Depositional provinces, dispersal, and origin of terrigenous sediments along the SE South American continental margin

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A B S T R A C T

Continental margin sediments of SE South America originate from various terrestrial sources, each conveying specific magnetic and element signatures. Here, we aim to identify the sources and transport characteristics of shelf and slope sediments deposited between East Brazil and Patagonia (20°–48° S) using enviromagnetic, major element, and grain-size data. A set of five source-indicative parameters (i.e., χsf%, ARM/IRM, S0.3T, SIRM/Fe and Fe/K) of 25 surface samples (16–1805 m water depth) was analyzed by fuzzy c-means clustering and non-linear mapping to depict and umix sediment-province characteristics. This multivariate approach yields three regionally coherent sediment provinces with petrologically and climatically distinct source regions. The southernmost province is entirely restricted to the slope off the Argentinean Pampas and has been identified as relic Andean-sourced sands with coarse unaltered magnetite. The direct transport to the slope was enabled by Rio Colorado and Rio Negro meltwaters during glacial and deglacial phases of low sea level. The adjacent shelf province consists of coastal loessoidal sands (highest hematite and goethite proportions) delivered from the Argentinean Pampas by wave erosion and westerly winds. The northernmost province includes the Plata mudbelt and Rio Grande Cone. It contains tropicaly weathered clayey silts from the La Plata Drainage Basin with pronounced proportions of fine magnetite, which were distributed up to ~24° S by the Brazilian Coastal Current and admixed to coarser relic sediments of Pampean loessoidal origin. Grain-size analyses of all samples showed that sediment fractionation during transport and deposition had little impact on magnetic and element source characteristics. This study corroborates the high potential of the chosen approach to access sediment origin in regions with contrasting sediment sources, complex transport dynamics, and large grain-size variability.

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1. Introduction

The SE South American continental margin (Fig. 1a,b) presents unusually wide-stretching sediment distribution patterns due to a complex oceanographic setting. The Brazil-Malvinas Current System creates a pronounced confluence zone off the Rio de La Plata estuary, formed by the warm poleward Brazil Current along the Brazilian and Uruguayan margins and the cold equatorward Malvinas Current along the Argentinian margin. These boundary currents drive shelf currents with seasonally varying intensity and meridional extent. As changing position and intensity of the involved currents on various time scales (seasonal, interannual, multi-decadal, multi-millennial, and glacial–interglacial) can be recorded in sediment properties and modern or past distribution patterns (e.g., Chiessi et al., 2007; Razik et al., 2013), these provide information of regional to global significance. The Brazil-Malvinas Current System plays an important climatic role due to its water exchange and heat transfer between the Southern Ocean and the tropical South Atlantic (e.g., Gordon, 1981). Delineating the depositional provinces, dispersal, and origin of terrigenous sediments off SE South America based on surface-sediment distribution is therefore a key to reconstruct the past dynamics of the large-scale coupled atmosphere–ocean circulation in this critical sector of the southern hemisphere (e.g., Mahiques et al., 2008; Lantzsch et al., 2014).

Several studies have tried to identify the sediment sources and transport paths along this continental margin across the Brazil-Malvinas Confluence: Urien and Ewing (1974), Martins et al. (2005), and Nagai et al. (2013) investigated the northward transport of coarse Argentinean shelf and fine Plata plume sediments with various sedimentary methods. The most extended study was undertaken by Mahiques et al. (2008) using Pb- and Nd-isotopes and showing that Plata plume sediments reach as far north as Cape Santa Marta (~28° S) (Fig. 1b). Multi-proxy studies of Mahiques et al. (2004, 2009) and Cyllencez et al. (2010), and the enviromagnetic investigation of Mathias et al. (2014) could detect the presence of Plata plume sediments up to São Sebastião.

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Island (~24° S). Clay and heavy-mineral analyses by Campos et al. (2008) and Corrêa et al. (2008) could track Argentinean shelf sediments in surface deposits up to the Subtropical Shelf Front (STSF; e.g., Piola et al., 2000) at 34°–36° S. Further north at the Rio Grande Cone (31°–34° S), Razik et al. (2013) found a mixture of fine sands from the Argentinean shelf and Plata plume silts and clays supplied during the Mid Holocene using rock magnetics, major elements, and grain-size analyses. Nd-isotope investigations from the same bulk sediment (Lantzsch et al., 2014) were dominated by the properties of the clayey and Nd-rich, but minor Plata plume sediments, leaving the possibility of an undetected northward transport of Nd-depleted Argentinean shelf sands.

However, the mineral composition (Komar, 2007; Garzanti et al., 2009), as well as major element (Whitmore et al., 2004) and isotopic signatures (Revel et al., 1996; Innocent et al., 2000) of coast and shelf sediments may depend on the deposited grain-size fractions and hence on the depositional environment, a fact, which can easily misguide provenance studies based on bulk sediments. Some studies have addressed this problem either by comparing equivalent grain-size fractions (which may not exist in the case of large-scale studies) or by combining independent source-specific parameters, thereby reducing the grain-size bias of each individual method (e.g., Hatfield, 2014).

Here, we apply the latter strategy to deduce sources and mixing of terrigenous surface sediments along the SE South American continental margin. For the first time, rock magnetic and major element properties of this region are being jointly investigated and compared with clastic grain-size distributions. Five concentration-independent parameter ratios ($\chi_{fd}$, ARM/IRM, $S_{0.3T}$, SIRM/Fe and Fe/K) are used for fuzzy $c$-means (FCM) cluster analysis and non-linear mapping (NLM) in order to define regionally coherent clusters representing geologically and hydrographically distinct sediment provinces and infer their source areas.

2. Hydrographic and sedimentary setting

2.1. Hydrography of SE South America

As a continuation of the Brazil-Malvinas Confluence Zone on the shelf (Fig. 1b), the north–south oriented STSF divides the cold and relatively fresh Subantarctic Shelf Water of the Patagonian Current from the warm and more saline Subtropical Shelf Water of the Brazil Current (Piola et al., 2000, 2005; Möller et al., 2008). To the south of the STSF, the La Plata Drainage Basin (LPDB) discharges large amounts of freshwater (710 km$^3$ yr$^{-1}$) at the Rio de La Plata estuary at ~35° S (e.g., Bernardes et al., 2012). The northeastward-directed Brazilian Coastal Current carries this Plata Plume Water at the inner continental shelf along the Uruguayan coast towards South Brazil (Souza and Robinson, 2004). The Plata Plume Water frequently reaches 24° S during
austral fall and winter (Piola et al., 2008; Palma et al., 2008), sporadically reaching as far north as 22°S (Stevenson et al., 1998). The Plata Plume Water mainly consists of the Rio Paraná water with a minor contribution from the Patos Lagoon (63 km$^3$ yr$^{-1}$) (Campos et al., 2013). While riverine runoff between 22° and 34°S is only of local importance, it is negligible at regional and continental scales under modern conditions (Campos et al., 2008; Corrêa et al., 2008).

2.2. Sedimentology off SE South America

The hydrographic circulation patterns are mirrored to a large degree by the distribution of terrigenous surface sediments, where so far the grain size is the only sedimentary information available for the entire SE South American margin (Frenz et al., 2013). South of 36°S (Fig. 1a), the continental shelf and slope off Patagonia and off the Argentinean Pampas (later referred to as 'the Pampas') are primarily covered with fine siliclastic sands (Urien and Ewing, 1974; Parker et al., 1997; Frenz et al., 2003; Martins et al., 2005). Gravel and mud are mainly restricted to the inner shelf (0–50 m water depth) off Patagonia and off the Rio de La Plata estuary. Mud is also found at contourite terraces of the mid and lower slope (Frenz et al., 2003; Hernández-Molina et al., 2009; Bozzano et al., 2011; Preu et al., 2013). In particular the sands contain high concentrations of igneous detritus (Potter, 1984, 1986; Bozzano et al., 2011) and were mainly deposited as coastline sediments under low sea-level conditions and later reworked by coastal processes processes under a predominantly northward along-shore transport.

The continental margin off Uruguay and South Brazil up to Cape Santa Marta (29°–36°S; Fig. 1a) shows a more heterogeneous sedimentary pattern. Along the inner shelf, siliciclastic sands constitute ~50% of the surface sediments (Urien and Ewing, 1974; Potter, 1984, 1986). On the outer shelf (100–160 m water depth), relic sands make up to 75% of the total sediment (Urien and Ewing, 1974; Franco-Fraguas et al., 2014; Lantzsch et al., 2014). Generally, the upper and mid continental slope is composed of sandy (~50%) and silty (~50–65%) deposits. However, the mid shelf (50–100 m; in particular the Plata mudbelt, a recently filled lowstand paleo-valley of the Rio Paraná to the northeast of the Rio de La Plata estuary; e.g., Lantzsch et al., 2014) and the continental slope of the Rio Grande Cone (31°–34°S) constitute exceptional sediment compositions: Their shelf deposits are characterized by coarse silts or even finer sediments (Urien and Ewing, 1974; Labarde, 1997; Violante and Parker, 2004; Lantzsch et al., 2014), which turn into silty to clayey muds at the upper and mid slope (Frenz et al., 2003). Those fine deposits were described as magnetite-rich sediments transported with the Plata Plume Water and deflected off-shelf at the STSF (e.g., Razik et al., 2013). Further to the north, clay content increases and reaches 60% at the slope off Cape Santa Marta (Frenz et al., 2003).

The continental margin off SE Brazil between Cape Santa Marta and Cape Frio (23°–29°S; Fig. 1a) exposes the coarsest deposits (125–500 μm) at the inner shelf, which decrease in grain-size towards the mid shelf. There, they regionally show very 'patchy' depositional patterns being locally identified as coarse, medium or fine silts (Mahiques et al., 2004; Gyllencreutz et al., 2010; Reis et al., 2013). Towards the outer shelf and the slope, sediments increase in grain-size being characterized as coarse sands (Mahiques et al., 2004; Reis et al., 2013). These 'patchy' distributions are an effect of intensive sediment remobilization and redistribution due to frequent up- and downwelling (Mahiques et al., 2002, 2004; Gyllencreutz et al., 2010). Eddies and vertical movements in the water column are generated by the meandering Brazil Current (Campos et al., 2000; Silveira et al., 2008; Calado et al., 2010).

The investigated continental margin off East Brazil to the north of Cape Frio is confined to 20°–23°S (Fig. 1a). The continental shelf to the north of the Rio Faralda do Sul shows the coarsest sediments in this region (i.e., coarse sands) (Reis et al., 2013). At the inner and the mid shelf southward of the Rio Faralda do Sul mouth, sediments become finer (i.e., medium sands) and change to fine sands to the northeast of Cape Frio. Directly southward of Cape Frio, surface deposits are identified as muds. This fining pattern is mainly caused by the upwelling of the South Atlantic Central water onto the shelf in the wake of the southward-directed flow of the Brazil Current (Oliveira et al., 2012; Mendoza et al., 2014). The upper slope (200–400 m) is primarily covered with medium to coarse sandy contouritic deposits (Viana, 2002). The middle slope (400–1500 m) being under the influence of the Intermediate Western Boundary Current is characterized by erosional surfaces, while the lower slope (1500–3500 m) serves as a deposition center for fine to medium sandy patches and separated plastered contouritic drifts.

3. Materials and methods

3.1. Materials

This study is based on 25 surface sediment samples collected at the continental margin of SE South America during RV Meteor cruises M23/2 (Bleil et al., 1994), M29/1+2 (Schulz et al., 1995), M46/2+3 (Schulz et al., 2001; Bleil et al., 2001), M49/3 (Bleil et al., 2002) and M78/3a–b (Kratzel and Wefer, 2011) (Fig. 1a; Table 1). They were obtained with giant box corers (GBC) and multi-corers (MC) from water depths between 16 and 1805 m. A 1.5-cm thick slice was sampled of the sediment top, representing a time span of 40–150 years assuming typical shelf and slope sedimentation rates of 10–40 cm kyr$^{-1}$ (Chiessi et al., 2007).

3.2. Methods

3.2.1. Grain-size analysis

Grain-size distributions of the terrigenous sediment fraction were determined by laser particle sizing after chemical removal of organic carbon, calcium carbonate (CaCO$_3$) and biogenic opal. Samples of 2–4 g were consecutively treated with 10 ml H$_2$O$_2$ (35%v/v), 10 ml MUC = Multi Corer and GBC = Giant Box Corer. 

<table>
<thead>
<tr>
<th>Surface sample (GeoB)</th>
<th>Latitude [° N]</th>
<th>Longitude [° E]</th>
<th>Water depth [m]</th>
<th>RV METEOR cruise</th>
<th>Recovery method</th>
</tr>
</thead>
<tbody>
<tr>
<td>2102-1</td>
<td>-24.0</td>
<td>-41.2</td>
<td>1805</td>
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<td>MUC</td>
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<tr>
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<tr>
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<td>1542</td>
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<td>MUC</td>
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<tr>
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<td>-55.0</td>
<td>576</td>
<td>M29/1</td>
<td>MUC</td>
</tr>
<tr>
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<td>1087</td>
<td>M29/1</td>
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<td>637</td>
<td>M78/3b</td>
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diphosphate decahydrate) was added to the sediment solutions before analysis.

The analyses were performed using a BECKMAN-COULTER LS200 laser particle sizer coupled to a water demineralization and degassing device at the MARUM – Center for Marine Environmental Sciences in Bremen (Germany). The grain-size detection range of the equipment is specified as 0.04–2000 μm. Due to the sediment pre-treatment and its settling properties, abundances of particles <2 μm might be under-represented. For data processing the BECKMAN-COULTER particle characterization software v.3.01 was used.

3.2.2. Major element analysis

Major element concentrations of Al, Ca, Fe, K, Si, and Ti were detected by energy dispersive polarization X-ray fluorescence (EDP-XRF). 3–6 cm³ of bulk sediment (~0.5–5 g of dry sediment) were freeze-dried, then powdered and homogenized with an agate mortar, and loosely packed into plastic sample holders with bottoms of Ultralene® X-ray transmission foil. EDP-XRF spectroscopy was performed on a SPECTRO XEPOS instrument at the MARUM, as described in Tjallingii et al. (2007). The device was operated with the Spectro X-Lab Pro v.2.4 software following the Turboquant method of Schramm and Heckel (1998). The analytical quality of the measurements was assessed by repeated analyses of the certified standard reference material MAG-1 (Govindaraju, 1994). The measured values were within 1% of accepted values. The root mean square deviation of replicated samples is ~2%. In the following, we focus on the Fe/K values.

3.2.3. Rock magnetic measurements

Frequency-dependent magnetic susceptibility (χfd%) was measured on a BARTINGTON MS2 unit with a B-type sensor operating at frequencies of 0.46 kHz and 4.6 kHz. Each sample was measured three times at a resolution of 1.0 × 10⁻⁶ SI with intermittent zero measurements. As the volume susceptibility χ values (not shown here) were all above 130 × 10⁻⁶ SI (reaching 3500 x 10⁻⁶ SI), the χfd% values can be treated as reliable (e.g., Dunlop and Özdemir, 2001).

Measurements of the anhysteretic and isothermal remanent magnetizations (ARM and IRM, respectively) were performed with an automated 2G ENTERPRISES 755R DC-SQUID pass-through magnetometer at the Marine Geophysics Section, University of Bremen (Germany). The sensitivity of this equipment is 1.0 × 10⁻¹² A m⁻¹ corresponding to 0.1613 × 10⁻⁶ A m⁻¹ for a cube sample of 6.2 cm³.

For ARM analyses, the samples were magnetized in a biasing direct field of 40 μT and a 0.1 T alternating magnetic field, followed by demagnetization over 11 field steps. IRM was acquired over 22 steps from 0 to 0.7 T in an internal pulse coil and over five further steps up to a maximum field of 2.6 T in an external pulse coil. Peak field magnetization was assumed as saturation IRM (SIRM), although saturation of hematite and goethite may not be complete (Dunlop and Özdemir, 2001). ARM/IRM was calculated for an IRM at 0.1 T. The saturation ratio (S0.3T) is the ratio of the remanences acquired at 0.3 T and 2.6 T.

3.2.4. Fuzzy c-means cluster analysis and non-linear mapping

Cluster analysis is a multivariate statistical method to discern similarities among multi-parametric data sets. Applied to sediment properties, it can detect groupings and their relations representing possible sediment sources and mixing, which may not be evident from univariate or bivariate analyses (Urbat et al., 1999; Schmidt et al., 1999; Watkins et al., 2007).

In FCM cluster analysis (Bezdek, 1981), likeness or similarity of a sample with respect to a cluster center is measured by a continuous function between 0 (completely different) and 1 (exactly the same). The memberships of one sample to all cluster centers sum up to 1. Hence, FCM cluster analysis allows gradual membership transitions between clusters, where intermediate cases can be recognized by similar memberships to two or multiple cluster centers. NLM produces a lower-dimensional projection of a multi-dimensional data cloud, such that the data point distances are minimally distorted during an iterative process (e.g., Vriend et al., 1988; Urbat et al., 1999). NLM makes no presumptions about cluster structures.

The MATHWORKS Matlab R12 ‘Fuzzy Logic Toolbox’ was used for FCM cluster analysis after Bezdek (1981) and for NLM after Sammon (1969). Prior to analysis, all parameters were standardized (i.e., normalized to a mean of 0 and a standard deviation of 1) to avoid over-representation of parameters with large values or variability. Subsequently, a two-tailed ‘Kolmogorov–Smirnov test’ at a significance level of α = 0.02 (e.g., Davis, 1986) was performed on each parameter to test for normal or log-normal frequency distribution (Fig. 2). Although the data sets contain three outliers deviating from the mean value by >3σ (i.e., χ0.3% of GeoB 13813-7 and 138171-1 in Fig. 2a; S0.3T of GeoB 13834-1 in Fig. 2b), we decided not to exclude them from the analysis as they carry meaningful sedimentary information. Analyses performed with

![Fig. 2](image-url)
and without these outliers (not shown) did not show significant differences in cluster configuration.

Input parameters for these multivariate statistics were carefully chosen securing that each parameter quantifies a distinct and unique property with a clear geological interpretation. Only concentration-independent interparametric ratios were used in order to eliminate their negligible influence on the cluster solution. Their environmental interpretation is summarized in Table 2.

The magnetogranulometric ratios $X_{80\%}$ and ARM/IRM must not be confused with elastic grain sizes, because small magnetic crystals can be contained within larger (carbonate, quartz, and feldspar) so-called ‘host’ grains, which mirror their origin (e.g., Hounslow and Maher, 1996; Otofuji et al., 2000; Hounslow and Morton, 2004). $S_{0.3T}$ compares the relative influences of magnetically ‘soft’ (magnetite and maghemite) and ‘hard’ (hematite and goethite) minerals. SIRM/Fe relates ferrimagnetic to paramagnetic Fe-bearing minerals. Fe/K differentiates less and more chemically weathered sediments. High Fe/K values, for instance, represent advanced chemical weathering due to the higher solubility of K over Fe in tropical soils (e.g., ferrasols, plinthosols, and acrisols) (Moore and Dennen, 1970; Middelburg et al., 1988; Govin et al., 2012). In conclusion, the parameter set differentiates both source rock (granites, basalts etc.) and weathering state (hematite, maghemite, clay) properties.

4. Results

This section starts presenting all grain-size distribution data to document the regional depositional conditions in the study area (Fig. 3). The FCM and NLM methods then allow to group and compare samples based on their joint magnetic and element properties (Fig. 4). Providing the ‘large pattern’ of sample relationships, these multivariate analyses are fully objective and independent from geographical information. By setting the obtained groupings into a geographical context, their regional associations are identified. The cluster membership coefficients are also translated into RGB colors, which are systematically used to show groupings in Figs. 3–6.

4.1. Regional grain-size distribution patterns

On the slope off Patagonia, the Pampas, and Uruguay (Fig. 3d), very fine to medium sands with modal values of 100–200 μm and some admixed medium to coarse silts are observed. The southernmost sample (GeoB 2719–2; Fig. 1) shows an exceptionally coarse bimodal distribution in the 100–300 μm range. The Pampean and Uruguayan shelf (Fig. 3c) is exclusively covered by very fine to fine sands with modal values of 100–200 μm. The shallowest sample in this study (GeoB 13834–1, collected at 16 m water depth; Table 1) has a slightly coarser mode of ~250 μm, most likely due to grain-size sorting by strong wave effects. The mid shelf off Uruguay (i.e., Plata mudbelt) and the Rio Grande Cone off South Brazil (Fig. 3b) feature fine sediments with modal values of ~6 μm, i.e. clay to fine silt. At the East and SE Brazilian margins (Fig. 3a), we find bimodal grain-size distributions merging very fine silt (modes of 4–8 μm) and very fine sand (modes of 40–90 μm). Solely based on grain-size distribution, the slope samples

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### Table 2

<table>
<thead>
<tr>
<th>Ratio parameter</th>
<th>Expression regarding source-rock petrology and pedogenesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_{80%}$</td>
<td>Proportion of superparamagnetic, i.e. ultrafine (~20 nm) to total magnetite and maghemite abundance</td>
</tr>
<tr>
<td>$S_{0.3T}$</td>
<td>Proportion of ferrimagnets (magnetite and maghemite) and antiferromagnets (hematite and goethite)</td>
</tr>
<tr>
<td>ARM$<em>{0.1T}$/IRM$</em>{0.1T}$</td>
<td>Proportion of fine (0.03–1 μm) to coarse (~10 μm) magnetite and maghemite</td>
</tr>
<tr>
<td>SIRM$_{2.0T}$/Fe</td>
<td>Proportion of ferri-/antiferromagnets to paramagnets (iron-bearing minerals)</td>
</tr>
<tr>
<td>Fe/K</td>
<td>Proportion of iron to potassium concentrations</td>
</tr>
</tbody>
</table>

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Fig. 3. Grain-size distribution curves of the terrigenous sediment fractions from (a) SE and East Brazilian slopes; (b) Plata mudbelt and Rio Grande Cone; (c) (Argentine) Pampean and Uruguayan shelves; and (d) Patagonian, (Argentine) Pampean, and Uruguayan slopes. Colors refer to the cluster memberships displayed in Fig. 4.
Fig. 4. Results of FCM cluster analysis showing the 25 investigated samples and their memberships to three cluster centers (CC) in (a) a ternary diagram, and (b) after transformation from the five-dimensional parameter space to a two-dimensional plane by NLM (axes have no units). The cluster centers are located at the corners of the ternary diagram in panel a) and represented as stars in panel b). CC 1 is displayed in red (RGB: 255 0 0), CC 2 in green (RGB: 0 255 0) and CC 3 in blue (RGB: 0 0 255). Samples associated to multiple clusters are displayed with their interpolated RGB colors. Arrow visualize mixing between clusters.

Fig. 5. Aeolian, fluvial, and ocean-current sediment transports to the SE South American continental margin displayed in (a) geographic map and (b) oceanographic section. Colors of sample locations refer to clusters in Fig. 4. All water masses between the coast and the white dashed line drawn in a) are displayed in a simplified way: Antarctic Bottom Water (AABW), Antarctic Intermediate Water (AAIW), Lower Circumpolar Deep Water (LCDW), North Atlantic Deep Water (NADW), South Atlantic Central Water (SACW), Subantarctic Shelf Water (SASW), Subtropical Shelf Water (STSW), Tropical Water (TW), and Upper Circumpolar Deep Water (UCDW) (compiled after Stramma and England, 1999; Piola and Matano, 2001; Piola et al., 2005; Preu et al., 2013).
off SE Brazil and off East Brazil are not distinguishable. Very large particles around 1000 μm occur in some distributions, but probably represent small not disintegrable pieces of debris and are therefore not further considered.

4.2. Sample grouping based on magnetic and element properties

Since the most appropriate number of clusters is not a priori known, FCM solutions were calculated for 2–5 clusters. The optimum cluster number was chosen by calculating the partition coefficient F (should be the highest) and the classification entropy H (should be the lowest) (Bezděk et al., 1984), as well as by comparing the various results from a sedimentological and geological perspective. Although F and H suggest a 2-cluster solution (Table 3), a 3-cluster solution with the second highest F and the second lowest H was given preference. Whereas the 2-cluster solution only divides the study area into one cluster localized north and one cluster south of the Rio de La Plata estuary, the 3-cluster solution provides a spatially consistent differentiation of the southern cluster into shelf and slope provinces. This 3-cluster solution is not in conflict with the 2-cluster solution, which represents a valid first approximation. Another argument favoring the 3-cluster solution is the assignment of rather pronounced parameter characteristics to each cluster (Table 4), i.e. no cluster can be regarded as transitional. Cluster center (CC) 1 has the highest χ₀%, ARM/IRM and Fe/K values and the lowest SIRM/Fe ratio. CC 2 shows the lowest S₀.3T and Fe/K values. CC 3 has the highest S₀.3T and SIRM/Fe and lowest χ₀% and ARM/IRM values. The Euclidean distances (Table 5) between cluster centers in the five-dimensional parameter space reveal that CC 1 is more distant and thus more dissimilar from both, CC 2 and CC 3, than the latter two with regard to each other.

By plotting the three membership coefficients of all samples into a ternary system (Fig. 4a) and identifying their geographical occurrences, there is a clear coherence between cluster grouping and regionality. The three FCM clusters were therefore named after their prevailing geographical occurrence as 'Plata plume' cluster (C1), 'Pampean shelf' cluster (C2), and 'Pampean slope' cluster (C3). Thereby, the slope off SE Brazil presents a mixed composition of C1 and C2 (Fig. 4a). The two shallowest slope samples off Uruguay show contributions from all three clusters. The southernmost sample GeoB 2719-2 from the Patagonian slope differs significantly from the Pampean slope sediments further north and should probably have its own cluster, which is prohibited by the lack of additional samples from that area.

Almost the same spatial arrangement of all samples, only with a (random) rotation, has been independently achieved by NLM (Fig. 4b), supporting the choice of three clusters. The robustness of the NLM solution is underlined by the very low Sammon’s error of 0.007 (Sammon, 1969). This value reveals that the distortion of the five-dimensional data cloud during projection into the plane is minimal. The distances between the three cluster centers are also in agreement with the Euclidean distances of the FCM analysis (Table 5).

NLM allocates cluster centers within their respective data clouds (Fig. 4b) rather than at extreme corners as in the case of the ternary FCM diagram (Fig. 4a). For example, the sample GeoB 6212-2 from the Rio Grande Cone, located at the uppermost corner of the ternary diagram (Fig. 4a), does not represent an end-member. Its properties are just closest to those of CC 1 as seen in NLM (Fig. 4b). The northernmost sample GeoB 6908-1 from the slope off SE Brazil is grouped closer to other SE Brazilian slope samples in NLM (Fig. 4b) than in the ternary FCM representation (Fig. 4a), suggesting a higher similarity between sample GeoB 6908-1 and the other three SE Brazilian samples.

5. Discussion

The geographical distribution of cluster memberships fostered the delineation of three major sediment provinces (Fig. 5), as well as of two boundary provinces, and of one prominent transition zone. The magnetic and major element characteristics of each grouping are now

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**Table 3**

Partition coefficient F and classification entropy H used for cluster number assessment.

<table>
<thead>
<tr>
<th>n clusters</th>
<th>F</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.689</td>
<td>0.209</td>
</tr>
<tr>
<td>3</td>
<td>0.637</td>
<td>0.282</td>
</tr>
<tr>
<td>4</td>
<td>0.633</td>
<td>0.318</td>
</tr>
<tr>
<td>5</td>
<td>0.576</td>
<td>0.384</td>
</tr>
</tbody>
</table>

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**Fig. 6.** Rock magnetic and major element ratios plotted versus median grain-size: (a) frequency-dependent susceptibility χ₀% (SP, superparamagnetic); (b) saturation-ratio S₀.3T (SD, single-domain; MD, multi-domain); (c) ratio of anhysteretic and isothermal remanent magnetization ARM₀.1T/IRM₀.1T; (d) ratio of saturation IRM and iron content SIRM₀.3T/Fe; (e) ratio of iron and potassium contents Fe/K. Colors refer to cluster memberships as in Fig. 4.
interpreted in terms of regional source signatures referring to petrological, sedimentological, and oceanographic literature. By cross-plotting the FCM and NLM input parameters against median grain size (Fig. 6), we discuss the issue of transport fractionation and its influence on source signatures. This compilation allows us to examine the sensitivity of our approach in relation to the previously published large-scale Nd-based provenance study of Mahiques et al. (2008).

5.1. Major terrigenous sediment provinces of the SE South American margin

5.1.1. Pampean slope sediment province

Samples associated to the Pampean slope province (Fig. 5a) are found from 35°–43° S in water depths of 200–1500 m (Fig. 5b). These sediments have modal values of 70–140 μm (Fig. 3d) and carry the lowest proportion of ultrafine ferrimagnets ($f_{d%}$, Fig. 6a), which are typically pedogenically formed, and by high ferrimagnetic (magnetite and maghemite) proportions with respect to secondary antiferromagnetic (hematite and goethite) ones (high $S_{0.3T}$ values; Fig. 6b). They also present the coarsest magnetic grain size of all sediment provinces (Fig. 5c). High SIRM/Fe values (Fig. 6d) also suggest the predominance of detrital Fe-oxides minerals, not much exposed to subaerial chemical weathering. In this geological context, such unaltered rock magnetic characteristics are indicative of mountainous origin and igneous source rock lithology implying primarily fluvial transport.

The two largest and closest Patagonian rivers are the Rio Colorado and Rio Negro, whose fluvial sands (Fig. 3d) mainly originate from the Andean Cordillera between 32° and 42° S (Fig. 1a) (e.g., Zárate and Blasi, 1993). Mafic and intermediate effusive effusives, as well as felsic intrusive and eruptive bodies are widely exposed in this area (Drake et al., 1982; Deruelle, 1982) and contain significant proportions of magnetic minerals (Rumble, 1976). However, the modern sediment load of the Patagonian rivers (-2.0 × 10^6 t yr⁻¹; Gaiero et al., 2003) is neither sufficient to produce vast deposits at the Pampean continental slope, nor able to reach the slope due to the strong northward shelf currents (Urrien and Ewing, 1974; Martins et al., 2005; Bozzano et al., 2011). Yet, this was possible during past glacial and deglacial periods of low sea levels, when the shoreline was closer to the shelf break. During these periods, both rivers were able to transport enhanced sediment loads powered by meltwaters from the Andes, delivering these loads directly to the upper continental slope (e.g., Zárate and Blasi, 1993). Past the shelf break, these fluvial sediments were distributed northwards by the Malvinas Current (Fig. 5b), which created a series of erosive and depositional features on the slope (Hernández-Molina et al., 2009; Preu et al., 2013). The most extensive bodies are terraces at different water depths covered by slope-parallel contourite drift deposits, which were identified as highly magnetic sands and silts (Bozzano et al., 2011). Our provenance-related findings corroborate the suggested Andean origin of such fluvial material. Only the silts and clays were assigned to eolian input by westerly winds from Patagonia, the Pampas, or from the glacially exposed shelf during sea-level lowstands.

5.1.2. Pampean shelf sediment province

Based on our cluster results (Fig. 5a), the Pampean shelf sediment province is mainly situated to the east of the Pampas, as well as off the Rio de La Plata estuary. It is composed of fine sands (modal values of 150–250 μm; Fig. 3c) and characterized by the highest proportion of antiferromagnetic to ferrimagnetic minerals (lowest $S_{0.3T}$ values; Fig. 6b). The closest terrestrial sediment deposits with the same grain-size distributions and petrologic characteristics are the loessoid sands of the southern Pampas (Fig. 1a) (Zárate and Blasi, 1993; Zárate, 2003). There, like in Chinese, Siberian and Alaskan loess deposits (e.g., Heller and Tung-sheng, 1986; Maher and Thompson, 1991; Maher, 1998; Evans and Rutter, 1998), antiferromagnets were vastly formed by pedogenesis during alternating wet-dry conditions. While Chinese loess paleosols are mostly magnetically enhanced, Pampean as well as Siberian and Alaskan soils are depleted in fine ferrimagnets with respect to the associated loessoid deposits (e.g., Heller and Tung-sheng, 1986; Maher and Thompson, 1991; Maher, 1998). The dissolution of ferrimagnets in Pampean soils has been associated with relatively high organic carbon concentrations and cation-exchange capacity. Also, higher clay contents inducing waterlogging may play a significant role on Fe-oxide dissolution. Under recurring phases of waterlogged acidic and arid soil conditions, only low amounts of new pedogenic ferrimagnets can be formed. This scenario of dissolution and inhibited neoformation seems to be valid for the Pampas explaining the relative high proportion of antiferromagnets in the Pampean shelf samples (Fig. 6b). This interpretation is corroborated by relatively low $X_{0.1}$ and ARM/IRM values if compared with LPDB sediments (Geob 6212-2, 13813-1 and 13817-3; Fig. 6a), suggesting preferential dissolution of ultrafine and fine magnetite particles that leaves a relative higher proportion of coarse detrital magnetite. Due to the colder climatic conditions of the Pampean humid season, chemical weathering is much less pronounced than in the LPDB (e.g., Garreau et al., 2009) as implied by the lowest Fe/K values (Fig. 6e) (Gevin et al., 2012; Mulitza et al., 2008).

The total eolian export from Patagonia and the Pampas towards the sea is estimated to be 29 × 10^6 t yr⁻¹ (Pierce and Siegel, 1979; Gaiero et al., 2003). However, ~86% of the modern dust particles have diameters <10 μm, mainly ranging between 5 and 20 μm. Consequently, the largest eolian portion is not deposited on the shelf, where we observe sandy sediments with grain size >100 μm (Fig. 3c), but in the deep Argentine Basin (e.g., Sachs and Ellwood, 1988). On the other hand, the much lower modern sediment load of Patagonian and Pampean rivers (-2.0 × 10^6 t yr⁻¹) is only deposited at their deltas (Fig. 1a) (Gaiero et al., 2003). The modern sandy shelf deposits are primarily nourished by cliff erosion accounting for another ~39 × 10^6 t yr⁻¹ of eroded loessoidal coastal sands (Gaiero et al., 2003), which are subsequently redistributed by the northward Patagonian Current (Fig. 1b).

Two samples from the continental slope at ~38° S (Geob 2701-4 and 2801-1) are also grouped within the Pampean shelf cluster (Fig. 1b, 3d and 5a,b). This is in accordance with the modern off-shelf deflection of the Subantarctic Shelf Water at the respective latitude (e.g., Piola et al., 2005; Palma et al., 2008). Analogous export of shelf sediment is observed at the Uruguay shoreline at 36°–37° S (Geob 2813-1 and 13801-1; Fig. 1) due to an off-shelf deflection of the southward recirculated Subantarctic Shelf Water. Thereby, Plata plume and Pampean shelf sediments are advected to Pampean shelf deposits (Figs. 4 and 5).

5.1.3. Plata plume sediment province

According to cluster grouping (Fig. 5a) and the flow of the Brazilian Coastal Current (Fig. 1b), the Plata plume sediment province departs from the Rio de La Plata estuary and follows the coast northwards.

**Table 4**

Properties of the three cluster centers (CC) calculated by FCM cluster analysis.

<table>
<thead>
<tr>
<th></th>
<th>CC 1: Plata plume</th>
<th>CC 2: Pampean shelf</th>
<th>CC 3: Pampean slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_{0.1}$K</td>
<td>5.17</td>
<td>2.64</td>
<td>1.94</td>
</tr>
<tr>
<td>$S_{0.1T}$</td>
<td>0.926</td>
<td>0.893</td>
<td>0.936</td>
</tr>
<tr>
<td>$ARM_{0.1T}$/IRM$_{0.1T}$ [10⁻²]</td>
<td>63.5</td>
<td>25.5</td>
<td>17.6</td>
</tr>
<tr>
<td>SIRM$_{0.1T}$/Fe [A m² kg⁻¹]</td>
<td>0.177</td>
<td>0.460</td>
<td>0.774</td>
</tr>
<tr>
<td>Fe/K</td>
<td>2.42</td>
<td>1.26</td>
<td>1.82</td>
</tr>
</tbody>
</table>

**Table 5**

Euclidean distances of the three cluster centers (CC) in the five-dimensional parameter space.

<table>
<thead>
<tr>
<th></th>
<th>CC 1: Plata plume</th>
<th>CC 2: Pampean shelf</th>
<th>CC 3: Pampean slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC 1</td>
<td>–</td>
<td>3.77</td>
<td>4.07</td>
</tr>
<tr>
<td>CC 2</td>
<td>3.77</td>
<td>–</td>
<td>2.77</td>
</tr>
<tr>
<td>CC 3</td>
<td>4.07</td>
<td>2.77</td>
<td>–</td>
</tr>
<tr>
<td>Mean distance</td>
<td>3.92</td>
<td>3.27</td>
<td>3.42</td>
</tr>
</tbody>
</table>
Proximal deposits of these clayey silts (Fig. 3b) are found at the Plata mudbelt off Uruguay and the Rio Grande Cone off South Brazil (Figs. 1a and 5a). These sediments are characterized by high proportions of ultrafine and fine magnetite as indicated by high $g_{\beta\theta}$ and ARM/IRM values (Fig. 6a,c). The fine magnetite may represent inclusions in igneous host rocks and the ultrafine magnetite likely reflects pedogenically formed Fe-oxides attached to clay minerals. The SIRM/Fe ratios are much lower than in the other provinces (Fig. 6d) indicating that Fe is predominantly paramagnetic and resides in secondary clay minerals rather than in primary minerals of the igneous source rock (e.g., Rumble, 1976; Maher, 1986, 1998; Schwertmann and Taylor, 1989). Pronounced chemical weathering in the tropics and subtropics is also reflected by the highest Fe/K values (Fig. 6e).

We assume, that most magnetic minerals of the Plata plume sediments originate from the upper Rio Paraná catchment in the northeast of the LPDB (Fig. 1a), where flood basaltic and intrusive felsic rocks crop out (Peate, 1997). The Rio Bermejo is considered to be the main sediment contributor to the Rio de La Plata estuary (Orfeo and Stevaux, 2002) due to its steep descent through unconsolidated Chaco Plain sediments. However, these sediments of Andean origin primarily contain diamagnetic quartz and feldspars (Zárate, 2003). Thus, they should be less represented by the rock magnetic properties of Plata plume sediments. The $92 \times 10^8$ t yr$^{-1}$ of silty to clayey sediments (Bernardes et al., 2012) discharged to the Rio de La Plata estuary (Figs. 1 and 5) are almost entirely deflected to the northeast by the Brazilian Coastal Current. In paleo-channels at the northeastern side of the Rio de La Plata estuary, their deposits create the Plata mudbelt (Urrien and Ewing, 1974; Violante and Parker, 2004; Lantzsch et al., 2014). Silt-dominated Plata plume sediments are also found in other places of the mid shelf (Urrien and Ewing, 1974; Laborde, 1997; Violante and Parker, 2004; Lantzsch et al., 2014). At the location of the STSF and further north (Fig. 5b), the sediment transport from mid shelf to upper slope follows the motion of the Subantarctic Shelf Water and of the Subtropical Shelf Water (Piola et al., 2008). Razik et al. (2013) could show that Late Holocene Plata plume silts were also deposited at the Rio Grande Cone in water depths below 500 m.

5.2. Boundary and transitional sediment provinces

5.2.1. Patagonian margin sediment province

At the Patagonian margin, the southernmost sample (GeoB 2719-2) of this study (Fig. 5a) shows no distinct membership to any of the three clusters (Fig. 4b). Although it resembles some properties of the two Pampean sediment provinces (Fig. 6), it significantly differs by a higher Fe/K (Fig. 6e) and a coarser, poorly sorted grain-size mode (Fig. 3d). The closest individual source for such poorly sorted sands (and gravels) of igneous origin are the post-glacial deltas of the Rio Chico, Rio Cruz, and Rio Gallegos draining southern Patagonia (49°–55° S; Fig. 1a) (Martins et al., 2005).

5.2.2. East Brazilian margin sediment province

The two East Brazilian margin sediment samples (GeoB 2102-1 and 2125-2; Fig. 5a) resemble those of the Plata mudbelt and Rio Grande Cone (Figs. 4 and 6). Compared to Plata plume sediments, they have very high Fe/K values (Fig. 6e) and contain proportionally less ultrafine magnetite (Fig. 6a) and more fine magnetite (Fig. 6c). This feature hints at a different source, for which primarily the adjacent Serra do Mar coastal mountain range is qualified (Fig. 1a). These mountains consist of Pre-Cambrian crystalline basement rocks with extensive exposures of Paleozoic granites and gneisses, as well as of other metamorphic rocks of igneous origin (De Almeida et al., 1981; Anjos et al., 2006), which are locally dissected by Mesozoic basaltic dykes. Granitic rocks directly exposed on the continental shelf and slope (Viana, 2002) are likely to be eroded by ocean currents.

The Serra do Mar is mainly drained to the east (Fig. 1a). Its major river is the Rio Paraíba do Sul, which delivers an important sediment load of $4.2 \times 10^8$ t yr$^{-1}$ (Bernardes et al., 2012) to the adjacent continental margin. The Quaternary lowland sediments and coastal plains to the north and south of the Rio Paraíba do Sul mouth are mainly composed of medium to very fine sands of igneous and metamorphic origin (Anjos et al., 2006). Wave erosion of these sandy coastal plains is a significant, if not major, discharge process of coarse sediments to the East Brazilian continental shelf and slope (Martin et al., 1985; Viana, 2002), especially during transgressions.

As the East Brazilian slope samples show a bimodal grain-size distribution (Fig. 3a) with modes of 5–10 μm and 60–100 μm, we argue that the finer mode was delivered more or less directly by the Rio Paráiba do Sul, while the coarser mode is shelf sand. Sediment transport north of Cape Frio is bidirectional due to seasonally varying surface currents, the southward directed Brazilian Current, and the northward directed mid-slope Intermediate Western Boundary Current (Fig. 5a,b) (Boebel et al., 1999; Viana, 2002; Oliveira et al., 2012; Mendoza et al., 2014).

5.2.3. Southeast Brazilian margin sediment mixing zone

Samples GeoB 6204-2, 2106-1, 6908-1, and 6201-3 (Fig. 5a) from the SE Brazilian slope delimited by Cape Santa Marta (29° S) and Cape Frio (23° S) show transitional magnetic and element signatures of Plata plume and Pampean shelf provinces (Fig. 4a,b). Their bimodal grain-size distributions (modes 4–8 μm and 40–90 μm; Fig. 3a) include characteristic modes of both provinces (Fig. 3b,c). On the NLM plot (Fig. 4b), the SE Brazilian slope samples fall on a straight mixing line between Plata mudbelt/Rio Grande Cone and Pampean shelf. The East Brazilian margin samples to the north lie apart from this mixing path and can therefore be ruled out as a provenance for SE Brazilian slope sediments. The northernmost and finest sample GeoB 6908-1 (Fig. 3d) carries the most typical Plata plume signature (Figs. 4b and 5a) suggesting decreased influx from the Pampean shelf province. This is supported by decreased proportions of coarse magnetite (Fig. 6c).

The continental margin off SE Brazil is starved from terrigenous input due to the lack of significant fluvial runoff (e.g., Reis et al., 2013). Over the past 2000 years, the Rio de La Plata estuary was the only significant contributor of fine sediments (Mahiques et al., 2009; Gyllencreutz et al., 2010; Mathias et al., 2014). As Plata Plume Water reaches frequently 24° S (Piola et al., 2008; Palma et al., 2008) and sporadically even 22° S beyond São Sebastião Island (Stevenson et al., 1998), we suggest that fine Plata plume sediments can reach all our SE Brazilian sample sites (Fig. 5a,b).

Under modern oceanographic conditions the relatively coarse sediments of the Pampean shelf cannot overcome the distance of 1300–2000 km to the SE Brazilian shelf. They were probably transported along the outer shelf and upper slope by northward coastal currents during multiple sea-level transgression–regression cycles. This lowstand scenario is in accordance with findings from sedimentological studies of the Uruguayan shelf and slope, where such a sandy facies has been described (Franco-Fraguas et al., 2014; Lantzsch et al., 2014). Because the SE Brazilian margin is affected by the meandering Brazil Current leading to the formation of eddies and vertical movements of the upper water column (Campos et al., 2000; Silveira et al., 2008; Calado et al., 2010), we argue that suspended Plata plume and remobilized relict shelf sediments of Pampean origin can reach the deeper South Atlantic Central Water (Fig. 5a,b), leading to their southward recirculation and deposition on the slope. This scenario is supported by the sediment-based investigations of Mahiques et al. (2002, 2004) and Gyllencreutz et al. (2010) on the upper continental margin of SE Brazil.

5.3. Comparison with isotope-based provenance studies

Only the provenance study of Mahiques et al. (2008) based on Nd- and Pb-isotopes covers the SE South American continental margin over a considerably large latitudinal range. The authors were able to
track surface sediments from the Argentinean shelf as far north as the Rio de La Plata estuary (−35° S). Our study shows that Pampean shelf sediments have migrated north of the modern STSF position (34°−36° S; Fig. 1b) reaching the slope off SE Brazil (Fig. 5a,b). We assume that the Nd-isotope signature of the Pampean shelf sediments could not be detected north of the STSF due to mixing of two sediment fractions with very different grain-size modes (Fig. 3a). As a heavy element, Nd is commonly enriched in the clay fraction (Revel et al., 1996; Innocent et al., 2000). Thus, a small contribution of clay-rich Plata plume sediment may contain a larger absolute Nd-content than a much larger contribution of Pampean shelf sand. In this scenario, the Nd-isotopic signature of Plata plume sediment will mask that of Pampean shelf sand.

This seems to be the case, where bimodal Mid Holocene grain-size distributions (Razik et al., 2013; Fig. 5a−e therein) are compared with Nd-isotope values (Lantzsch et al., 2014; Fig. 8B therein) from the same sediment core. This dependency was not detected by Mahiques et al. (2008), as measurements were performed on bulk sediments and the obtained values were displayed against clay concentration (see Fig. 7 therein). Since the clay fraction dominates the bulk Nd-isotopic signature, these values remain more or less constant independently from clay concentration, as far as the clays are derived from the same source. Consequently, a comparison of Nd-isotopic signatures and clay content does not guarantee grain-size independency of sediment provenance signatures.

Another aspect differentiating our study from that of Mahiques et al. (2008) is our ability to discriminate the Pampean slope vs. the Pampean shelf provinces. Nd- and Pb-isotopes demonstrate that all Argentinian margin sediments originate from Andean source rocks. Our approach distinguishes between unaltered fluvial and altered loessoidal Andean sources by making use of the (paleo-)environmental sensitivity of Fe-minerals.

5.4. Provenance signatures vs. fractionation effects

Especially in continental margin settings, the effect of multiple fractionation processes from source to sink on sedimentary mineral composition is a major concern for every provenance-oriented study. Particle size, stability, and density are mineral properties which may produce fractionation along the transport pathway. Near-source fractionation is not problematic for this study, as sediments and source rocks are not directly compared. The large-scale and long-term patterns of continental weathering regimes are rather a second classification element besides source-rock petrology to delimit shelf and slope sediment provinces. More critical is the ‘environmental bias’ introduced by (i) long-distance transport in the marine realm, (ii) grain-size sorting due to different settling conditions, and (iii) potential post-depositional effects of diagenesis and authigenesis. A rigorous empirical test of the chosen approach would be a study of its own, but a number of supportive statistical and geological arguments can be raised.

The median clastic grain-sizes within the study area vary over two orders of magnitude from 4 to 300 μm (Fig. 6); there is hence no overlap between silt and sand-dominated regions (Fig. 3). A visual inspection of all scatter plots of Fig. 6 shows that no analyzed parameter covaries systematically with median grain-size. The three main clusters occupy different parts of the grain-size spectrum and of the parameter ranges, not suggesting overarching grain-size dependence. In the example of SIRM/Fe (Fig. 6d), the values of the Plata plume cluster remain nearly constant from 4 to 20 μm, while the Pampean slope cluster varies by a factor of 2 between 63 and 125 μm.

For several petrological arguments, strong grain-size dependence should not be expected (e.g., Franke et al., 2007). Ferrimagnetic Fe-oxide crystals in volcanic, plutonic, and metamorphic rocks occur in different grain-sizes, but are generally not larger than a few microns. They are hence much smaller than surrounding matrix minerals. In most coarser sediments, ferrimagnetic crystals are found as inclusions in quartz or feldspar grains or trapped in lithic fragments. Source-specific magnetite crystal size is therefore minimally related to clastic grain size (e.g., Hatfield, 2014). ARM/IRM values of both Pampean clusters with Andean origin show little variation from 63 to 250 μm (Fig. 6c). Pedogenesis creates ultrafine maghemite encrustations or attachments on larger particles distinguishing different alteration states (e.g., Maher, 1986, 1998). Coarse loessoidal Pampean shelf sediments therefore have higher xFl% than finer fluvial Pampean slope sediments (Fig. 6a). The different weathering regimes of arid cold and humid warm climates at land are mirrored by S₀.₃T, SIRM/Fe, and Fe/K (Fig. 6b,d,e) and again affect source rocks quite irrespectively of clastic grain-size.

While the above arguments rebut grain-size related issues (i) and (ii), the possibility (iii) of diagenetic or authigenic overprint, e.g. by reduction or precipitation of Fe-oxides, requires geochemical reasoning. As all studied samples were taken from the oxic sediment surface, detrital magnetite should be very stable, while authigenic magnetic Fe-sulfides (greigite) would quickly decay. We should therefore not expect a post-depositional overprint. Important biogenic magnetite precipitation (magnetic enhancement) would entail much higher ARM/IRM (e.g., Just et al., 2012) and SIRM/Fe ratios and is therefore unlikely. The applied interparametric ratios can therefore be considered as relatively independent of grain-size fractionation effects and should primarily carry source-derived signatures targeted in this study.

6. Conclusions

Applying cluster analytical methods to enviromagnetic and major element data of 25 surface sediment samples covering the SE South American continental margin from 20° to 48° S, we identified and delineated three major terrigenous sediment provinces with their boundary and transition zones. The five analyzed interparametric ratios mainly reflect igneous source-rock petrology and weathering state. They are intrinsically independent of mineral concentrations and also largely independent of clastic grain size. Co-interpreting cluster properties with additional terrigenous grain-size data, we could infer associated transport pathways and accumulation conditions.

The muddy sand of the Pampean slope province is characterized by high proportions of coarse primary ferrimagnetic Fe-oxides with little subaerial chemical weathering. These sediments are thought to originate from the Andes and to be delivered to the shelf break by meltwaters of the Rio Colorado and Rio Negro during glacial and deglacial periods of low sea level. The northeastwards flowing Malvinas Current redistributes these sediments up to the Rio de La Plata estuary (35° S). The fine to medium sandy Pampean shelf province is marked by the highest proportions of secondary antiferromagnetic Fe-oxides formed in alternating wet-arid weathering conditions. These sediments originate from the Pampean coastal loessoidal deposits and are supplied to the inner shelf by wave erosion and westerly winds. They are subsequently redistributed along and off the shelf by the northward directed Patagonian Current. For the first time, Pampean shelf sediments were tracked as far north as 24° S near the shelf break.

The muddy Plata plume province shows the highest proportions of secondary fine and ultrafine Fe-oxides and paramagnetic Fe-bearing silicates reflecting pronounced chemical weathering. The Brazilian flood basaltts constitute the major contributor of magnetic minerals to the Rio de La Plata estuary. The Brazilian Coastal Current distributes these sediments up to about 24° S. Accordingly, SE Brazilian margin sediments show mixed magnetic and element properties of Plata plume and Pampean shelf provinces, which are also reflected by their bimodal grain-size distributions. These sediments are occasionally swept off-shelf by the Brazil Current south of 24° S during up- and downwelling events.

At the borders of our study area, the samples from the East Brazilian and Patagonian slope differ noticeably from the above described provenance signatures. The East Brazilian slope sediments were probably supplied by lowland erosion and riverine input from the Serra do Mar coastal mountain range. Patagonian slope sediments have even coarser
and less sorted grain-sizes than Pampean slope sediments and are thought to originate from the erosion of south Patagonian river deltas. The multivariate sediment discrimination scheme based on joint magnetic and element ratios proved to be a sensitive, efficient, and promising approach for source tracking over an oceanographically complex continental margin sector with large grain-size variability. Our findings regarding depositional provinces, dispersal, and origin of terrigenous sediments off SE South America support core–model-based studies on present and past dynamics of terrestrial climate and atmosphere–ocean interactions in the southern hemisphere.

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