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Characterization of Nd Radiogenic Isotope Signatures in Sediments From the Southwestern Atlantic Margin

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Based on radiogenic isotope systems of neodymium [Epsilon Neodymium-$\varepsilon_{Nd(0)}$, $^{143}Nd/^{144}Nd$, $^{147}Sm/^{144}Nd$, and Sm-Nd Depleted Mantle Model ages-T_{DM}] from current and previous data of continental rocks and associated sediments, this work provides the provenance of Holocene sediments from the Southwestern Atlantic Margin. The isotopic variability reported along the cores 7616 and 7620 are related to paleoceanographic and paleoclimatic changes. Further, we display the first Nd radiogenic isotope system distribution map of the study area. The map is the result of the principal component and clustering analyses of data compiled from the Ribeira belt, Luís Alves craton, and Paraná basin rocks. Differences in Nd isotopic signatures allowed the distinction between the sediment sources of the cores. The Core 7616 exhibits $\varepsilon_{Nd(0)}$ average value of -10.5, $T_{DM} = 1.4$ Ga and $^{143}Nd/^{144}Nd = 0.512103$, while the Core 7620 shows $\varepsilon_{Nd(0)}$ average value of -17.5, $T_{DM} = 1.8$ Ga and $^{143}Nd/^{144}Nd = 0.51177$. The relative more radiogenic Nd ratios from the Core 7616 are associated to the contribution of sediments from the Paraná basin, nevertheless less radiogenic values are observed along the Core 7616 between ~2,000 and 1,800 cal. yr BP. We have attributed the lower Nd ratios, recorded during this interval, to the decreasing influence from the Rio de la Plata estuary in the Core 7616. Remarkable less radiogenic Nd ratios are also recorded in the Core 7620 during the late Holocene. The intensification of the NE winds and the South America Summer Monsoon (SASM) enhanced the terrigenous input from the Paraíba do Sul River and southwards sediment transport by the Brazil Current (BC), providing higher contribution of less radiogenic metasediments from the Paraíba do Sul geotectonic domain to the Core 7620.

Keywords: radiogenic isotopes, provenance, Epsilon Neodymium-$\varepsilon_{Nd(0)}$, Southwestern Atlantic margin, Paraná basin, Ribeira belt

INTRODUCTION

An efficient way to reconstruct sediment provenance is the use of radiogenic isotope systems (e.g., Allégre et al., 1996; Wealdeab et al., 2002; Cruces et al., 2004; Fagel et al., 2014) because most of them are not affected by significant fractionation, when submitted by environmental processes (Dickin, 1995; Banner, 2004). Neodymium isotopes are recognized as excellent tracers of sediment origin, providing the characterization of the detrital material in relation to their sources rocks, through the establishment of radiogenic isotope systems [e.g., $^{143}Nd/^{144}Nd$, $\varepsilon_{Nd(0)}$ values and Sm-Nd model ages] (e.g., O'nions et al., 1983; Nelson and Depaolo, 1988; Nascimento et al., 2003; Roig et al., 2005; de Mahiques et al., 2008; Bazhenova et al., 2017; Theiling et al., 2017).

Metasediments from the Ribeira belt have been considered as relevant sources of sediments to the SE Brazilian shelf (e.g., Suguio et al., 1972; Rocha et al., 1975; Gyllencreutz et al., 2010). Nevertheless, the influence of basalts from the Paraná basin [i.e., contribution of low TiO_2 tholeiitic basalts from the Paraná Magmatic Province (PMP), Marques et al., 1999] on the S/SE Brazilian shelf has been reported since the seventies (e.g., Carraro et al., 1974; Miliman, 1975; Rocha et al., 1975), and related to the sediment transport by the Rio de La Plata plume (e.g., de Mahiques et al., 2008; Nagai et al., 2014).

In this study, rocks from the Paraná basin, and Precambrian terrains of the Ribeira belt and the Luís Alves craton (**Figure 1**) are evaluated as possible sources of the SW Atlantic margin. The strengthened of the SASM (Cruz et al., 2005) provides an efficient sediment transport from the hydrographic systems to the shelf. This terrigenous input has been associated with the relative high proportion of detrital material deposited in the estuary of Rio de la Plata (Chiessi et al., 2010).

During austral winter, the distribution of sediments along the South Atlantic coast is affected by the expansion of the Plata plume, which is transported northwards by the Brazilian Coastal Current (de Souza and Robinson, 2004) (**Figure 1**). These hydrodynamic configuration is enhanced with the intensification of the southerly winds (e.g., Möller et al., 2008), enabling the transport of material previously deposited in the Rio de La Plata estuary under the influence of the increased SASM. On the other hand, during the austral summer, the NE winds are associated to

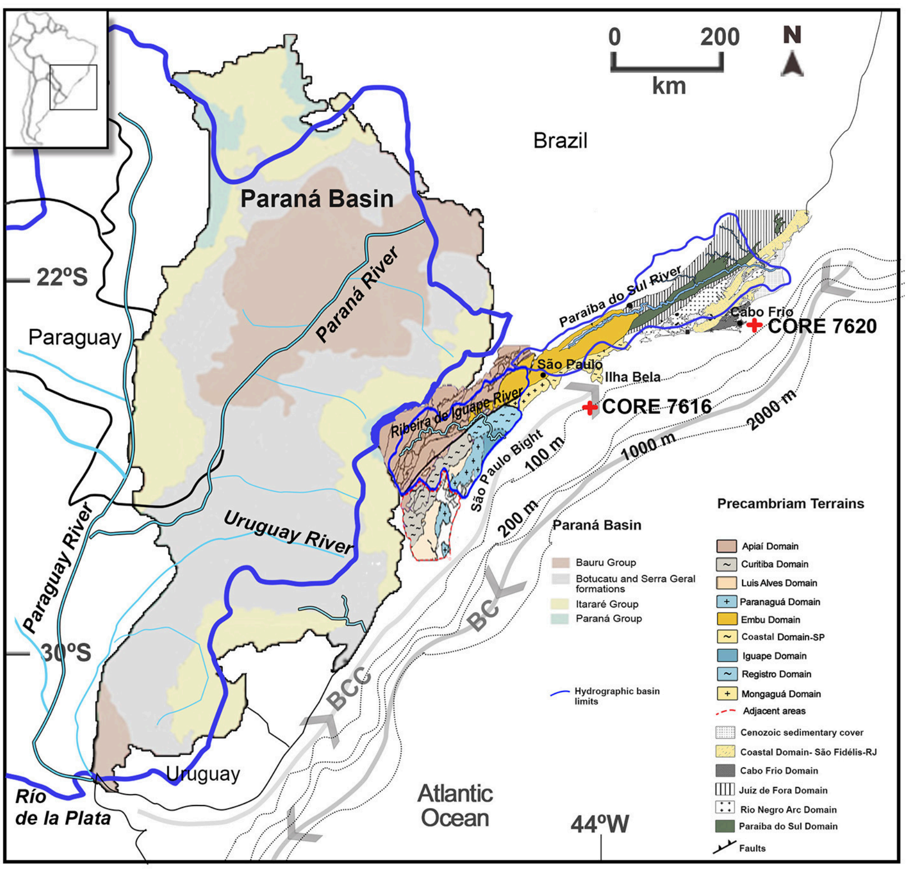

FIGURE 1 | Regional geotectonic context of the area investigated as possible sources for cores 7620 and 7616 (red marks), showing Paraíba do Sul, Río de la Plata, and Ribeira de Iguape River basin limits (blue lines). Gray lines show major surface current directions in the study area: BC (Brazil Current) and BCC (Brazilian Coastal Current). Compiled from Siga (1995), Milani et al. (1996), Campanha and Sadowski (1999), Carlos Pedrosa-Soares et al. (1998), Marques et al. (1999), Milani and Thomaz Filho (2000), Dias Neto (2001), Heilbron et al. (2004), Passarelli et al. (2004), and Valladares et al. (2008).

the southwards sediment transport along the east coast of South America by the BC flow (**Figure 1**).

We have characterized the Nd radiogenic isotope system of the sediments from cores 7616 and 7620, and compared with previously reported Nd isotopic data from the basement rocks of the Brazilian shield, sedimentary and volcanic rocks of the Paraná basin, and associated sediments in order to assess the source of sediments from the east coast of South America.

The deposition of sediments from the Rio de la Plata estuary in the Core 7616, and coarser sediments in the Core 7620 from the Rio Paraíba do Sul have been indicated by previous work (Gyllencreutz et al., 2010), based on the grain size analysis. The aim of the present study is to provide Nd isotopic signatures from the cores 7616 and 7620 in order to refine previous reported paleoceanographic interpretations, pointing out the paleoclimatic events and the associated hydrodynamic circulation patterns prevailing over the SW Atlantic margin during the late Holocene.

STUDY AREA

Since river basins and oceanographic setting play a crucial role in the distribution and transport of sediments on the SW Atlantic Margin, our first attempt at understanding the sediment provenance of the cores 7616 and 7620 was to determine the geotectonic domains drained by river systems that could contribute with sediment load to the shelf, and investigate the paleoceanographic circulation off the continental area. We have considered Paraíba do Sul (PS), Paraná-la Plata (PP), and Ribeira de Iguape (RI) as river systems with potential weathering flux, draining rocks from the Paraná basin and the Ribeira belt, which is inserted in the Precambrian terrains (**Figure 1**).

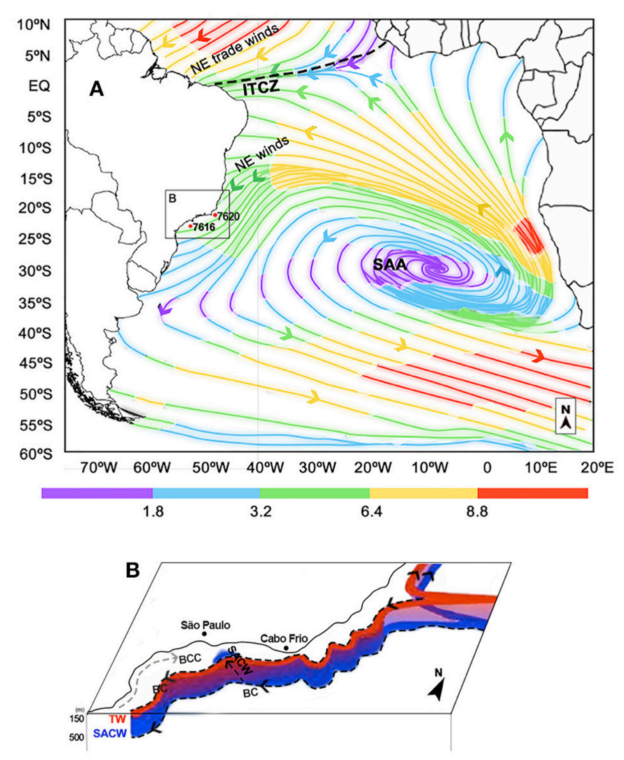

FIGURE 2 | (A) Wind field average in 1,000 hPa, for summer months (DJF) obtaining from daily National Centers for Environmental Prediction (NCEP) data during a period from 1978 to 1997: colored lines representing wind current speed (m/s), modified after Bastos and Ferreira (2008). **(B)** Zoom of currents and water masses prevailing in the study area, showing the displacement of the South Atlantic Coastal Water (SACW) and the Tropical Water (TW) transport by Brazil Current (BC); water masses are simplified from Calado (2006).

Continental Setting

Geology, Hydrography, and Morphology

The geological setting of the Ribeira belt is divided in 13 geotectonic domains: Embú, Paraíba do Sul, Juíz de Fora, Rio Negro Magmatic Arc, Cabo Frio, Apiaí, Curitiba, Paranaguá, Iguape, Registro, Mongaguá-Itanhaém, and Coastal, which includes metasediments of the Coastal domains of São Paulo and São Fidélis (**Figure 1**) (Siga, 1995; Campanha and Sadowski, 1999; Heilbron et al., 2004; Valladares et al., 2008; Bento dos Santos et al., 2011; Dias Neto, 2001; Passarelli et al., 2004). The Paraná basin, located in the SW portion of the South America (**Figure 1**), is characterized as an intracratonic basin constituted by sedimentary sequences (e.g., Milani et al., 1996) and volcanic rocks from the PMP (Marques et al., 1999). Some geotectonic domains occur near the coastline and therefore are considered here as potential sources of sediments (e.g., medium to high grade metamorphic terrains from the Luiz Alves craton, Registro, Iguape, Mongaguá-Itanhaém, and Coastal domains).

The sedimentary rocks of the Paraná basin are the result of erosion of the Serra do Mar that is a 1.500 km ridge, which has provided eroded material from the Upper Continental Crust (UCC) to the continental basin (e.g., the Bauru Group from the Paraná basin) since the late Cretaceous (Almeida and Carneiro, 1998). Gallagher et al. (1994) suggested that the sedimentation related to the uplift of the Serra do Mar ridge has also provided thick debris from the Ribeira belt, as well as a high proportion of material from coastal basalts of the Serra Geral formation to the ocean and to the continental basin. Holocene tectonism is active in the area (e.g., the Taubaté tectonic basin, Riccomini et al., 2004) and may have been still providing detrital material from the basement to the studied area. Thus, we can consider that large proportion of sediments eroded from the Paraná basin is a mixture between mantle rocks (e.g., the basalts from the Serra Geral formation) and the UCC rocks (e.g., metasediments from the Ribeira belt).

To the north of Iha Bela (24°30′S) (**Figure 1**), the basement rocks of the Ribeira belt deep close to the coastline, compared to the sector to the south of the Island, where a greater distance from the ridge to the ocean is observed. The hydrographic network of the PS is the largest drainage basin that flows into the ocean to the north of the Core 7620 (**Figure 1**). It has an outflow of ∼1.118 m^3/s.

The PP hydrographic systems, including the Paraná, Uruguay and La Plata rivers (**Figure 1**), convey material eroded from the basalts (e.g., the Serra Geral formation) and sedimentary rocks of the Paraná basin adding sediment load to the Rio de La Plata estuary (Pasquini and Depetris, 2007). PP hydrographic system is the second largest drainage basin area in the South America, with an outflow of around 23.000 m^3/s and 57 million m^3/year of sediment delivered into the South the Atlantic ocean. This system accounts for about 80% of its total discharge to the SW Atlantic Ocean (Pasquini and Depetris, 2007) and contributes with almost 60% water discharge to the Rio de La Plata (López Laborde, 1997).

The main morphological feature of the RI is the Ribeira valley. It has developed inside the Serra do Mar ridge facing to the sea where metasediments of the Ribeira belt have been subjected to intense erosion since the late Cretaceous (Gallagher et al., 1994; Almeida and Carneiro, 1998; Castanheira, 2006). The RI river system constitutes the largest group of rivers flowing directly to the ocean off the São Paulo state (**Figure 1**), and it may influence the sedimentation of the Core 7616.

Oceanographic and Climatic Setting

The studied cores are located in a sector of the SW Atlantic margin called the São Paulo Bight (Zembruski, 1979) (**Figure 1**). The geomorphological differentiation is one of the factors that conditioned the sediment distribution over the shelf. The sedimentation over the São Paulo bight presents a marked differentiation to the north and south of Ilha Bela. This Island has been considered as a mark that distinguishes sedimentary patterns prevailing on the inner shelf off SE Brazil (Rocha et al., 1975; Kowsmann and Costa, 1979; de Mahiques et al., 1999, 2004). According to de Mahiques et al. (1999), to the south of the Island, the deposition of muddy sediments and terrigenous organic matter are observed oceanward. To the north of Ilha Bela, larger amounts of fine sediments and organic matter are deposited on the inner shelf.

The water masses dynamics prevailing on the SW Atlantic margin have been strongly influenced by the wind regime (e.g., de Mahiques et al., 2002). The southwards migration of the Intertropical Convergence Zone (ITCZ) (e.g., Haug et al., 2001), the configuration of the South Atlantic anticyclone (SAA), the intensification on the NE wind system (**Figure 2A**), as well as the strengthening of the SASM have influenced continental and oceanic processes over the South America and the South Atlantic Ocean, during the late Holocene. The SAA, a system of high pressure center located around the latitude of 30°S in the South Atlantic Ocean, differently influences the climate of Brazil. During the austral summer, the SAA displaces slightly southeastwards assuming a more oriented anticyclonic circulation shape (e.g., Bastos and Ferreira, 2008). This configuration enhances the moisture on the coast off Cabo Frio and throughout the southeast Brazilian coast, whereas the SASM, facilitated by the NE trade winds (**Figure 2A**), provides higher moisture penetration in the Amazon basin. These main climate systems can indirectly affect the availability of sediments in river mouths and their distribution on continental shelves. During the austral summer, the strengthening of the NE winds and configuration of the SAA may facilitate the southward sediment transport by the BC. The BC is part of the South Atlantic subtropical meander, integrating a western boundary current system that takes at least 3 km from the water column. On the inner shelf, the action of the BC water masses, the Tropical Water (TW) and the South Atlantic Central Water (SACW) (**Figure 2B**), play the major role over the sedimentation (de Castro Filho et al., 1987). The displacement of the less dense Costal Water (CW), during the rainy seasons, transports terrigenous sediments and organic matter to the south of Ilha

TABLE 1 | Nd systematics isotopic data of the Core 7616.

Depth (cm)	Cal. Age Yr. (BP)	$\varepsilon_{Nd(0)}$	$^{143}Nd/^{144}Nd$	Error[a]	T_{DM}(Ga)	Error (2σ)	$^{147}Sm/^{144}Nd$	Error[a]
1	925	−10.7	0.512078	0.000011	–	–	–	–
3	964	−10.4	0.512075	0.000007	–	–	–	–
9	1,079	−10.6	0.512094	0.000012	1.48	0.092	0.116	0.006
27	1,423	−10.6	0.512093	0.000009	–	–	–	–
49	1,832	−11.0	0.512076	0.000004	–	–	–	–
57	1,976	−10.3	0.512109	0.000010	1.43	0.086	0.115	0.006
65	2,118	−10.1	0.512117	0.000007	1.46	0.090	0.117	0.006
87	2,496	−10.4	0.512105	0.000007	–	–	–	–
109	2,864	−10.7	0.512091	0.000008	–	–	–	–
111	2,897	−9.8	0.512134	0.000011	1.41	0.087	0.116	0.006
113	2,930	−10.2	0.512113	0.000007	–	–	–	–
123	3,097	−10.3	0.512109	0.000008	–	–	–	–
145	3,473	−10.4	0.512105	0.000004	–	–	–	–
175	4,026	−10.3	0.512106	0.000011	1.46	0.092	0.116	0.006
199	4,511	−10.8	0.512085	0.000008	–	–	–	–
223	5,037	−10.2	0.512113	0.000010	1.42	0.084	0.114	0.006
245	5,548	−10.5	0.512100	0.000006	–	–	–	–
271	6,176	−9.9	0.512125	0.000010	1.38	0.081	0.113	0.006
283	6,472	−10.6	0.512095	0.000006	–	–	–	–
299	6,869	−9.6	0.512143	0.000008	1.32	0.072	0.110	0.006

[a]*Error to calculate $^{147}Sm/^{144}Nd$ ratios: Sm = 4.44% e para Nd = 3.3%.T_{DM} referred to the model age Sm-Nd Depleted Mantle (T_{DM}), de Paolo, 1981.*

Bela toward the deeper parts of the shelf (de Mahiques et al., 1999, 2004). The cold and dense SACW moves toward the coast during the austral summer, generating a seasonal upwelling (de Mahiques et al., 1999). According to de Mahiques et al. (2005), the increase of the upwelling process off Cabo Frio is related to the intensification of the BC. On the other hand, the BCC flows to the north of the east coast of South America (**Figure 1**). The BCC transports sediments from the Rio de La Plata estuary to lower latitudes. This transport is facilitated during the austral winter, when the Rio de La Plata plume expansion occurs, and the SW winds are prevailing (e.g., Piola et al., 2000; Möller et al., 2008).

MATERIALS AND METHODS

Cores 7616 and 7620 were collected on the SE Brazilian shelf, on board the R.V. *Prof. W. Besnard*, in 2005. The Core 7620 was retrieved in the shelf off Cabo Frio at 22°94′S and 41°98′W, and water depth of 44 m. The Core 7616 was collected off Santos city, in the São Paulo state, at the latitude 25°5.88′S and longitude 45°38.64′W, and water depth of 100 m. The coring locations are shown in **Figure 1**.

The sediment samples were analyzed for Nd radiogenic isotopes. We avoid the use of strong acids in the Sm-Nd isotope system since the use of HCl (1N) (Revel et al., 1996) induces significant REE removal (Clauer et al., 1993), and dramatically alters ^{147}Sm /^{144}Nd and ^{143}Nd /^{144}Nd ratios (Innocent et al., 2000). Different procedures of acid attacks, detailed in Mantovanelli (2013), were tested to determine the optimal leaching sequence for our sediments. Thus, the samples passed through a partial extraction to remove bioclasts. According to our results on Nd isotopes, we followed the procedures described in Bayon et al. (2002). We used HOAc (10% vv) to attack 500 mg of each previously powdered bulk sediment samples, which remained in an ultrasonic bath for 4 h. The samples were dissolved with HF-HNO_3, and then passed through ion exchange columns (RE) and (Ln) to separate REE and Nd respectively, according to the Geochronological Research Center of São Paulo University (CPGeo- IGc-USP) analytical protocol. Nd isotopic analyses were conducted with a FINNIGAN MAT 262 mass spectrometer. Nd ratios were normalized to a ^{146}Nd/^{144}Nd = 0.7219 (de Paolo, 1981). The parameter $\varepsilon_{Nd(0)}$ corresponds to the current value ($t = 0$) and is calculated according to the equation: = {[(^{143}Nd/^{144}Nd)] m /0.512638] −1} * 104, where ^{143}Nd/^{144}Nd chondritc uniform reservoir (CHUR) = 0.512638 (Hamilton et al., 1983). The JNdi standard from January to July 2012 was run for the ^{143}Nd/^{144}Nd ratio with each batch of samples, resulting in the mean value of 0.512099 ± 0.000008. The analytical blanks during the analyses were about 0.03 ng.

The Rare Earth Elements (REE) concentrations were calculated by ICP-MS, and other trace elements by ICP-OES, for each sample in the Chemistry Laboratory of IGc-USP.

REE patterns for selected samples from the cores (values normalized according to Taylor and McLennan, 1995) (Supplementary Figures 1–3). The concentration of Samarium (Supplementary Table 1) was used to obtain ^{147}Sm/^{143}Nd ratios in order to calculate the model ages (T_{DM}) of the cores. The details of the analytical procedure used for ICP-MS are in Navarro et al. (2008) and ICP-OES are available in Janasi et al. (1997). The determination of the concentration of chemical elements was performed by mass spectrometry inductively-coupled plasma ICP-MS equipped with a quadrupole spectrometer, Perkin Elmer/Sciex model ELAN 6100DRC and *spectometer with minitorch* model ARL 3410ICP.

TABLE 2 | Nd systematics isotopic data of the Core 7620.

Depth (cm)	Cal. Age Yr (BP)	$\varepsilon_{Nd(0)}$	^{143}Nd/^{144}Nd	Error[a]	T_{DM}	Error	^{147}Sm/^{144}Nd	Error[a]
					(Ga)	(2σ)		
9	530	−17.5	0.511743	0.000008	–	–	–	–
23	775	−17.1	0.511759	0.000011	–	–	–	–
41	1,022	−17.0	0.511766	0.000001	1.82	0.093	0.107	0.006
77	1,579	−17.4	0.511746	0.000011	1.84	0.093	0.106	0.006
79	1,610	−16.8	0.511778	0.000008	–	–	–	–
113	2,165	−16.9	0.511774	0.000006	1.77	0.087	0.105	0.006
135	2,551	−17.0	0.511765	0.000007	–	–	–	–
155	2,922	−16.8	0.511776	0.000001	1.82	0.094	0.108	0.006
183	3,477	−17.0	0.511768	0.000006	–	–	–	–
215	4,165	−16.7	0.51178	0.000007	1.81	0.093	0.107	0.006
235	4,626	−16.6	0.511788	0.000008	–	–	–	–
253	5,060	−16.5	0.511794	0.000011	1.78	0.092	0.107	0.006
275	5,613	−16.1	0.511813	0.000007	–	–	–	–
297	6,186	−16.3	0.511804	0.000001	1.78	0.093	0.108	0.006
309	6,505	−16.3	0.511801	0.000009	–	–	–	–
323	6,881	−16.2	0.511809	0.000013	1.74	0.088	0.106	0.006

[a]*Error to calculate ^{147}Sm/^{144}Nd ratios: Sm = 4.44% e para Nd = 3.3%. T_{DM} referred to the model age Sm–Nd Depleted Mantle (T_{DM}), de Paolo, 1981.*

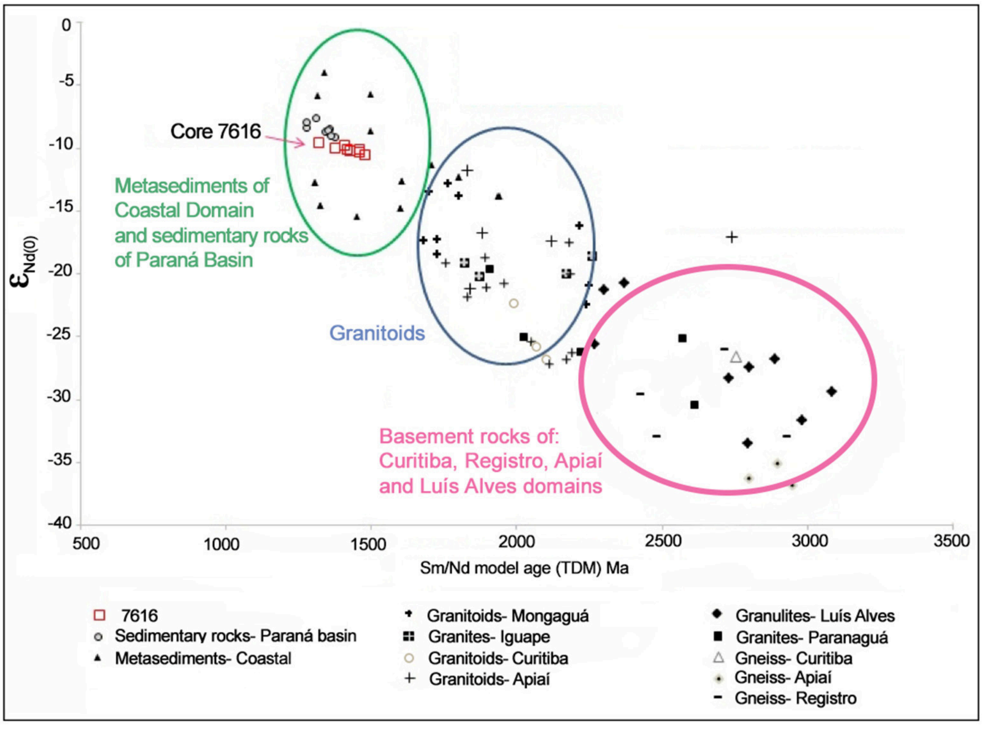

FIGURE 3 | Diagram showing $\varepsilon_{Nd(0)}$ values vs. Sm/Nd model ages (T_{DM}) of the Core 7616 and investigated source rocks (Ma).

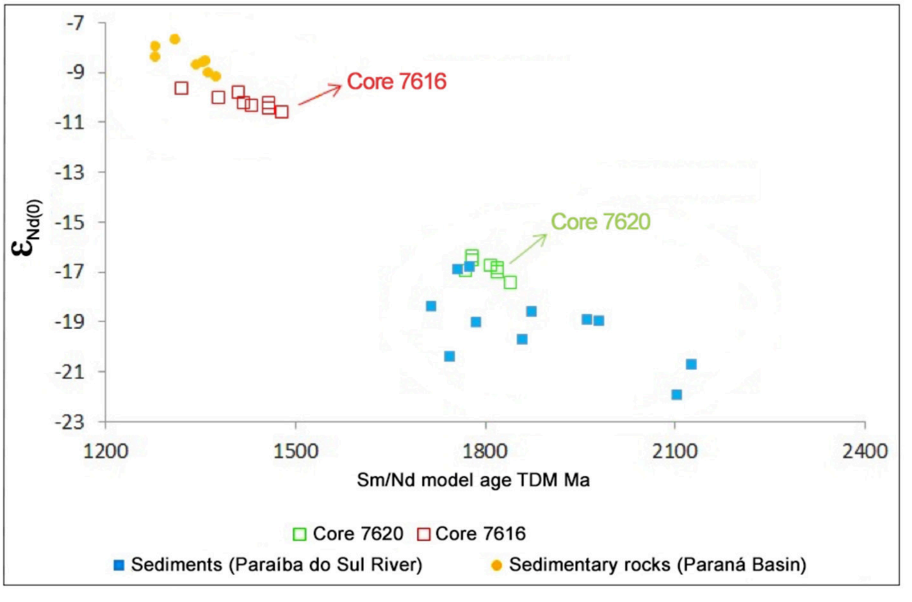

FIGURE 4 | Diagram of $\varepsilon_{Nd(0)}$ vs. Sm/Nd model age (T_{DM}) (Ma): showing the comparison between isotopic signatures of the Core 7616 and sedimentary rocks from the Paraná basin, and the Core 7620 and sediments from the Paraíba do Sul River.

We performed a cluster analysis using the $\varepsilon_{Nd(0)}$, $^{147}Sm/^{144}Nd$, $^{143}Nd/^{144}Nd$, and T_{DM} as parameters of sediment provenance, after obtaining the Principal Component Analysis (PCA) using the Past v.2.17 software (Hammer et al., 2001). The data fit the condition for a suitable PCA, showing normal distribution and correlation between Nd parameters with $r^2 > 0.96$. The cluster analysis of the samples was based on a quantitative similarity index (Euclidean). A neighbor joining clustering was performed with the scores resulted from the PCA of the normalized parameters. The first component (PC1) explains 77.7% of the total variance.

In order to characterize the provenance of the sediments from the cores, we present the first summarized data of Nd radiogenic isotope system from multiple sources: Do Carmo Fonseca (1994), Reis Neto (1994), Siga (1995), Campanha and Sadowski (1999), André et al. (2009), Ragatky et al. (2000), Tupinambá et al. (2012), Dias Neto (2001), Dos Prazeres Filho et al. (2003), Heilbron et al. (2004), Passarelli et al. (2004), Silva (2006), Junior et al. (2007), Valladares et al. (2008), Bento dos Santos et al. (2011), Mendes et al. (2011), and Dantas et al. (2017), as well as a Nd distribution map for the study area. The compilation has included isotopic data from marine and river sediments related to the evaluated continental rocks: (A) $\varepsilon_{Nd(0)}$ data of superficial sediments from the Rio de La Plata estuary and Argentinian shelf (Basile et al., 1997; de Mahiques et al., 2008); (B) Nd data associated with eroded rocks of Coastal Domain of the Ribeira belt; (C) Nd radiogenic isotope signatures of Paraíba do Sul River suspended load (Roig et al., 2005). The data of the compilation is available in the Supplementary Table 2 and in Mantovanelli (2013). The details of the model age from the cores 7616 and 7620, based on ^{14}C dating, are available in de Mahiques et al. (2011).

RESULTS AND DISCUSSION

Neodymium

The $^{147}Nd/^{143}Nd$ ratios of the Core 7616 vary between 0.51207 and 0.51214 with an average of 0.51210, $\varepsilon_{Nd(0)}$ values range from −11.0 to −9.6; the $^{147}Sm/^{144}Nd$ ratios are varying from 0.110 to 0.117 and the Sm-Nd model ages (T_{DM}) are around 1.4 Ga (**Table 1**). The $^{147}Nd/^{143}Nd$ ratios of the Core 7620 vary between 0.51174 and 0.51181 with an average of 0.51180; the values of $^{147}Sm/^{144}Nd$ range from 0.105 to 0.108; $\varepsilon_{Nd(0)}$ values vary from −17.5 to −16.1, exhibiting a significant decrease compared to the Core 7616 (**Table 2**).

In relation to the Core 7616, a relevant increase of 0.4 Ga in Sm-Nd model ages (T_{DM}) is observed in the Core 7620. Lower $\varepsilon_{Nd(0)}$ values and older Sm-Nd model ages (T_{DM}) show a particular contribution of UCC components in the Core 7620.

The diagram of $\varepsilon_{Nd(0)}$ values and T_{DM} displays a comparison among samples of the Core 7616, rocks from the southernmost part of the Ribeira belt, the Luís Alves craton and sedimentary rocks of the Paraná basin (**Figure 3**). The diagram shows that sedimentary rocks of the Paraná basin, metasediments from the Coastal Domain and the Core 7616 present similar Nd radiogenic values. The granitoids present an intermediate aspect, while the metamorphic rocks of the adjacent Luís Alves craton,

TABLE 3 | Nd isotope systematic averages of potential sources.

Lithology-domain	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	Error	T_{DM} (Ga)	$\varepsilon_{Nd(0)}$	References
Metasediments-Apiaí	0.1623	0.512307	0.000013	2.1	−6.5	Reis Neto, 1994
Gneiss-Apiaí	0.1085	0.511554	0.000013	2.1	−21.1	Reis Neto, 1994
Granites-Apiaí	0.1008	0.511577	0.000012	2.0	−20.7	Dos Prazeres Filho et al., 2003
Granites-Curitiba*	0.0911	0.511356	0.000021	2.1	−25.0	Siga, 1995; Junior et al., 2007
Gneiss-Migmatites-Curitiba*	0.1180	0.511322	0.000021	2.7	−25.7	Siga, 1995; Junior et al., 2007
Granitoids-Setuva*	0.0929	0.510787	0.000021	2.9	−36.1	Siga, 1995; Junior et al., 2007
Granites-Paranaguá*	0.0995	0.511337	0.000021	2.3	−25.4	Siga, 1995; Junior et al., 2007
Gneiss-Registro	0.1039	0.511146	0.000008	2.6	−30.4	Passarelli et al., 2004
Granitoids-Mongaguá/Itanhaém	0.1155	0.511789	0.000007	1.9	−17.0	Passarelli et al., 2004
Granites-Iguape	0.1132	0.511661	0.000014	2.0	−19.5	Passarelli et al., 2004
Suíte granítica- Serra do Mar	0.1295	0.511468	0.000008	2.4	−24.5	Passarelli et al., 2004
Metasediments-Costeiro-SP	0.1242	0.512115	0.000014	1.5	−10.9	Dias Neto, 2001
Granites/migmatites/metasediments-Embú	0.0901	0.511578		1.8	−17.5	Dantas et al., 2017
Gabroids-Arco Rio Negro	0.1392	0.512248	0.000040	1.6	−7.7	Tupinambá et al., 2012
Metasediments-Cabo Frio	0.1212	0.512131		1.5	−9.5	da Silva Schmitt et al., 2004
Orthogneiss- Cabo Frio	0.1239	0.510915	0.000027	2.5	−33.9	Do Carmo Fonseca, 1994
Supracrustals-Coastal-São Fidélis-RJ	0.1330	0.512087	0.000052	1.6	−10.8	Mendes et al., 2011
Granites-Coastal-São Fidélis-RJ*	0.0760	0.511679	0.000003	1.8	−18.7	Mendes et al., 2011
Orthogneiss-Juíz de Fora	0.0977	0.511225	0.000012	2.4	−27.4	André et al., 2009
Metasediments-Juíz de Fora	0.1118	0.511566	0.000018	2.3	−21.0	Ragatky et al., 2000
Metasediments-Paraíba do Sul	0.1035	0.511635	0.000016	1.9	−19.6	Ragatky et al., 2000
Sedimentary rocks-Paraná Basin	0.1953	0.512276	0.000020	1.2	−7.1	Silva, 2006
Core 7616	0.1146	0.512118	0.000007	1.4	−10.1	Present work
Core 7620	0.1068	0.511777	0.000008	1.8	−16.8	Present work

*$^{143}Nd/^{144}Nd$ reported were normalized to $^{146}Nd/^{144}Nd = 0.72190$. $\varepsilon_{Nd(0)}$ calculated relative to CHUR(0) = 0.512638. $^{143}Nd/^{144}Nd$ analytical errors are up to 0.00004. T_{DM} referred to the model age Sm-Nd Depleted Mantle (de Paolo, 1981), and * (DePaolo et al., 1991), and present inaccuracies of the order of 0.1 Ga.*

and the Apiaí Domain from the Ribeira belt exhibit a distinct behavior (**Figure 3**). On the other hand, Nd isotopic signatures of sediments from the PS river and the Core 7620 show similar composition values (**Figure 4**), pointing out the metasediments from the Paraíba do Sul and correlated Embú domains [$\varepsilon_{Nd(0)}$ average of about −16 and T_{DM} ~1.7 Ga, Ragatky et al., 2000] as potential source rocks of the Core 7620 [$\varepsilon_{Nd(0)}$ average of about −17 and T_{DM} ~1.8].

Multivariate Analysis: Nd Systematic

The results obtained so far are further analyzed with the aid of principal components and cluster analyses based on the values from the compilation of Nd isotopic signatures of Precambrian metamorphic terrains of the Ribeira belt, Luís Alves craton, sedimentary rocks of the Paraná basin and sediments from the cores 7616 and 7620 (**Figure 1** and Supplementary Table 2). For simplicity of comparison, we calculated the average for all samples from each lithology of the distinct domains (**Table 3**). The dendogram distinguishes three principal groups with similar isotopic characteristics (**Figure 5**).

The Core 7616 are in Group 1 (**Figure 5**), corroborating the Nd systematic diagram previously explained (**Figure 3**), where the isotopic signatures from the Core 7616, metasediments of the Coastal domains and sedimentary rocks of the Paraná basin are relatively similar. The range of $\varepsilon_{Nd(0)}$ values of Group 1 (from −10.9 to −6.0) prevents the distinction between sedimentary rocks from the Paraná basin and the rocks from the Coastal Domain. Rocks and sediments with mantle components have higher $\varepsilon_{Nd(0)}$ than −10.9, and therefore we added the Subgroup 1A with $\varepsilon_{Nd(0)}$ values ranging from −7.7 to −6.0.

Metasediments of the Ribeira belt from the Apiaí Domain have very old T_{DM} ages (2.1 Ga) to be considered source of the Core 7616, although they are in Group 1 (**Figure 5**), probably because of the low $\varepsilon_{Nd(0)}$ parameter (−6.5), which has relevant importance on the PCA. The mantle components from the Rio Negro Domain allowed its isotopic signatures to be in Group 1. However, this domain is situated out of the fluvial system and coastline areas that could affect the sedimentation in the Core 7616.

The Core 7620 is in Group 2 (**Figure 5**), pointing out the friable metasediments of the Paraíba do Sul and correlated Embú domains as its main source, as indicated from the Nd diagram previously showed (**Figure 4**). It is unlikely that granites and granitoids from Group 2 have contributed to large amounts of sediments to the shelf due to their resistance under weathering conditions, as reported by Castanheira (2006).

It is very worthwhile to observe that the Cabo Frio orthogneiss and the Setuva granitoids although they are located in different places (**Figure 1**) they are in Group 3 probably because they belong to old basement rocks. On the other hand, metasediments from Cabo Frio are in Group 1 together with metasediments from Coastal domains in the São Paulo state (**Figure 1**).

Finally, based on multivariate analysis, we present the neodymium isotope distribution map of the investigated source rocks (**Figure 6**).

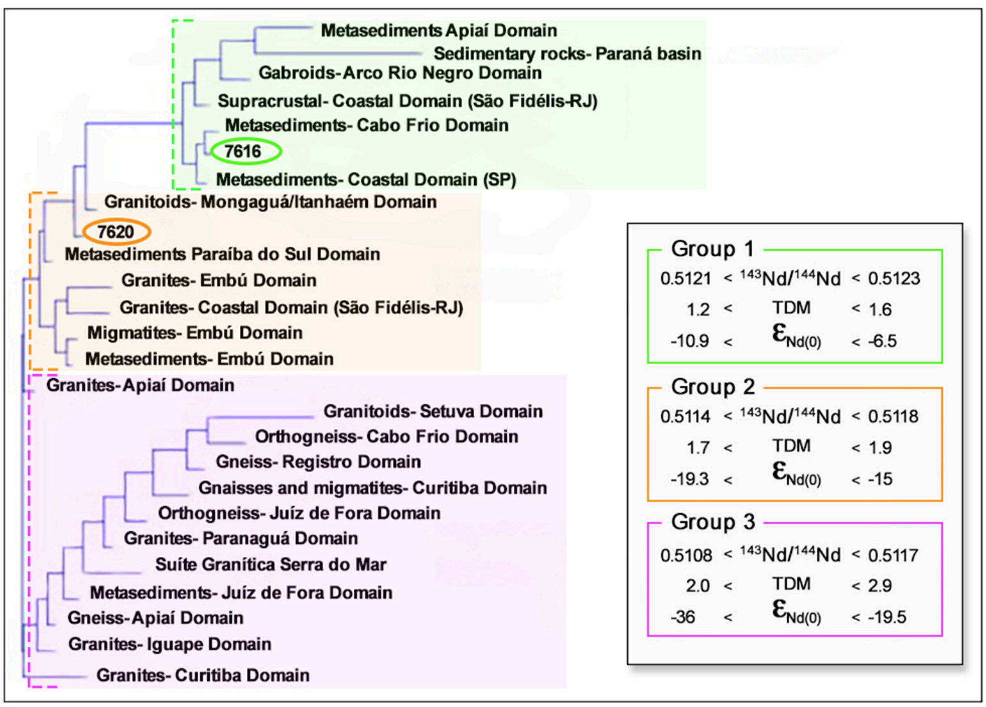

FIGURE 5 | Dendogram elaborated from cluster after PCA analyses on Nd isotopic data, showing three major groups: Group 1 with $^{143}Nd/^{144}Nd$ from 0.5121 to 0.5123, T_{DM} from 1.2 to 1.6 and $\varepsilon_{Nd(0)}$ from −10.9 to −6.5; Group 2 with $^{143}Nd/^{144}Nd$ from 0.5114 to 0.5118, T_{DM} from 1.7 to 1.9 and $\varepsilon_{Nd(0)}$ from −19.3 to −15; Group 3 with $^{143}Nd/^{144}Nd$ from 0.5108 to 0.5117, T_{DM} from 2.0 to 2.9 and $\varepsilon_{Nd(0)}$ from −36 to −19.5.

How Are the Mantle Components Incorporated in Sediments From the SE Brazilian Shelf?

The Nd isotopic signatures of sedimentary rocks of the Paraná basin and the Rio de La Plata sediments coincide with those of the Core 7616 (**Figures 4**, **7**, respectively) The question is whether the mantle component present in the Core 7616 is from local or distal source contribution.

Since Nd isotopic variation is registered along the Core 7616, we have considered an influence of alternating higher/lower contribution of sediments with less radiogenic Nd ratios from the local Coastal Domain, and more radiogenic Nd ratios from the distal Rio de La Plata estuary. The influence of the Rio de La Plata sediments on the Core 7616 is restricted to the northwards transport of clay by the expansion of the La Plata plume and the action of the BCC, on the intervals with relative higher $\varepsilon_{Nd(0)}$ values.

River Input and Oceanic Circulation

Intensification of the SASM recorded by oxygen isotope of speleothems (Cruz et al., 2005) and associated increase on chemical weathering over the SE South America provided higher sediment input into the Rio de La Plata (Chiessi et al., 2010) during the late Holocene. The variability in precipitation have influenced the studied sites in different ways. Besides the cores be relatively close together (~400 km), we must emphasize that the cores 7616 and 7620 are located to the south and the north of Ilha Bela, respectively, therefore in areas under distinct geomorphological and sedimentological configurations and, distinct hydrodynamic systems.

Isotopic variations along the Core 7616 are here associated with changes in provenance, reflecting the action of different mechanisms that govern the paleoenvironmental processes. We interpret that the remarkable isotopic signal of the UCC [relative lower $\varepsilon_{Nd(0)}$ values and older TDM ages of -11 and 1.65 Ga, respectively] registered in the Core 7616 between 2000 and 1800 cal. yr BP (**Figure 8**) is related to the intensification of the SASM, which probably favored the chemical weathering over the local domains increasing terrigenous sediment input to the shelf. According to previous work during the austral summer, the CW transports fine sediments toward the outer shelf since muddy sediment deposits are observed to the south of Ilha Bela. This clay could be transported back to the inner shelf by the action of the

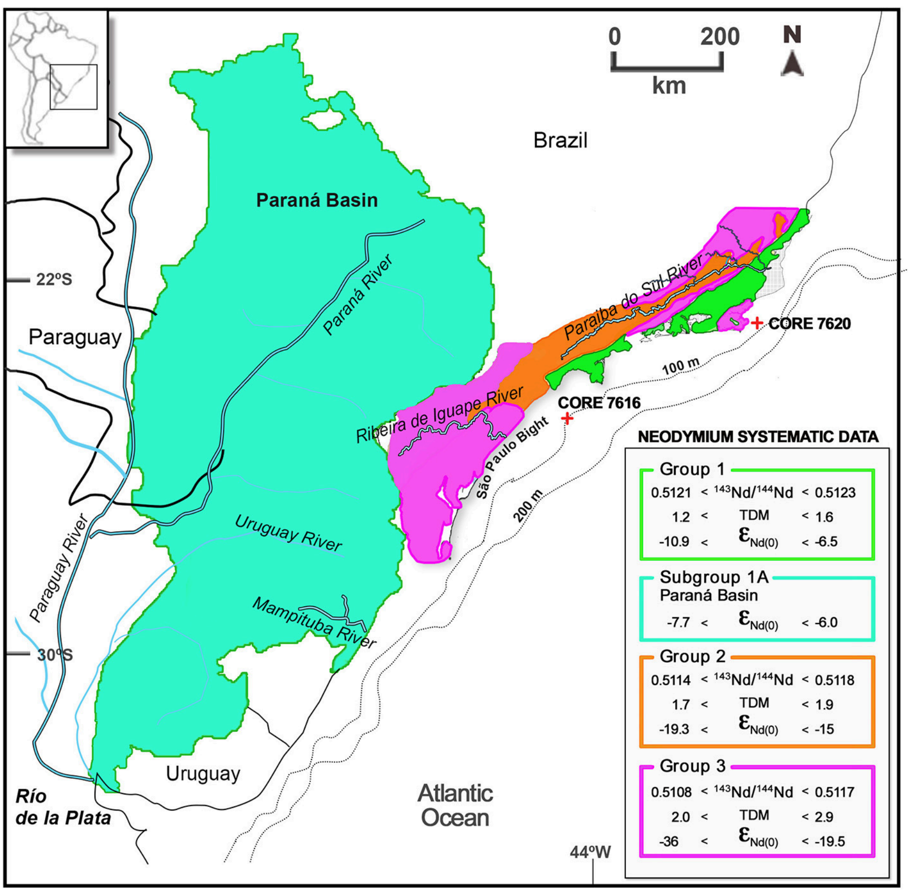

FIGURE 6 | Neodymium isotope distribution map of the investigated source rocks based on PCA and Cluster analyses results. Group 1: represented by the green (Coastal domains from the Ribeira belt and bluish green subgroup 1A (sedimentary rocks of the Paraná basin); Group 2: represented by the orange (Paraíba do Sul and Embú domains from the Ribeira belt); Group 3: represented by the pink (Rocks from older pre-Cambrian domains of the Ribeira belt and the Luís Alves craton).

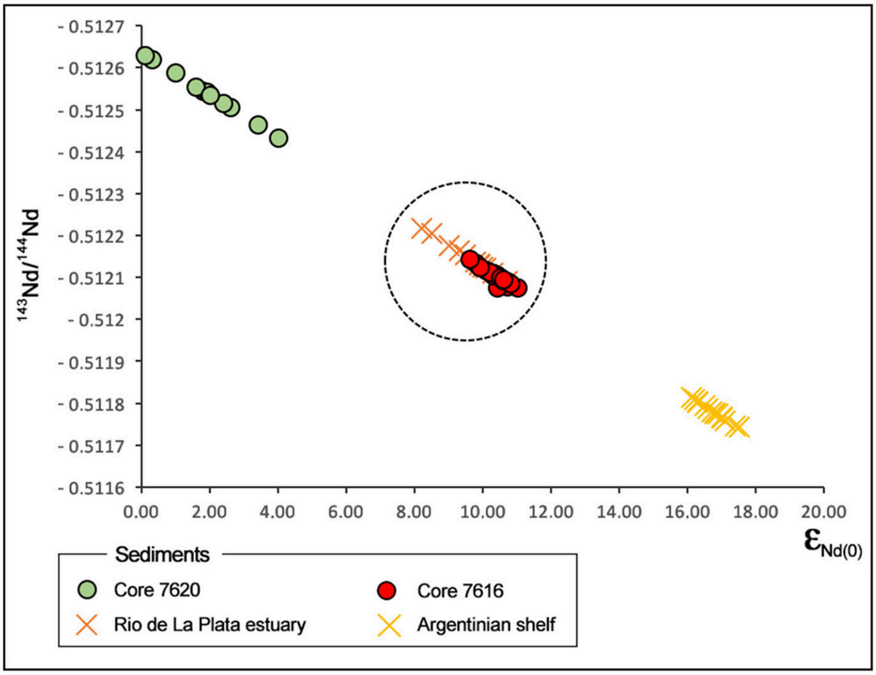

FIGURE 7 | Diagram of $\varepsilon_{Nd(0)}$ values vs. $^{143}Nd/^{144}Nd$ showing the similarities between the Core 7616 and sediments from the Rio de La Plata estuary.

SACW during episodes of strong intensification of NE winds and resurgence process over the São Paulo bight. Thus, our results evidence an enhanced action of the SACW in the Core 7616 and, consequent, decreasing influence of the La Plata estuary sediments, transported northwards by the BCC, from 1,800 to 2000 cal. yr BP.

Our isotopic data indicates that the register of continental input from the Paraíba do Sul River associated with the southwards sediment transport by the BC superimposed the intensification of the resurgence processes off Cabo Frio on the inner shelf, during the late Holocene. This hypothesis is consistent with the high proportion of coarser sediments transported from the Paraíba do Sul River to the inner shelf off Cabo Frio reported by Gyllencreutz et al. (2010), and with the increasing trend of relative lower $\varepsilon_{Nd(0)}$ values, registered in this work, toward to the top of the Core 7620 (**Figure 8**).

CONCLUSIONS

The use of Nd radiogenic isotopes proved to be very promissory in identifying sources areas of marine sediments. Our compilation of Nd radiogenic data from the Ribeira belt, rocks of the Paraná basin and the Luís Alves craton resulted in a Nd systematic distribution map.

The comparison of the Nd radiogenic isotopes between the cores indicated distinct source rocks. Both are under influence of the metasediments from the Ribeira belt. However, the more radiogenic Nd ratios and higher $\varepsilon_{Nd(0)}$ values from the Core 7616 are attributed to the contribution from sources with mantle composition (e.g., basalts from the Serra Geral formation), corroborating the similar isotopic signatures from the sedimentary rocks of the Paraná basin, sediments from the Rio de La Plata estuary and the Core 7616.

The influence of UCC components in the Core 7616 can be explained by the contribution from local crustal sources related to the history of the uplift of the Serra do Mar ridge, which have provided detrital material from the Ribeira belt since the late Cretaceous and, up to the recent, through neotectonics. On the other hand, the mantle component may have its origin related to the younger distal source, by the northward transport of the fine size fraction of sediments from the Rio de La Plata, facilitated by the SW wind dynamics, as well as through the contribution from the erosion of coastal basalts.

The isotopic variation along the Core 7616 permitted to bring new interpretations about the sedimentation on the SW Atlantic margin. A relevant continental crust isotopic signature is registered in the Core 7616 from 2000 to 1800 cal. yr BP, probably resulted from the enhanced NE winds and, consequent, intensification of the SACW transporting the muddy sediment, previously taken to the outer shelf by the CW, back to the inner shelf, indicating decreasing influence of sediments from the Rio de La Plata estuary during the late Holocene.

Observing the average values of the Nd data and the results from the Principal component and clustering analyses, we have concluded that the Core 7620 is under the influence of the sediment input from PS River, particularly from the metasediments of the Paraíba do Sul Domain inserted in the Ribeira belt.

The southward migration of the ITCZ, the intensification of the SASM, and concomitant strengthen of the BC sediment transport to the south left their record in the Core 7620 through episodes of enhanced fluvial transport (i.e. the great input of

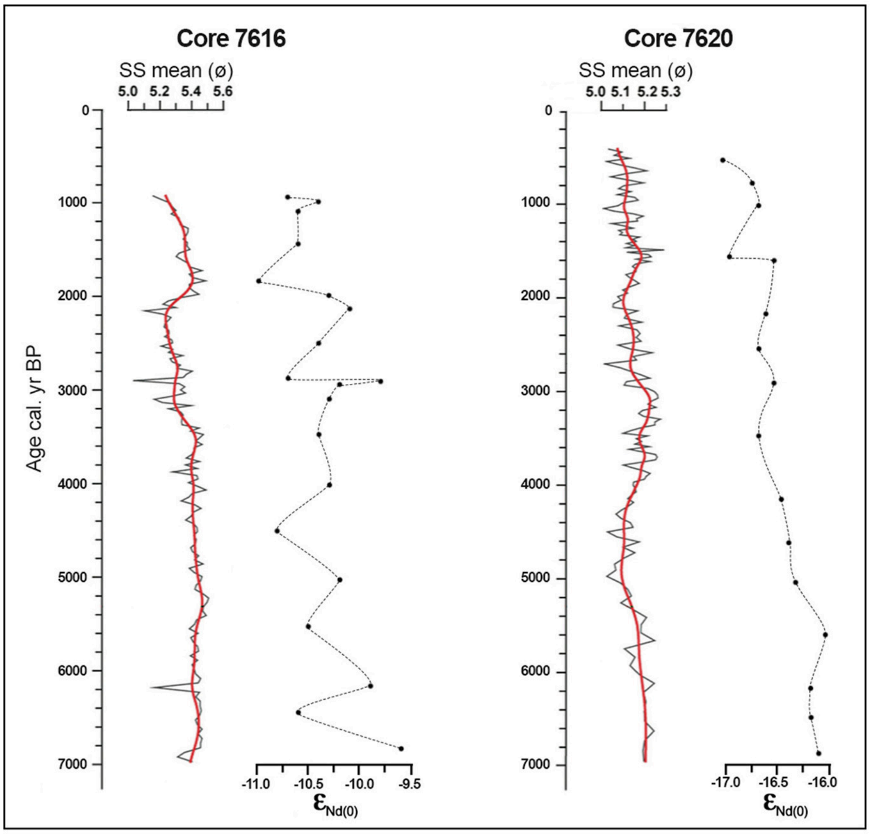

FIGURE 8 | Comparison between the sortable silt (SS) mean reported by Gyllencreutz et al. (2010) and the $\varepsilon_{Nd(0)}$ data from the present work for the cores 7616 and 7620. The red line represents the smoothed curve; the black dots are the variation of $\varepsilon_{Nd(0)}$ data from the present work.

sediments from the Paraíba do Sul River) registered by the relatively lower $\varepsilon_{Nd(0)}$ values and less Nd radiogenic ratios during the late Holocene.

AUTHOR CONTRIBUTIONS

SM analyses, discussion of data, and writing of the manuscript. CT analyses and discussion of data. MM collection and discussion of data. LJ discussion of data and writing of the manuscript. EB discussion of data.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feart.2018.00074/full#supplementary-material

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