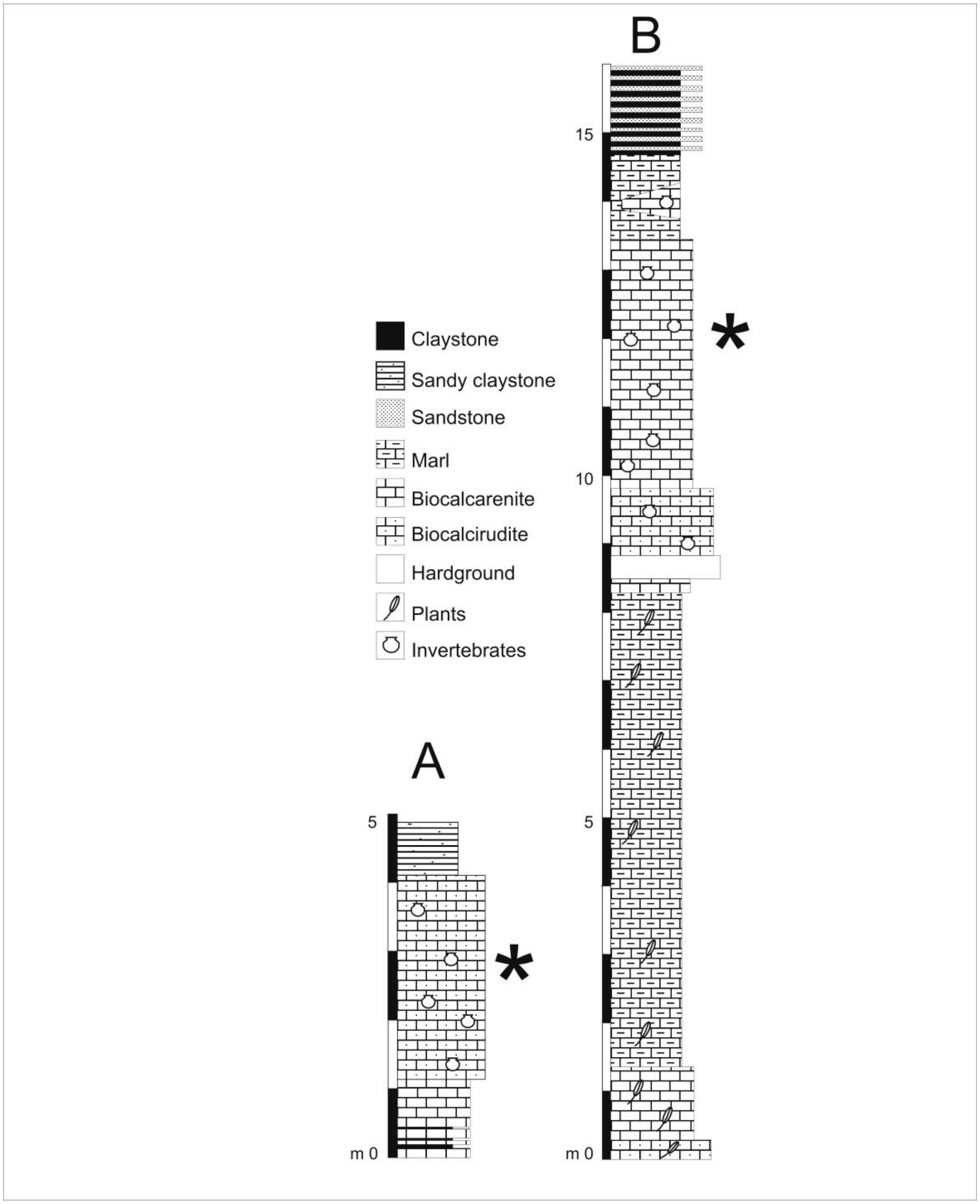

Figure 3. Stratigraphic sections of Ilha de Fortaleza (A) and Quarry B5 (B) (modified from GOES et al. 1990). The fossils used for the Sr analyses come from the beds indicated by asterisks.