PROVENANCE OF FINE-GRAINED SEDIMENTARY ROCKS DERIVED FROM Rb-Sr AND Sm-Nd ANALYSES: THE EXAMPLE OF THE SANTA MARIA FORMATION (TRIASSIC, PARANA BASIN, SOUTHERN BRAZIL)

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Resumo: Os métodos radiométricos (Rb-Sr e Sm-Nd) têm sido aplicados em rochas sedimentares visando a obtenção de informações sobre proveniência. O método Sm-Nd, apesar de ser uma técnica relativamente nova quando aplicada a rochas sedimentares, tem se tornado uma ferramenta fundamental para auxílio na determinação das potenciais áreas fontes. Neste trabalho, foram aplicados os métodos radiométricos Rb-Sr e Sm-Nd em amostras de rochas sedimentares da Formação Santa Maria (Triássico da Bacia do Paraná). As informações obtidas com o método Sm-Nd e, por vezes, integradas com as da metodologia Rb-Sr permitiram inferências e reconstrução das áreas de proveniência. Estes resultados são fundamentais para o aprimoramento destas metodologias quando aplicada em rochas sedimentares.

Resumen: Los métodos radiométricos (Rb-Sr e Sm-Nd) han sido aplicados en rocas sedimentarias objetivando la obtención de informaciones sobre origen. El método Sm-Nd, a pesar de ser una técnica relativamente nueva en la aplicación a rocas sedimentarias, se ha tornado una herramienta fundamental en el auxilio a la determinación de origen. En este trabajo, fueron aplicados los métodos radiométricos Rb-Sr y Sm-Nd en muestras de rocas sedimentarias de la Formación Santa Maria (Triásico de la Cuenca del Paraná). Las informaciones obtenidas con el método Sm-Nd y, por veces, integradas con as de la metodología Rb-Sr permitieron la presunción y reconstrucción de las áreas de origen. Estes resultados son fundamentales para el aperfeccionamiento de estas metodologías cuando aplicadas a rocas sedimentarias.

Abstract: In this work, the Rb-Sr and Sm-Nd methods were applied to fine-grained sedimentary rock samples of the Santa Maria Formation (Triassic, Paraná Basin) in order to have provenance informations. The Sm-Nd, although being considered as a new technique when applied to sedimentary rocks is an important parameter to the determination of potentials source rocks. The acquired informations with the Sm-Nd method and the integration with Rb-Sr data allowed to propose the reconstruction of the source areas concerning Santa Maria Formation. The results are fundamental to improve these methodologies when applied in sedimentary rocks.

Keywords: sedimentary rocks, Rb-Sr methodology, Sm-nd methodology, provenance.

INTRODUCTION

Provenance studies of clastic sedimentary rocks are traditionally based on paleocurrent analysis and petrographically derived data (mineralogical composition and quantification). Sometimes these techniques are not conclusive when applied to sediments lacking flow indicators or having undergone extensive diagenetic processes. In this case, when the detrital composition is not diagnostic, it is possible to make inferences about the provenance indicators by using isotopic variations of the Sm-Nd system (Nelson and DePaolo, 1988).

The parameters of the Sm-Nd system, such as the $^{143}Nd/^{144}Nd$ ratios, ε_{Nd} and T_{DM} model ages, are distinctive of mantle *vs.* crustal origin of igneous and metamorphic rocks. The relatively immobile character of the rare earth elements (REE's) in most terrestrial processes allows the application of this isotopic system for determining provenance (Nelson and DePaolo, 1988; McLennan *et al.*, 1990), despite possible slight modifications during the sedimentary cycle (Zhao *et al.*, 1992). The Sm-Nd system was successfully applied to Paleozoic marine basins in North America (Gleason *et al.*, 1994, 1995) and Africa (Andersson *et al.*, 2003), where inferences of sedimentary provenance depend on properties of the Sm-Nd system that record and preserve age information about sedimentary source rocks.

Concerning some aspects, Rb-Sr isotope systematics in sediments is analogous to the Sm-Nd system. In contrast with the rare-earth ratios, Rb/Sr ratios may be strongly altered by sedimentary process, beginning with the preferential solubility of Sr during weathering (Nelson and DePaolo, 1988). Diagenetic effects can also perturb the Rb-Sr system. So, it is possible that Rb-Sr fractionation during the sedimentary process change or destroy age information about the source rocks.

In order to test the applicability of the Rb-Sr and Sm-Nd systems in obtaining geologically significant provenance tracing, fine-grained sedimentary rocks from the Triassic Santa Maria Formation were sampled and analyzed. The Santa Maria Formation was selected because of its well-known sedimentology and stratigraphy (Pierini, 2001), as well as the good preservation and knowledge of the vertebrate fossil content (Scherer *et al.*, 2000).

GEODYNAMICS AND STRATIGRAPHIC FRAMEWORK

Paraná Basin - general characterization

The Paraná Basin occupies an area of 1,700,000 km², covering part of the territories of Brazil, Argentina, Paraguay and Uruguay (Figure 1). Its basement is made up of Archean/Paleoproterozoic cratonic nuclei and Neoproterozoic mobile belts amalgamated in the context of the Brasiliano/Pan-African cycle (900-540 Ma) during the assembly of Gondwana. The tectonostratigraphic evolution of the Paraná Basin is closely related to the geodynamic processes occured in the Gondwanides belt, during the subduction of the Panthalassan plate underneath the southwestern margin of Gondwana (Milani, 2000).

The geological record of the Paraná Basin is divided into six supersequences bounded by regional-scale unconformities, each one produced by a different paroxism of the Gondwanides belt. The Ordovician-Silurian (or Rio Ivaí) supersequence comprises the fluvial deposits of the Alto Garças Formation, the glacial facies of the Iapó Formation and the transgressive marine deposits of the Vila Maria Formation, dated at the Llandoverian (Mizusaki *et al.*, 2002). The Devonian (or Paraná) supersequence is composed by the Furnas and Ponta Grossa formations, made up of fluvio-deltaic to marine deposits and recording a trangressive event.

During the Devonian-Carboniferous boundary, the Paraná Basin was affected by a very unstable period due to a long glaciation (Caputo and Crowell, 1985) and to convergent tectonic processes which resulted in a regional angular unconformity representing a large non-deposition hiatus (Milani, 2000). At the end of the glaciation, sedimentation was resumed and the Carboniferous-Eotriassic (or Gondwana I) supersequence developed. This 2,500 m thick package, at its base, is made up of the diamictites, sandstones and siltstones/mudstones of periglacial origin of the Itararé Group. Stratigraphically above, occur the coal-bearing fluvio-deltaic deposits of the Rio Bonito Formation, and the transgressive marine deposits of the Palermo and Irati formations (Holz and Carlucci, 2000). A new continentalization trend is represented by the Serra Alta, Teresina, and Rio do Rasto formations, which culminates with fluvio-eolian deposits (Menezes, 2000).

The Neotriassic (or Gondwana II) supersequence, the main focus of this study, crops out only in the southern portion of the basin, in the Rio Grande do Sul State, Brazil. This package is made up of the Sanga do Cabral, Santa Maria, Caturrita and Mata formations, all deposited in a continental, fluvio-lacustrine setting (Scherer *et al.*, 2000). Stratigraphically above, the Jurassic-Eocretaceous (or Gondwana III) supersequence is composed by the eolian sandstones of the Botucatu
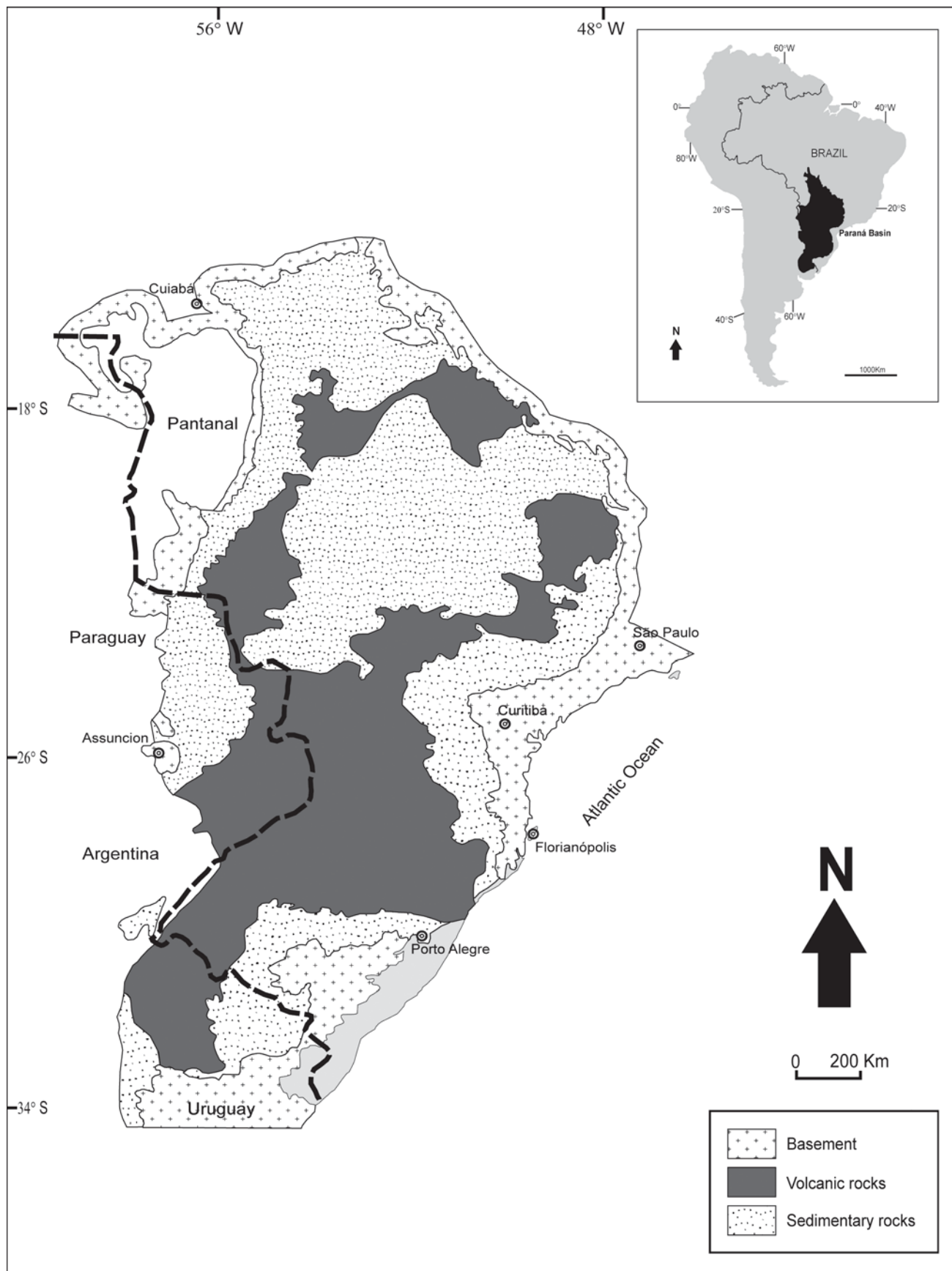
Figure 1. Location map of Paraná Basin (modified Milani *et al.*, 1997).
Figura 1. Mapa de localização da Bacia do Paraná (modif. de Milani *et al.*, 1997).

Formation and by the tholeiitic basaltic flows of the Serra Geral Formation, with subordinated andesites and rhyolites (Roisenberg and Viero, 2000). Finally, the Neocretaceous (or Bauru) supersequence is represented by the fluvial deposits of the Bauru and Caiuá formations, accummulated in depressions formed by the cooling of the Cretaceous basaltic flows.

The Gondwana II supersequence - the Triassic package of southern Paraná Basin

The sedimentary rocks of the Gondwana II supersequence, cropping out in the central lowlands of the Rio Grande do Sul State, southern Brazil, were extensively revised by Scherer *et al.* (2000) and Zerfass *et al.* (2003, 2005) in terms of sedimentology, stratigraphy and tectonics. The cited authors subdivide this package in unconformity-bounded depositional sequences, with depositional ages determined through their fossil content.

The Eoscytian sequence corresponds to the Sanga do Cabral Formation, which base is composed by poorly sorted intraformational conglomerates and conglomeratic sandstones, with trough- and planar-cross stratifications, suggesting deposition in braided fluvial streams. Upsection, siltstones and mudstones occur, with interlayered fine-grained rippled sandstones and desiccation cracks, representing deposition in a periodically dry lacustrine setting. At the top of this package, coarse-grained and conglomeratic sandstones crop out, associated with fine-grained sandstones, with either horizontal stratification or large scale eolian trough-cross stratification. Paleocurrents point to northeast and the fossil content is composed by reptiles and amphibia of the Eoscytian *Lystrosaurus* biozone.

The Ladinian-Eonorian sequence, main focus of the present paper, corresponds in the lithostratigraphy to the Santa Maria Formation and to the base of the Caturrita Formation. The sequence begins with fine-grained to conglomeratic sandstones and sub ordinate reddish siltstones and mudstones, diagnostic of braided fluvial streams (the Passo das Tropas Member). Stratigraphically above (the Alemoa Member), massive or thinly laminated siltstones dominate, associated with desiccation cracks, caliches and paleosols. These characteristics suggest the dominance of floodplain areas over the fluvial channels, which should be more sinuous and with stable margins. Upsection (the Caturrita Formation), coarse-grained sandstones are more common, suggesting a new braided fluvial system, with wide

and shallow channels. Paleocurrents suggest a northeastward flow, and a rich Ladinian to Eonorian paleotetrapod fauna, associated with plant fossils and invertebrates is recorded.

The Rethic sequence, represented by the "Mata Sandstone", comprises fine-grained to conglomeratic quartzose sandstones, with small- to medium-scale trough-cross stratifications. These rocks contain a significant occurrence of silicified fossil conifer stems. The Neojurassic sequence is represented by the Guará Formation (Scherer and Lavina, in press), a succession made up of fine-grained to conglomeratic sandstones, with trough-cross and horizontal stratifications. A progressive southwards grain-size decreasing, associated with consistent southward paleocurrents, suggest that the basin depocenter, at that time, was located in Uruguay, where the correlated Taquarembó Formation contains gastropoda, reptiles and fishes of Late Jurassic age. The Gondwana II supersequence is unconformably overlain by the Cretaceous eolian sandstones of the Botucatu Formation and by the basaltic lava flows of the Serra Geral Formation.

Basement of the southern Paraná Basin - the Sul-rio-grandense Shield

During the Mesozoic, the basement of the Paraná Basin in its southern portion was represented by the igneous, metamorphic and sedimentary units of the Sul-rio-grandense Shield, with formation ages from the Late Archean to the Ordovician. This area developed through accretionary and collisional events during the Transamazonian (Paleoproterozoic) and Brasiliano/Pan-African (Neoproterozoic) orogenic cycles (Chemale Jr. *et al.*, 1995; Fernandes *et al.*, 1995; Babinski *et al.*, 1996; Hartmann *et al.*, 1998). Tectonic activity during the Paleozoic and Mesozoic was identified by means of petrographic analysis of sandstones (Zerfass, 2000), identification of tectonic structures (Zerfass *et al.*, 2005) and apatite fission-track data (Borba *et al.*, 2002, 2003a). Thus, a detailed description of the isotopically-distinct basement domains of the Sul-rio-grandense Shield is necessary for comparison with the obtained data and identification of possible source areas.

The Taquarembó Domain comprises the Paleoproterozoic Santa Maria Chico granulitic complex, of juvenile island-arc TTG origin. The magmatic ages are between 2.55 and 2.35 Ga, and a 2.02 Ga old metamorphic overprint is recorded. Initial $^{87}Sr/^{86}Sr$ ratios are very low (ca. 0.703) and Sm-Nd isotopic data reveal

T_{DM} ages between 2.3 and 2.6 Ga and ε_{Nd}(t) around +3 (Hartmann *et al.*, 1999; Soliani Jr. *et al.*, 2000).

The São Gabriel Domain consists of a Neoproterozoic juvenile terrain made up of TTG-type metagranitoids of the Cambaí Complex, with magmatic ages ranging from 879 ± 14 Ma to 703 ± 13 Ma (Leite *et al.*, 1998). Initial $^{87}Sr/^{86}Sr$ ratios are also very low and Sm-Nd model ages vary between 930 and 800 Ma and ε_{Nd}(t) values between +0.7 and +4.4 (Babinski *et al.*, 1996). Remnants of oceanic crust, island-arc volcanics and sedimentary cover are assembled in the Vacacaí Supercomplex, also with juvenile characteristics, unit which is dated at 753 ± 2 Ma and 705 ± 2 Ma (Machado *et al.*, 1990; Hartmann *et al.*, 2003; Saalmann *et al.*, 2005).

The Santana da Boa Vista Domain is made up of the Paleoproterozoic Encantadas gneisses (Jost and Bitencourt, 1980), with Sm-Nd T_{DM} ages of 2.0 to 3.2 Ga and ε_{Nd}(t) of +5 (Soliani Jr. *et al.*, 2000). This unit is unconformably overlain by the supracrustal Porongos complex, with Neoproterozoic metamorphosed volcanic rocks (783 ± 6 Ma, Porcher *et al.*, 1999) and sedimentary units of Paleoproterozoic provenance (Vasconcellos *et al.*, 2003).

The Pelotas Domain is made up of granitic rocks emplaced within a major shear zone (the Dorsal de Canguçu shear zone, DCSZ), active between 658 - 625 Ma under transpressive regime, and 625 - 600 Ma under transtractive regime. These granitoids display mixed mantle-crust Sm-Nd data (T_{DM} ages between 1.53 and 2.27 Ga, Frantz *et al.*, 1999). Post-collisional (Bitencourt and Nardi, 1993) intrusive suites outside DCSZ are younger than 612 ± 2 Ma and are rich in Paleoproterozoic metamorphic xenoliths (Babinski *et al.*, 1997; Philipp and Machado, 2002). Large Paleoproterozoic xenoliths and roof-pendants are ascribed to the Várzea do Capivarita metamorphic suite (Frantz *et al.*, 1984) and the Arroio dos Ratos gneissic complex (Fernandes *et al.*, 1990). A recent proposal suggests an allochthonous origin for the Pelotas Domain (or Cuchilla Dioniso Terrane in Uruguay) and a 530 Ma left lateral (strike-slip) collisional event (Bossi and Gaucher, 2004).

The "Camaquã Basin" (Paim *et al.*, 2000), designation of a series of fault-bounded sedimentary and volcanosedimentary basins, represents the post-collisional phase of the Neoproterozoic orogenic events. From base to top, the stratigraphic units represent an overall continentalization trend. The Maricá Formation (Leinz *et al.*, 1941), considered to be Neoproterozoic (Paim *et al.*, 2000), is made up of fluvial and shallow marine sedimentary rocks (Borba *et al.*, 2004) with crustal,

Paleoproterozoic Sm-Nd parameters (Borba *et al.*, 2006). The Bom Jardim Group comprises andesites of the Hilário Formation (*ca.* 592 ± 5 Ma, Remus *et al.*, 1997) and alluvial, fluvio-lacustrine deposits of the Arroio dos Nobres Formation. The Acampamento Velho Formation is made up of rhyolitic lavas and pyroclastic rocks dated at 549 ± 5 Ma (Sommer *et al.*, 2003), and the Camaquã Group comprises the alluvial, fluvial and eolian deposits of the Santa Bárbara and Guaritas formations, younger than 540 Ma (Borba and Mizusaki, 2003b; Scherer *et al.*, 2003). Shoshonitic to alkaline granitoids with ages in the 590 - 550 Ma interval (*e.g.* Lavras do Sul, Jaguari, Caçapava do Sul, São Sepé granitoids) are widespread in the entire Sul-rio-grandense Shield.

METHODOLOGY AND SAMPLING

Rb-Sr system

The Rb-Sr dating method is related to the process of radioactive decaying of ^{87}Rb to ^{87}Sr, with a half-life value of 48.8 Ga, and it is traditionally applied to the absolute dating of igneous suites. During the crystallization of a magma, ^{87}Sr has considerable mobility, and it migrates between mineral phases when the temperature is above 300 - 350ºC. The result is called the isotopic homogenization of Sr, which is stopped by the cooling of the formed rocks below the referred temperature. Thus, a Rb-Sr age records the crystallization of a given igneous suite. An important parameter of the Rb-Sr system is the initial $^{87}Sr/^{86}Sr$ ratio (R_i), which distinguishes acidic, crust-derived igneous rocks, with higher R_i values, from basaltic, mantle-related suites, with R_i around 0.703. The Rb-Sr dating of a single granite sample, analyzed by mass spectrometry, can be obtained by attributing an initial $^{87}Sr/^{86}Sr$ ratio (conventional age). Otherwise, when R_i is unknown, the obtained $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios for a series of co-magmatic samples are plotted in the isochron diagram, the slope of the best-fitting line meaning the crystallization age.

During the sedimentary cycle, characterized by lower temperatures, the behavior of the Rb and Sr ions is different. This difference is associated to the sedimentary process beginning with preferential Sr solubility during weathering. Rb is more easily adsorbed by clay minerals, while Sr is released from the crystal lattice of the minerals, and incorporated to the interstitial fluids. This fact is thought to favor a process called the "isotopic uniformization" of Sr during the deposition
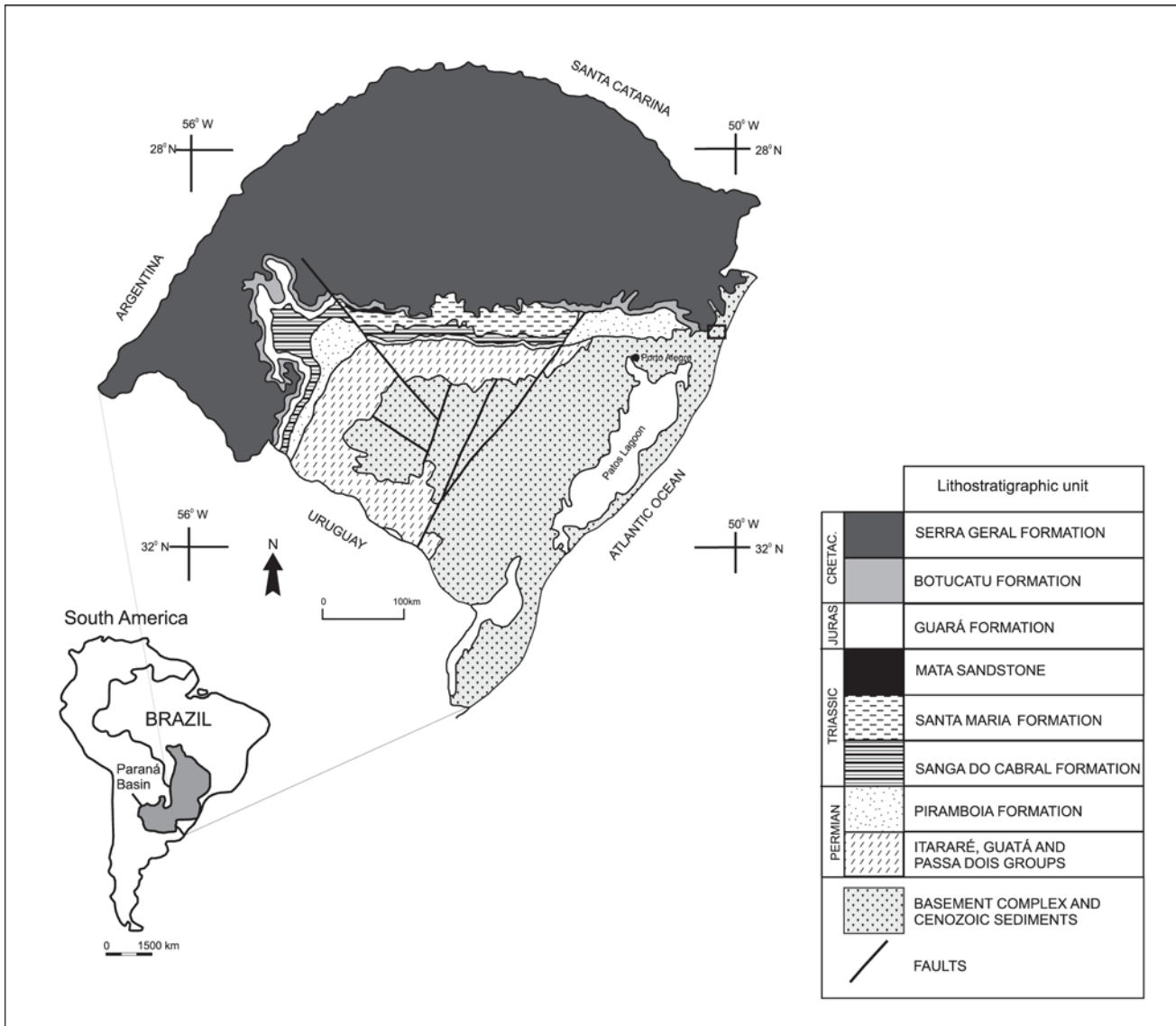
Figure 2. Geological map of Paraná Basin in Rio Grande do Sul state (modified Scherer *et al.*, 2000).
Figura 2. Mapa geológico da Bacia do Paraná no estado do Rio Grande do Sul (modif. de Scherer *et al.*, 2000).

of fine-grained sediments in a sedimentary basin (Compston and Pidgeon, 1962; Faure, 1986). In this case, there is a tendency to the $^{87}Sr/^{86}Sr$ ratio of the samples became very homogeneous especially when the sediments are fine grained and the mineralogical composition is enriched in expansive clay minerals.

Sm-Nd system

The relatively immobile character of the rare earth elements (REE's) in most terrestrial processes (DePaolo, 1988; McLennan *et al.*, 1990) allows the application of

the Sm-Nd isotopic system to provenance research, even considering a possible slight modification of parameters during the sedimentary cycle (Awwiller and Mack, 1991; Zhao *et al.*, 1992). Relatively lower $^{143}Nd/^{144}Nd$ ratios (^{144}Nd is the reference stable isotope) indicate crustal sources, while higher $^{143}Nd/^{144}Nd$ ratios suggest the input of mantle-derived juvenile material (DePaolo, 1988). The difficult visualization of the meaning of Nd ratios is overcome by the ε_{Nd} parameter and by mantle extraction ages T_{DM}. Positive or near-zero ε_{Nd} values, and T_{DM} values near the crystallization age of an igneous suite, correspond to juvenile, mantle-de-

rived components. On the other hand, negative results and significant difference between ages of extraction (T_{DM}) and crystallization point to contamination by inherited, crustal material.

The early study of Nelson and DePaolo (1988) in continental, semi-arid, fault-bounded basins of the Tertiary of southwestern United States demonstrated the applicability of the parameters cited above to provenance studies by recognizing two isotopic end-members (Precambrian basement and Oligocene volcanics) and their mixing in post-Oligocene rocks. McLennan *et al.* (1990) showed that recent sediments draining shield areas and depositing in passive margin basins have strongly negative, present-day ε_{Nd} parameters (between-9,9 and -24,9), while sediments from fore-arc basins display positive values from +0,7 to +8,3. The Sm-Nd parameters have also been applied to Paleozoic marine basins in North America (Gleason *et al.*, 1994; 1995) and Africa (Andersson *et al.*, 2003), as well as to Neoproterozoic sedimentary (Ball and Farmer, 1998; Farmer *et al.*, 2001) and metasedimentary (Pimentel *et al.*, 2001) successions.

Sampling and analytical procedures

The analyzed samples are representative of the upper package of the Santa Maria Formation, the Alemoa Member, comprising siltstones with desiccation cracks, caliches and paleosols, cropping out along a E-W trending area in the central lowlands of Rio Grande do Sul State, southern Brazil (Fig. 2). Sample collection was performed along two distinct stratigraphic sections, with slightly different grain-size, distant some 50 kilometers from one another in the E-W direction. In the first profile (Fig. 3a), located near the urban area of Santa Maria city, samples SM-1 to SM-5 were collected, while in the second (Fig. 3b), located near Agudo, samples SM-7 to SM-12 were obtained. All the twelve samples were analyzed for Rb-Sr, while ten samples were submitted to Sm-Nd procedures. The selection of samples was performed according to the criteria of Mizusaki (1992), by considering macroscopic characteristics and previous results by X-ray diffraction (Pierini, 2001).

The Rb-Sr and Sm-Nd isotopic analyses were performed in the Laboratório de Geologia Isotópica of the Universidade Federal do Rio Grande do Sul (LGI-CPGq/UFRGS). Initially, the samples were dried under controlled temperature (up to 70ºC) in order to avoid damage to the structure of the clay minerals. The semi-
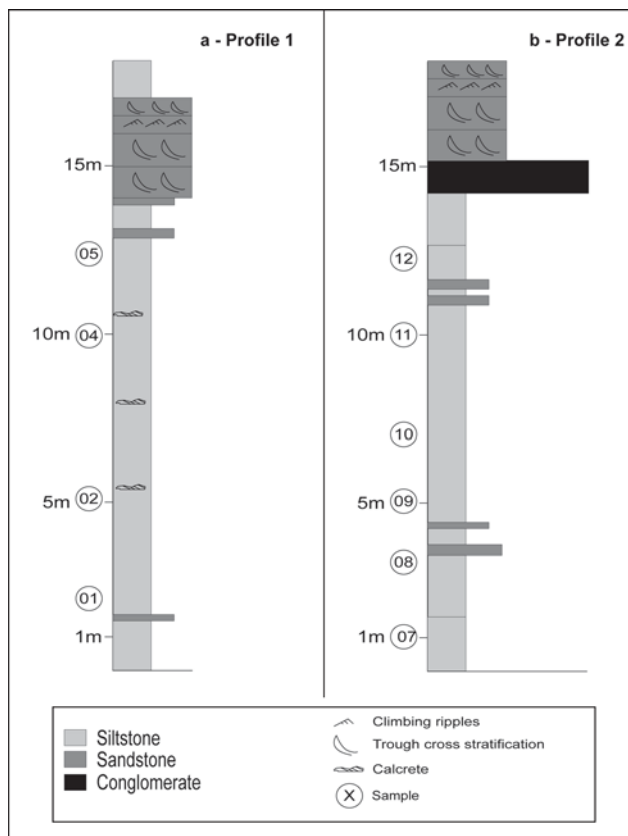

Figure 3. Stratigraphic profile of Santa Maria Formation samples; a) profile 1, samples SM-01 a SM-05; b) profile 2, samples SM-07 a SM-12 (modified Pierini, 2001).

Figura 3. Perfil estratigráfico das amostras da Formação Santa Maria; a) perfil 1, amostras SM-01 a SM-05; b) perfil 2, amostras SM-07 a SM-12 (modif. de Pierini, 2001).

quantitative and quantitative determination of the Rb, Sr, Sm and Nd contents was achieved by X-ray fluorescence. About 0.1 to 0.2 g of powdered rock from each sample was dissolved with HNO_3 and HF in Savilex vials, with the addition of isotopic tracers. Rb, Sr and REE's were separated in cationic exchange AG-50W-X8 resin columns (200 to 400 mesh), and Sm was separated from Nd with anionic exchange LN-B50-A resin columns (100 to 200 mm). Isotopic ratios were obtained using a VG SECTOR 54 mass spectrometer, with multi-collection system and 1.0 V ion beam, at the Laboratório de Espectometria de Massas do LGI-CPGq/UFRGS. Rb-Sr and Sm-Nd results were calibrated respectively against standards NBS-987 (Strontium carbonate, mean 0.71026 ± 0.000014) and La Jolla (mean 0.511859 ± 0.00001). Blank values were lower than 150 pg for Sr and Sm, and 750pg for Rb and Nd.
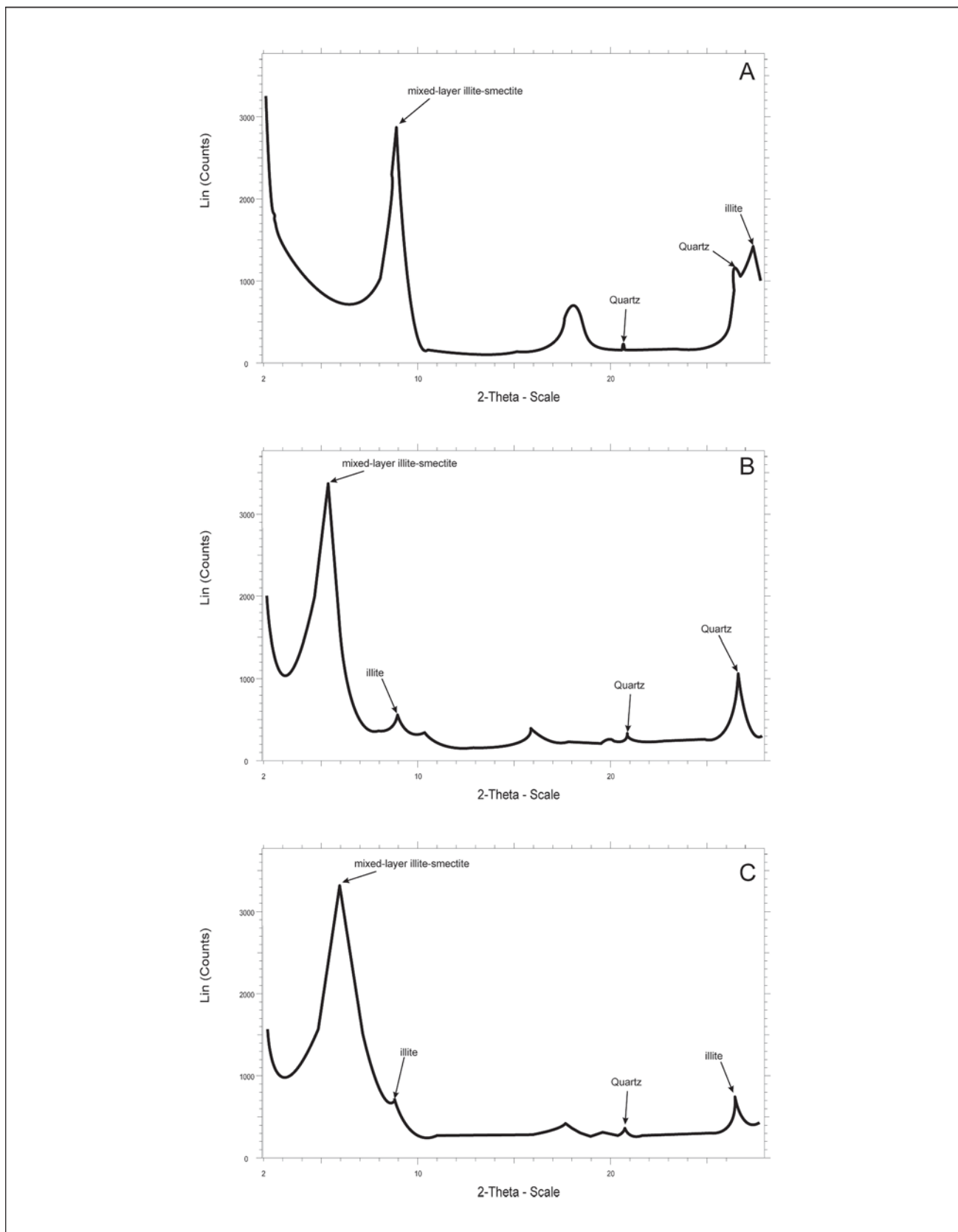
Figure 4. X-ray diffraction patterns to sample SM-4, Santa Maria Formation. a) Normal sample; b) Glicolated sample; c) Calcinated sample (modified Pierini, 2001).
Figura 4. Difratogramas da amostra SM-4, Formação Santa Maria. a) Amostra normal; b) Amostra glicolada; c) Amostra calcinada (modif. de Pierini, 2001).

Sample	Rb (ppm)	Sr (ppm)	Sm (ppm)	Nd (ppm)	$^{87}Sr/^{86}Sr$	$^{87}Rb/^{86}Sr$	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$\varepsilon_{Nd\,(0)}$	$\varepsilon_{Nd\,(t)}$	t (Ma)	T_{DM}
SM-1*	105.9	110.6	4.9	25.3	0.72298 ± 0.00019	2.7655 ± 0.03577	0.19393 ± 0.00233	0.512168 ± 0.000023	-9.18	-6.95	230	1376
SM-2*	119.3	85.5	4.3	22.6	0.72807 ± 0.00024	4.0366 ± 0.05495	0.19149 ± 0.0023	0.512568 ± 0.000028	-1.37	0.91	230	749
SM-4*	104.5	116	10.1	49.9	0.72229 ± 0.00013	2.6027 ± 0.03366	0.20298 ± 0.00244	0.512573 ± 0.00002	-1.27	0.81	230	796
SM-5*	103.6	114.9	4.3	22	0.72296 ± 0.00026	2.6047 ± 0.03336	0.19785 ± 0.00237	0.5122 ± 0.000019	-8.55	-6.39	230	1359
SM-7	133.6	163	4.6	23.5	0.71921 ± 0.00016	2.3681 ± 0.03368	0.19488 ± 0.00234	0.512192 ± 0.000016	-8.71	-6.49	230	1346
SM-8	123.3	139.2	4.4	22	0.72063 ± 0.00016	2.5580 ± 0.03468	0.19809 ± 0.00238	0.512196 ± 0.000016	-7.65	-5.79	230	1311
SM-9	110	124.5	5	25.6	0.72192 ± 0.00026	2.5512 ± 0.03312	0.19685 ± 0.00236	0.512231 ± 0.000019	-8.63	-6.45	230	1356
SM-10	85.8	134.7	3.4	17.7	0.71968 ± 0.00014	1.8358 ± 0.02194	0.18951 ± 0.00228	0.512207 ± 0.000023	-8.4	-6.1	230	1279
SM-11	90.2	119.3	3.8	19.7	0.72147 ± 0.00027	2.1828 ± 0.02722	0.19365 ± 0.00232	0.512173 ± 0.000021	-9.07	-6.84	230	1365
SM-12	87.9	109.3	3.7	19.2	0.72242 ± 0.00028	2.3216 ± 0.02848	0.19398 ± 0.00233	0.512229 ± 0.000019	-7.98	-5.75	230	1280

Table 1. Isotope ratios of Santa Maria Formation samples (errors values of the isotope ratios are presented in absolute SD). * samples refered to profile 1.

Tabela 1. Razões isotópicas das amostras da Formação Santa Maria (os valores dos erros das razões isotópicas estão em SD absoluto). * amostras referentes ao perfil 1.

RESULTS

The analyzed samples can be described as reddish, oxidized, massive siltstones. Their close field relationship with lens-shaped sandstone beds, as well as the stratigraphic position within the Ladinian-Eonorian sequence, relate them with floodplain deposits of a fluvial system.

The siltstones are usually well to moderately sorting and are classified as arkoses concerning McBride's (1963) scheme. Quartz, feldspar and lithic fragments are the main framework constituents. Lithic fragments embrace about 12% of detrital grains, with altered volcanics being common in most samples. Metamorphic, chert and intrabasinal grains (mostly mudclasts) are also described representing about 2% of the detrital composition (Pierini, 2001).

In most cases, the samples do not feature any important diagnetic event. However, it is common the precipitation of authigenic, reddish brown iron oxides. Occasionally the iron oxides form distint levels that can more clearly be observed in the most fine grained,

well laminated samples or between the detrital grains.

The X-ray diffraction procedures in the FF < 2μm fraction of the samples allowed the recognition of discrete illite and illite-smectite (I/S) mixed-layered clay minerals with minor amounts quartz (Fig. 4).

The results of the application of the Rb-Sr and Sm-Nd isotopic methods in whole rock are in Table I. In the first profile, Rb values are between 103 and 119 ppm, Sr varies from 85 to 116 ppm, Sm from 4 to 10 ppm and Nd between 22 and 50 ppm. The $^{87}Sr/^{86}Sr$ ratio spreads from 0.722 to 0.728, while the $^{87}Rb/^{86}Sr$ ratio are between 2.60 and 4.03. The values for the $^{147}Sm/^{144}Nd$ ratio are from 0.191 to 0.203, and the $^{143}Nd/^{144}Nd$ spreads from 0.5121 and 0.5125. These results correspond to $\varepsilon_{Nd(0)}$ values of –1.27 to –9.18, and $\varepsilon_{Nd(t)}$ from +0.91 to –6.95, considering the depositional age of 230 Ma. The T_{DM} ages spread from 750 to 1360 Ma.

In the second profile, Rb values are between 85 and 133 ppm, Sr between 109 and 163 ppm, Sm from 3 to 5 ppm and Nd from 17 to 25 ppm. The $^{87}Sr/^{86}Sr$ values spread from 0.719 to 0.722 and the $^{87}Rb/^{86}Sr$ from 1.83 to 2.55. The values of the $^{147}Sm/^{144}Nd$ ratio are from

0.189 to 0.198, and the $^{143}Nd/^{144}Nd$ spreads from 0.5121 and 0.5122. These results correspond to $\varepsilon_{Nd(0)}$ values of -7.98 to -9.07, and $\varepsilon_{Nd(t)}$ from -5.75 to -6.84 (t=230 Ma). The obtained T_{DM} ages are between 1280 and 1365 Ma.

DISCUSSION

Sm-Nd and Rb-Sr analyses: provenance research

Provenance studies are capable of reconstructing the tectonic, geographic and climatic parameters of a given sedimentary basin. The most widely used provenance tools are conglomerate clast-counting, sandstone petrography (modal counting of detrital components), and geochemical analyses. Isotopic analyses by the Rb-Sr and Sm-Nd systems can also contribute in the identification of source areas for sediments and sedimentary rocks (Nelson and DePaolo, 1988; McLennan *et al.*, 1990), especially those deposited under dry climatic conditions, where erosion and transport are dominated by physical instabilization and ephemeral, short-lived, high-energy subaqueous flash-floods.

The Gondwana II Supersequence of the Paraná Basin, which corresponds to the Triassic section of southern Brazil, comprises the Sanga do Cabral, Santa Maria, Caturrita and Mata formations, deposited in fluvial and lacustrine systems (Scherer *et al.*, 2000), in a rift basin with preferential transport to north-northeast. The Santa Maria Formation is subdivided in the Passo das Tropas (basal sandstones) and Alemoa (upper siltstones and shales) members.

The analyzed samples are positioned at the base of the Alemoa Member, interpreted as deposited under floodplain and ephemeral lakes (Pierini, 2001) periodically dried (mudcracks, calcretes). The deposition of the Alemoa Member was processed during the Ladinian-Carnian interval, and then the reference age of 230 Ma was used for the calculation of $\varepsilon_{Nd(t)}$. In the first profile, located near the town of Santa Maria, the SM-1 and SM-5 samples yielded negative values of $^{87}Sr/^{86}Sr$, from 0.72298 and 0.72296, $^{143}Nd/^{144}Nd$ of 0.512168 and 0.5122, $\varepsilon_{Nd(t)}$, of -6.39 and -6.95, corresponding to T_{DM} of around 1.3 Ga. On the other hand, the samples SM-2 and SM-4 yielded positive values of $^{87}Sr/^{86}Sr$, from 0.72807 and 0.72229, $^{143}Nd/^{144}Nd$ of 0.512568 and 0.512573, $\varepsilon_{Nd(t)}$, from 0.81 to 0.91, corresponding to T_{DM} ages from 750 to 800 Ma. In the second profile, distant some 50 km eastward, near the town of Agudo, a more significant uniformity of values was observed, with all samples showing negative $\varepsilon_{Nd(t)}$ values, from -

5.75 to -6.84, $^{87}Sr/^{86}Sr$ of 0.71921 to 0.72242, $^{143}Nd/^{144}Nd$ of 0.512173 to 0.512231 and T_{DM} ages around 1.3 Ga (Fig. 5).

The values obtained for the SM-2 and SM-4 suggest significant contribution of mantle-derived source rocks, formed by juvenile accretion during the Neoproterozoic Brasiliano/Pan-African Cycle. The Cambaí Complex and Vacacaí Supercomplex (Fig. 6 e 7), units that compose the São Gabriel Domain, are the only units of the Sul-rio-grandense Shield to show Sm-Nd data compatible with the obtained results. Thus, these juvenile rocks were probably exposed and available for erosion during the deposition of the analyzed interval, especially in its western portion. On the other hand, the rest of the samples show values which suggest mixing of mantle-derived juvenile and crustal source areas. The Sm-Nd parameters, including T_{DM}, are very similar to those obtained by Borba *et al.* (2003b) for samples of the Camaquã Group (Santa Bárbara and Guaritas formations), which could be the main sources of sediments of the studied section in its eastern part.

Concerning the $^{87}Sr/^{86}Sr$ parameter it is possible to observe that all values are around 0.719 to 0.722 (Table I), the exception being sample SM-02 (0.72807). As the $^{87}Sr/^{86}Sr$ ratio may be altered by sedimentary process, specially the preferential solubility during weathering it is possible to say that Santa Maria samples are under an Sr *isotopic uniformization* process in order to show these homogeneous values (Cordani *et al.*, 2004). This behavior is related to the fine grained samples, mineralogical composition rich in expansive clay minerals and depositional system. So, the $^{87}Sr/^{86}Sr$ ratio does not indicate provenance but conditions associated to the sedimentary deposition. The sample SM-02 is possible contaminated by the presence of detrital minerals as the Rb/Sr ratio is very high when comparing with the analyzed samples.

In summary, it can be suggested that rock units located in the Sul-rio-grandense Shield, such as the Vacacaí, Cambaí and Camaquã units, were uplifted and available for erosion during the evolution of the Alemoa siltstones of the Triassic rift of southern Brazil. Evidences for uplifting during the Triassic were obtained previously by means of apatite fission-track thermochronology (Borba *et al.*, 2002, 2003a) and structural analysis (Zerfass *et al.*, 2005). The uplifted area, possibly bounded by NW-SE trending structures, would be composed, in the western portion, by juvenile rocks of the Cambaí/Vacacaí units, partially covered by sedimentary rocks of the Santa Bárbara Formation. In the
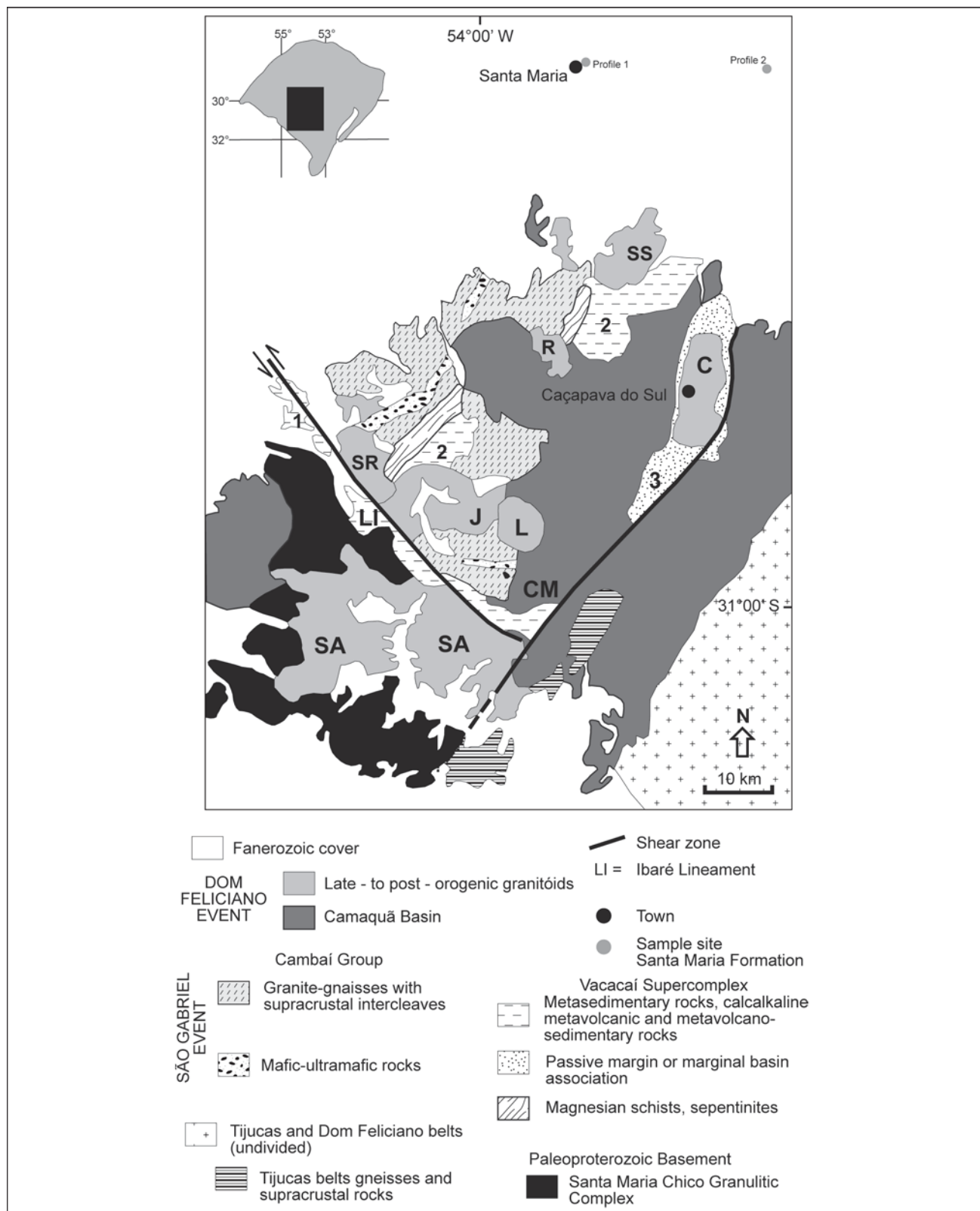
Figure 5. Geological map of Cinturão Vila Nova and Bloco Taquarembó (modified Chemale Jr. *et al.*, 1995) – 1 = Complexo Ibaré, 2 = Complexo Palmas/Bossoroca, 3 = Complexo Passo Feio and CM = Cerro Mantiqueiras. Granitic massives are: C = Caçapava do Sul, SS = São Sepé, R = Ramada, SR = Santa Rita, J = Jaguari, L = Lavras and SA = Santo Afonso.
Figura 5. Mapa geológico do Cinturão Vila Nova e Bloco Taquarembó (modif. de Chemale Jr. *et al.*, 1995) – 1 = Complexo Ibaré, 2 = Complexo Palmas/Bossoroca, 3 = Complexo Passo Feio e CM = Cerro Mantiqueiras. Os corpos graníticos são: C = Caçapava do Sul, SS = São Sepé, R = Ramada, SR = Santa Rita, J = Jaguari, L = Lavras e SA = Santo Afonso.
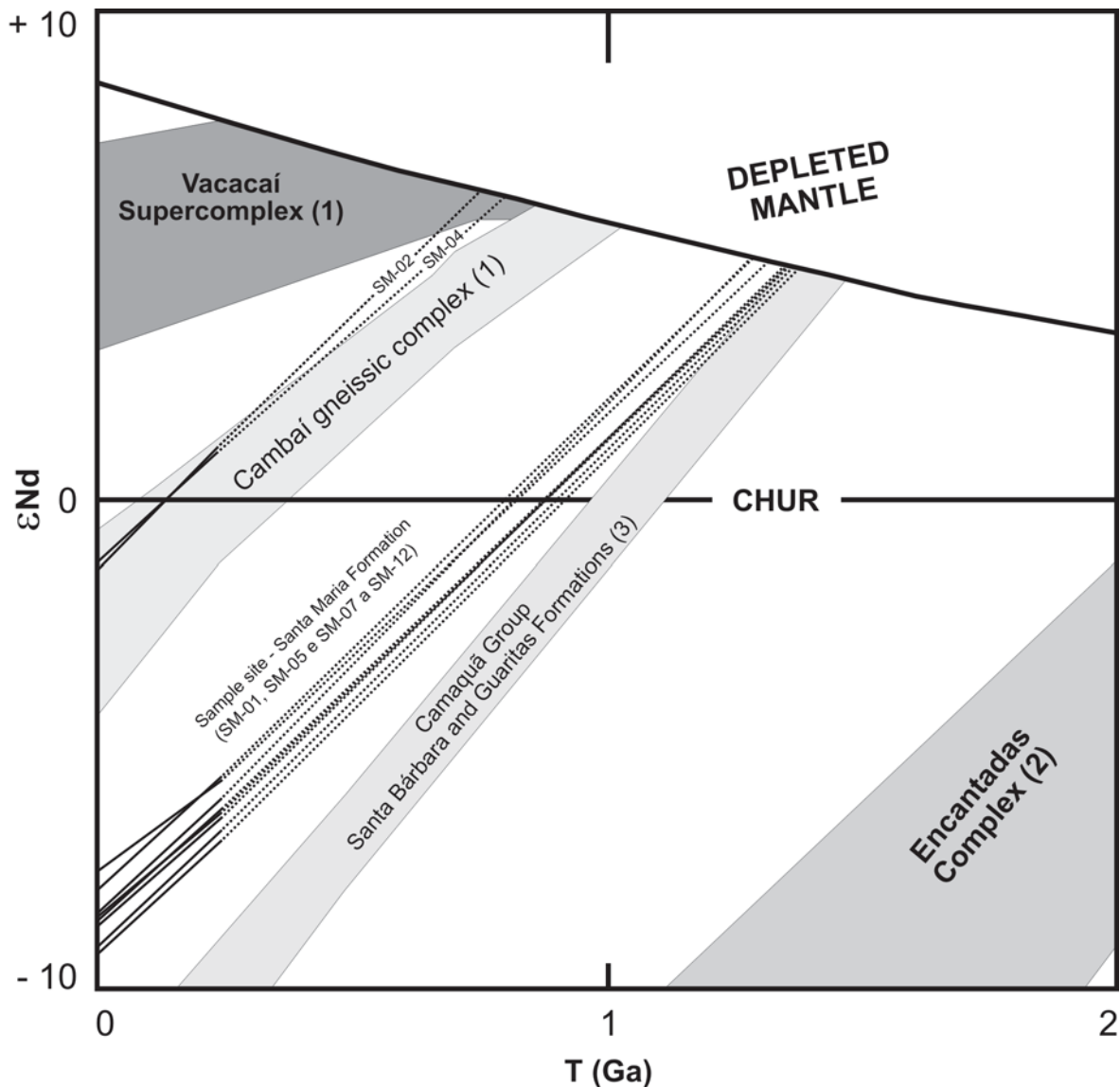
Figure 6. Diagram åNd vs. Time (DePaolo, 1981) Santa Maria Formation samples (1 - Babinski *et al.*, 1996; 2 - Chemale Jr., 2000; 3 - Borba *et al.*, 2004).

Figura 6. Diagrama åNd vs. Tempo (DePaolo, 1981) para as amostras da Formação Santa Maria (1- Babinski *et al.*, 1996; 2 - Chemale Jr.*,* 2000; 3 - Borba *et al.*, 2004).

east, a thicker sedimentary pile of the Camaquã Group would be the only available source rock, also limited by NW-SE faults.

CONCLUSIONS

The Rb-Sr and Sm-Nd isotopic systems were successfully applied to siltstone and sandstones samples collected from the Alemoa Member of the Santa Maria Formation, deposited in the Ladinian-Carnian inter-

val, Triassic (*ca*. 230 Ma).

The provenance parameters, obtained by the Sm-Nd procedures, allowed the proposition of a configuration of paleoborders, with Brasiliano juvenile units (Cambaí/Vacacaí) exposed in the west and sedimentary rocks of the Camaquã Group (Santa Bárbara Formation) available for erosion to the east, near Caçapava do Sul.

The $^{87}Sr/^{86}Sr$ ratio when applied as provenance indicator is not very conclusive especially to fine grained

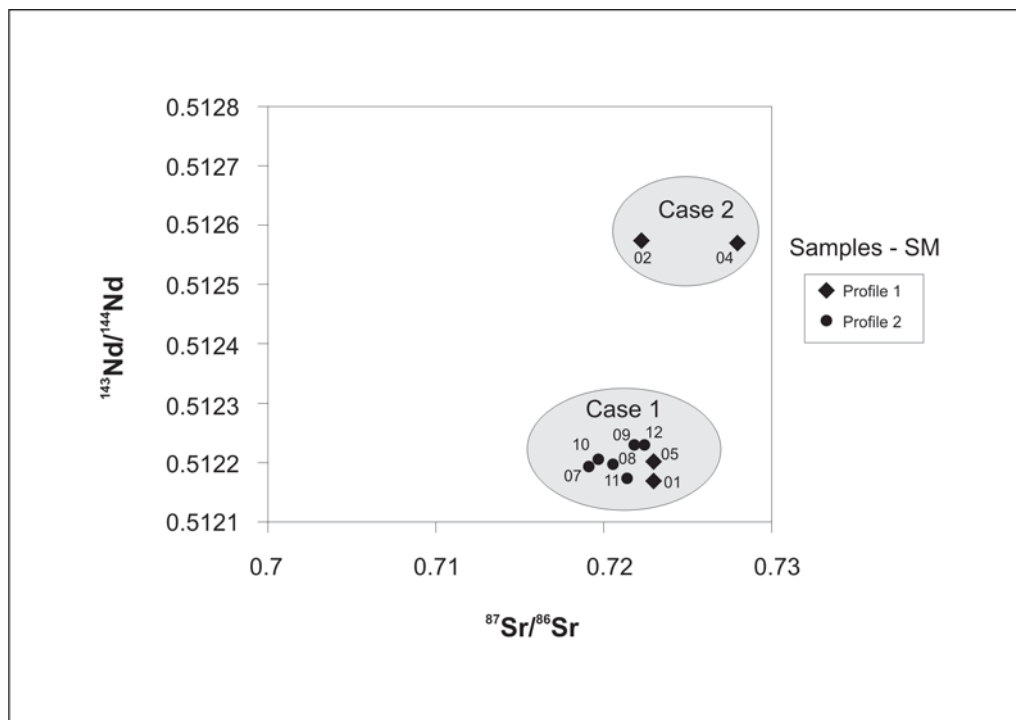**Figure 7.** Diagram $^{143}Nd/^{144}Nd$ vs. $^{87}Sr/^{86}Sr$. Case 1 = provenance: Camaquã Group (Santa Bárbara Formation); Case 2 = provenance: Vacacaí Supercomplex/Cambaí gneissic complex.

Figura 7. Diagrama $^{143}Nd/^{144}Nd$ vs. $^{87}Sr/^{86}Sr$. Caso 1 = proveniência: Grupo Camaquã (Formação Santa Bárbara); Caso 2 = proveniência: Supercomplexo Vacacaí/Complexo Gnáissico Cambai.

rocks as the Santa Maria samples. In this special case, there is possibility that an Sr *isotopic uniformization* process is being observed. Then, the $^{87}Sr/^{86}Sr$ ratio is useful to dating sedimentary process as deposition or diagenesis (Cordani *et al.*, 2004; Mizusaki *et al.*, 2002). Therefore, when associated with others provenance indicators as the $^{143}Nd/^{144}Nd$ ratio, it is a secondary information aiming inferences about the possible source rocks to the sedimentary unit analyzed.

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REFERENCES

Andersson, P.O.D., Å. Johansson and R.A. Kumpulainen, 2003. Sm-Nd isotope evidence for the provenance of the Skoorsteenberg Formation, Karoo Supergroup, South Africa. *Journal of African Earth Sciences* 36:173-183.

Awwiller, D.N. and L.E. Mack, 1991. Diagenetic modification of Sm-Nd model ages in Tertiary sandstones and shales, Texas Gulf Coast. *Geology* 19:311-314.

Babinski, M., F. Chemale Jr., L.A. Hartmann, W.R. Van Schmus and L.C. Silva, 1996. Juvenile accretion at 750-700 Ma in southern Brazil. *Geology* 24:439-442.

Babinski, M., F. Chemale Jr., W.R. Van Schmus and L.C. Silva, 1997. U-Pb and Sm-Nd geochronology of the Neoproterozoic granitic-gneissic Dom Feliciano Belt, southern Brazil. *Journal of South American Earth Sciences* 10:263-274.

Ball, T.T. and G.L. Farmer, 1998. Infilling history of a Neoproterozoic intracratonic basin: Nd isotope provenance studies of the Uinta Mountain Group, Western United States. *Precambrian Research* 87:1-18.

Bitencourt, M.F.A.S. and L.V.S. Nardi, 1993. Late- to post-collisional Brasiliano magmatism in southernmost Brazil. *Anais da Academia Brasileira de Ciências* 65:3-16.

Borba, A.W. and A.M.P. Mizusaki, 2003. Santa Bárbara Formation (Caçapava do Sul, southern Brazil): depositional sequences and evolution of an Early Paleozoic post-collisional basin. *Journal of South American Earth Sciences* 16:365-380.

Borba, A.W., M.L. Vignol and A.M.P. Mizusaki, 2002. Uplift and denudation of the Caçapava do Sul granitoids (southern Brazil) during Late Paleozoic and Mezosoic constraints from apatite fission track data. *Journal of South American Earth Sciences* 15:683-692.

Borba, A.W., E.F. Lima, M.L. Vignol, A.M.P. Mizusaki, I. Sparrenberg and C.E. Barros, 2003a. Significance of Late Paleozoic fission-track ages in volcanic rocks from the Lavras do Sul region, southernmost Brazil. *Gondwana Research* 6:79-88.

Borba, A.W., A.M.P. Mizusaki, D.R.A. Silva and K. Kawashita, 2003b. Razões isotópicas $^{87}Rb/^{86}Sr$, $^{87}Sr/^{86}Sr$ e $^{143}Nd/^{144}Nd$ como traçadores de proveniência de rochas sedimentares siliciclásticas: exemplos no Grupo Camaquã. *Pesquisas em Geociências* 30:39-50.

Borba, A.W., A.J. Maraschin and A.M.P. Mizusaki, 2004. Stratigraphic analysis and depositional evolution of the Neoproterozoic Maricá Formation (southern Brazil): constraints from field data and sandstone petrography. *Gondwana Research* 7:871-886.

Borba, A.W., A.M.P. Mizusaki, D.R.A. Silva, E. Koester, F.L. Noronha and J. Casagrande, 2006. Provenance of the Neoproterozoic Maricá Formation (Sul-rio-grandense Shield, southern Brazil): petrographic and Sm-Nd isotopic Constraints. *Gondwana Research* 9:464-474.

Bossi, J. and C. Gaucher, 2004. The Cuchilla Dionisio Terrane, Uruguay: an allochtonous block accreted in the Cambrian to SW-Gondwana. *Gondwana Research* 7:661-674.

Caputo, M.V. and J.C. Crowell, 1985. Migration of glacial ceters across Gondwana during Paleozoic era. *Geological Society of America Bulletin* 96:1020-1036.

Chemale Jr. F., L.A. Hartmann and L.C. Silva, 1995. Stratigraphy and tectonism of the Brasiliano Cycle in southern Brazil. *Communications of the Geological Survey of Namibia* 10:151-166.

Chemale Jr. F., 2000. Evolução Geológica do Escudo Sul-rio-grandense. In Holz, M. & L.F. DeRos (Eds.). *Geologia do Rio Grande do Sul*. Porto Alegre. Centro de Investigação do Gondwana/Universidade Feredeal do Rio Grande do Sul, p. 13-52.

Compston, W. and R.T. Pidgeon, 1962. Rubidium-Strontium dating of shales by the whole-rock method. *Journal of Geophysical Research* 67:3493-3502.

Cordani, U.G., A.M.P. Mizusaki, K. Kawashita and A. Thomaz Filho, 2004. Rb-Sr systematics of Holocene pelitic sediments and their bearing on whole rock dating. *Geological Magazine* 141:233-244.

DePaolo, D.J., 1988. *Neodymium Isotope Geochemistry*. Springer-Verlag, Berlin, 187 pp.

Faure, G., 1986. *Principles of isotope geology*. Jonh Wiley & Sons, New York, 587 pp.

Farmer, G.L., G. Espinoza, M. Morales, M.W. Martín and S.A. Bowring, 2001. Nd isotope constraints on sources of Neoproterozoic to Early Cambrian siliciclastic sedimentary rocks in northern Sonora. *Journal of South American Earth Sciences* 14:437-446.

Fernandes, L.A.D., A. Tommasi and C.C. Porcher, 1990. Esboço estrutural de parte do Batólito Pelotas, região de Quitéria-Capivarita. *Acta Geologica Leopoldensia* 30:117-138.

Fernandes, L.A.D., R. Menegat, A.F.U. Costa, E. Koester, C.C. Porcher, A. Tommasi, G. Kraemer, G.E. Ramgrab and E. Camozzato, 1995. Evolução tectônica do Cinturão Dom Feliciano no Escudo Sul-rio-grandense, Parte I - uma contribuição a partir do registro geológico. *Revista Brasileira de Geociências* 25:351-374.

Frantz, J.C., E.F. Lima, R.P. Machado and M. Naumann, 1984. Contribuição à geologia de Encruzilhada do Sul-RS. In: Congresso Brasileiro Geologia, 33, 1984, Rio de Janeiro. *Anais..., Sociedade Brasileira de Geologia* 5:2407-2416.

Frantz, J.C., N.F. Botelho, M.M. Pimentel, A. Potrel, E. Koester and R.S. Teixeira, 1999. Relações isotópicas Rb-Sr e Sm-Nd e idades do magmatismo granítico brasiliano da região leste do Cinturão Dom Feliciano no Rio Grande do Sul: evidências de retrabalhamento de crosta continental paleoproterozóica. *Revista Brasileira de Geociências* 29:227-232.

Gleason, J.D., P.J. Patchett, W.R. Dickinson and J. Ruiz, 1994. Nd isotopes link Ouachita turbidites to Appalachian sources. *Geology* 22:347-350.

Gleason, J.D., P.J. Patchett, W.R. Dickinson and J. Ruiz, 1995. Nd isotopic constraints on sediment sources of the Ouachita-Marathon fold belt. *Geological Society of America Bulletin* 107:1192-1210.

Hartmann, L.A., L.C. Silva, M.V.D. Remus, J.A.D. Leite and R.P. Phillip, 1998. Evolução geotectônica do Sul do Brasil e Uruguai entre 3,3 Ga e 470 Ma. Actas, *II Congreso Uruguayo de Geología*, p. 277-284, Punta del Este, Uruguay.

Hartmann, L.A., J.A.D. Leite, N.J. McNaughton and J.O.S. Santos, 1999. Deepest exposed crust of Brazil - SHRIMP establishes three events. *Geology* 27:947-950.

Hartmann, L.A., A.P. Lopes, Y. Wang, D. Liu and M.A.Z. Vasconcellos, 2003. Oceanic plateau accretion at 705 Ma in the southern Brazilian shield. Short papers 4th South American Symposium on Isotope Geology 1:178, Salvador, Brazil.

Holz, M. and R. Carlucci, 2000. Litoestratigrafia, Estratigrafia de Seqüências e Evolução Paleofisiográfica da zona de borda da Bacia do Paraná no Rio Grande do Sul durante o Eo-Permiano. In Holz, M., L.F. De Ros (Eds.). *Geologia do Rio Grande do Sul*, Centro de Investigação do Gondwana/Universidade Feredeal do Rio Grande do Sul, p. 303-322.

Jost, H. and M.F.A.S. Bitencourt, 1980. Estratigrafia e tectônica de uma fração da Faixa de dobramentos Tijucas no Rio Grande do Sul. *Acta Geologica Leopoldensia* 4:27-59.

Leinz, V., A.F. Barbosa and E. Teixeira, 1941. Mapa Geológico Caçapava-Lavras. Boletim 90, Secretaria da Agricultura, Indústria e Comércio - RS.

Leite, J.A.D., L.A. Hartmann, N.J. McNaughton and F. Chemale Jr., 1998. SHRIMP U/Pb zircon geochronology of Neoproterozoic juvenile and crustal-reworked terranes in southernmost Brazil. *International Geology Reviews* 40:688-705.

Machado, N., J.C. Koppe and L.A. Hartmann, 1990. A late Proterozoic U-Pb age for the Bossoroca Belt, Rio Grande do Sul, Brazil. *Journal of South American Earth Sciences* 3:87-90.

McBride, E. F., 1963. A classification of common sandstones. *Journal of Sedimentary Geology* 33:664-669.

McLennan, S.M., S.R. Taylor, M.T. McCulloch and J.B. Maynard, 1990. Geochemical and Nd-Sr isotopic composition of deep-sea turbidites: crustal evolution and plate tectonic associations. *Geochimica et Cosmochimica Acta* 54:2015-2050.

Menezes, J.R.C., 2000. Estratigrafia do Neopermiano da Bacia do Paraná no Rio Grande do Sul. In Holz, M., L.F. De Ros (Eds.). *Geologia do Rio Grande do Sul*, Centro de Investigação do Gondwana-Universidade Federal do Rio Grande do Sul, p. 323-334.

Milani, E.J., 1997. *Evolução Tectono-Estratigráfica da Bacia do Paraná e seu Relacionamento com a Geodinâmica Fanerozóica do Gondwana Sul-Ocidental*. Unpublished M.Sc. Dissertation, Instituto de Geociências/Universidade Federal do Rio Grande do Sul, 255 pp.

Milani, E.J., 2000. Geodinâmica Fanerozóica do Gondwana sul-ocidental e a Evolução Geológica da Bacia do Paraná. In: Holz, M., L.F. De Ros (Eds.). *Geologia do Rio Grande do Sul*, Centro de Investigação do Gondwana/Universidade Federal do Rio Grande do Sul, p. 275-302.

Mizusaki, A.M.P., 1992. *Comportamento do Rb e do Sr em sedimentos recentes: implicação na datação radiométrica de rochas sedimentares.* Unpublished Ph.D. Thesis, Universidade de São Paulo, 144 pp.

Mizusaki, A.M.P., J.H.G. Melo, M.L. Vignol-Lelarge and **P. Steemans,** 2002. Vila Maria Formation, Paraná Basin, Brazil - an example of integrated geochronological and palynological dating. *Geological Magazine*, Cambridge 139:453-463.

Nelson, B.K. and **D.J. DePaolo,** 1988. Comparison of isotopic and petrographic provenance indicators in sediments from Tertiary continental basins of New Mexico. *Journal of Sedimentary Petrology* 58:348-357.

Paim, P.S.G., Chemale Jr. F., and **R.C. Lopes**, 2000. A Bacia do Camaquã. In: Holz, M., L.F. De Ros (Eds.). *Geologia do Rio Grande do Sul*, Centro de Investigação do Gondwana/Universidade Federal do Rio Grande do Sul, p. 231-274.

Philipp, R.P. and **R. Machado,** 2002. Ocorrência e significado dos septos do embasamento encontrados nas suítes graníticas do Batólito Pelotas, RS, Brasil. *Pesquisas em Geociências* 29:43-60.

Pierini, C., 2001. *Uso integrado de técnicas analíticas na análise estratigráfica de Sistemas Fluviais - o exemplo das formações Santa Maria e Caturrita (Triássico Superior, Bacia do Paraná, RS).* Unpublished M.Sc. Dissertation, Universidade Federal do Rio Grande do Sul, 128 pp.

Pimentel, M.M., M.A. Dardenne, R.A. Fuck, M.G. Viana, S.L. Junges, D.P. Fischel, H.J.Seer and **E.L. Dantas,** 2001. Nd isotopes and the provenance of detrital sediments of the Neoproterozoic Brasília Belt, central Brazil. *Journal of South American Earth Sciences* 14:571-585.

Porcher, C.C., N.J. McNaughton, J.A.D. Leite, L.A. Hartmann and **L.A.D. Fernandes,** 1999. Idade SHRIMP em zircão: vulcanismo ácido do Complexo Metamórfico Porongos. Boletim de Resumos, *1º Simpósio sobre Vulcanismo e Ambientes Associados*, p. 110, Gramado, Brazil.

Remus, M.V.D, N.J. Mcnaughton, L.A. Hartmann and **I.R. Fletcher,** 1997. Zircon SHRIMP dating and Nd isotope data of granitoids of the São Gabriel Block, southern Brazil: evidence for an Archean Paleoproterozoic basement, *II International Symposium on granites and associated mineralization*, p. 271-272, Salvador, Brazil.

Roisenberg, A. and **A.P. Viero,** 2000. O Vulcanismo Mesozóico da Bacia do Paraná no Rio Grande do Sul. In: Holz, M., L.F. De Ros (Eds.). *Geologia do Rio Grande do Sul*, Centro de Investigação do Gondwana/Universidade Federal do Rio Grande do Sul, p. 355-374.

Saalmann, K., L.A. Hartmann, M.V.D. Remus, E. Koester and **R.V. Conceição,** 2005. Sm-Nd isotope geochemistry of metamorphic volcano-sedimentary successions in the São Gabriel Block, southernmost Brazil: evidence for the existence of juvenile Neoproterozoic oceanic crust to the east of the Rio de la Plata craton.

Precambrian Research 136:159-175.

Scherer, C.M.S., U.F. Faccini and **E.L. Lavina,** 2000. Arcabouço Estratigráfico do Mesozóico da Bacia do Paraná. In: Holz, M. & L.F. DeRos (Eds.). *Geologia do Rio Grande do Sul.* Porto Alegre. Centro de Investigação do Gondwana/Universidade Federal do Rio Grande do Sul, p. 335-354.

Scherer, C.M.S., P.S.G. Paim and **M.A. Melo,** 2003. Estratigrafia de alta resolução em sucessões flúvio-eólicas: o exemplo do Alogrupo Guaritas (Bacia do Camaquã) na localidade da Pedra Pintada, Rio Grande do Sul, Brasil. *I Encontro sobre a Estratigrafia do Rio Grande do Sul: Escudo e Bacias*. Anais, p. 99-104, Porto Alegre, Brazil.

Scherer, C.M.S. and **E.L.C. Lavina,** in press. Stratigraphic evolution of a fluvial-eolian succession: the example of the Upper Jurassic-Lower Cretaceous Guara and Botucatu formations, Parana Basin, southernmost Brazil. *Gondwana Research*, in press.

Soliani Jr., E., E. Koester and **L.A.D. Fernandes,** 2000. Geologia isotópica do Escudo Sul-rio-grandense, parte II: os dados isotópicos e interpretações petrogenéticas. In Holz, M.; L.F. De Ros (Eds.). *Geologia do Rio Grande do Sul.* Centro de Investigação do Gondwana/Universidade Federal do Rio Grande do Sul, p.175 230.

Sommer, C.A., E.F. Lima, L.V.S. Nardi, J.D. Liz, R. Pierosan and **B.L. Waichel,** 2003. Stratigraphy of the Acampamento Velho Alloformation in the Ramada Plateau, Vila Nova do Sul region, RS. In *I Encontro sobre a Estratigrafia do Rio Grande do Sul: Escudo e Bacias.* Anais, p. 105-110, Porto Alegre, Brazil.

Vasconcellos, M.A.Z., G. Giuriatti, L.A. Hartmann, D. Liu and **R.P. Philipp,** 2003. Integrated geochronological and structural evaluation of the significance of detrital zircon crystals from the Porongos complex, southern Brazilian shield. *4th South American Symposium on Isotope Geology,* Short papers 1:134-137, Salvador, Brazil.

Zerfass, H., A J.V. Garcia, A M. Susczynski and **E.L. Lavina,** 2000. Análise de proveniência nos arenitos neopermianos e triássicos da Bacia do Paraná na região de São Pedro do Sul (RS): uma contribuição para arquitetura estratigráfica e evolução tectonosedimentar. *Acta Geologica Leopoldensia* 23:61-84.

Zerfass, H., E.L. Lavina, C.L. Schultz, A.J.V. Garcia, U.F. Faccini and **F. Chemale Jr.,** 2003. Sequence stratigraphy of continental Triassic strata of southernmost Brazil: a contribution to Southwestwern Gondwana palaeogeography and palaeoclimate. *Sedimentary Geology* 161:85-105.

Zerfass, H., F. Chemale Jr. and **E.L. Lavina,** 2005. Tectonic control of the Triassic Santa Maria Supersequence of the Paraná Basin , southernmost Brazil , and its correlation to the Waterberg Basin, Namibia. *Gondwana Research* 8:163-176.

Zhao, J.X., M.T. McCulloch and **V.C. Bennett,** 1992. Sm-Nd and U-Pb zircon isotopic constraints on the provenance of sediments of the Amadeus Basin, central Australia: evidence for REE fractionation. *Geochimica et Cosmochimica Acta* 56:921-940.