Glacial-interglacial terrigenous provenance in the southeastern Atlantic Ocean: The importance of deep-water sources and surface currents

Jennifer C. Latimer* Department of Geological Sciences, University of Michigan, Ann Arbor, Michigan 48109, USA
Gabriel M. Filippelli Department of Geology, Indiana University-Purdue University at Indianapolis, Indianapolis, Indiana 46202-5132, USA
Ingrid L. Hendy
James D. Gleason
Joel D. Blum
– Department of Geological Sciences, University of Michigan, Ann Arbor, Michigan 48109, USA

ABSTRACT

Identifying terrigenous sources in deep-sea sediments may reveal temporal trends in paleocirculation and the relative role of eolian, upwelled, and hemipelagic Fe sources to surface waters. Bulk elemental and isotopic geochemistry of deep-sea sediments recovered during Ocean Drilling Program Leg 177 in the southeastern Atlantic sector of the Southern Ocean reveal several important aspects of paleocirculation and terrigenous provenance. The sites studied span 43°–53° S and represent different oceanographic settings relative to regional hydrography and sediment type. Bulk sediment geochemistry indicates that terrigenous provenance varied over the past 600 k.y. Site 1089, the northernmost site, exhibits clear glacial-interglacial variability in provenance, while provenance appears to vary regardless of climate state at the more southerly sites (Site 1093 and 1094). Nd and Sr isotopes and Sm/Nd ratios of the terrigenous fraction indicate that study sites have geochemically distinguishable provenance. Nd and Sr isotopes further suggest that Sites 1089 and 1094 both contain detrital components that originated in South America over the past 30 k.y.; however, Site 1089 is also influenced by southern African sources and the strength of the Agulhas Current. The ε_{Nd} data support a more hemipelagic source for the terrigenous material rather than an eolian source based on comparisons with Antarctic ice core data and known sea-ice extent.

Keywords: Southern Ocean, provenance, terrigenous materials, glacial, interglacial.

INTRODUCTION

The Iron Hypothesis, as first posited by Martin (1990), suggested that higher eolian Fe fluxes to the Southern Ocean during the last glacial led to higher levels of biological productivity and ultimately contributed to atmospheric CO_2 drawdown. As a result, many studies have focused on terrigenous Fe fluxes and depositional processes in the Southern Ocean, including eolian pathways (Grousset et al., 1992; Basile et al., 1997; Mahowald et al., 1999), hemipelagic sources (Diekmann et al., 2000; Walter et al., 2000; Latimer and Filippelli, 2001; Rutberg et al., 2002, 2005), and the influence of ice-rafted debris (Kanfoush et al., 2000, 2002). However, understanding sedimentation and terrigenous fluxes is complicated by the dispersal of hemipelagic sediments by surface currents and redistribution by bottom currents. Sediment focusing is especially problematic in the Southern Ocean (Kumar et al., 1995; Frank et al., 1995; Sachs and Anderson, 2003) because of the presence of strong bottom currents associated with the Antarctic Circumpolar Current (ACC).

In addition to providing micronutrients, detrital input also provides clues about paleocirculation of the oceans and atmosphere. By identifying provenance and understanding changes in provenance, transport pathways and paleocirculation can be reconstructed. Provenance changes in ocean sediments and the importance of different transport pathways can be evaluated by the following proxies. For example, particle size analysis (Boven and Rea, 1998; Hassold et al., 2003) provides information about how material is deposited, and clay mineralogy (Kuhn and Diekmann, 2002; Diekmann et al., 2003) and pollen analyses (Dupont and Wyputta, 2003) provide clues to determining where the terrigenous material originated. Other proxies include those based on sediment geochemistry of bulk sediments or of the isolated terrigenous fraction. Here we present Al/Ti and Fe/Ti ratios of bulk sediment and Nd and Sr isotopes and Sm/Nd ratios from the terrigenous fraction.

Downcore Al/Ti ratios have been used as a proxy for both export production (Murray and Leinen, 1996; Kryc et al., 2003) and variability in provenance (Murray et al., 1993; Yarnicik et al., 2000; Latimer and Filippelli, 2001). In sediments with relatively low detrital inputs (<5 wt%), the Al/Ti ratio is heavily influenced by particulate scavenging and reflects particle fluxes and export production (Kryc et al., 2003). However, when the terrigenous fraction exceeds 5 wt%, the terrigenous Al dilutes any Al reaching the sediments due to particulate scavenging and the Al/Ti ratios reflect changes in terrigenous provenance. Because the terrigenous content at the study sites examined here is >5 wt% (Kuhn and Diekmann, 2002), the downcore Al/Ti ratios (Fig. 1) indicate temporal variability in terrigenous provenance. Because of the interest in Fe sources and variability over time, Fe/Ti ratios are also utilized as a provenance indicator here. While these ratios are useful for identifying changes in provenance, more data are needed to identify the actual sources. Radiogenic isotopes of Nd and Sr have been used to evaluate terrigenous provenance in ocean sediments (Bareille et al., 1994; Walter et al., 2000; Bayon et al., 2003; Rutberg et al., 2005) and ice core dust records (Grousset et al., 1992; Basile et al., 1997; Delmonte et al., 2004). Nd and Sr isotopes are robust in ocean sediments because they are not readily influenced by weathering processes, sediment transport, or postburial diagenetic reactions, although there are some grain size sorting effects, especially with Sr (Walter et al., 2000). If the isotopic signature of the source areas is known, provenance can be determined and mixing relationships between sources can be identified. Comparisons of the Nd and Sr isotopic values between source regions and our samples will help to discriminate the relative contributions of the source areas. Our purpose here is to evaluate changes in terrigenous provenance across the southeastern Atlantic using Al/Ti and Fe/Ti ratios for the past 600 k.y., and to identify terrigenous sources for the last glacial interval and the Holocene using Nd and Sr isotopes and Sm/Nd ratios. We present evidence that provenance of Southern Ocean sediments varies considerably, and that each study site has a unique record of temporal variability. Fur-

*Current affiliation: Department of Geography, Geology, and Anthropology, Indiana State University, Terre Haute, Indiana 47809, USA.

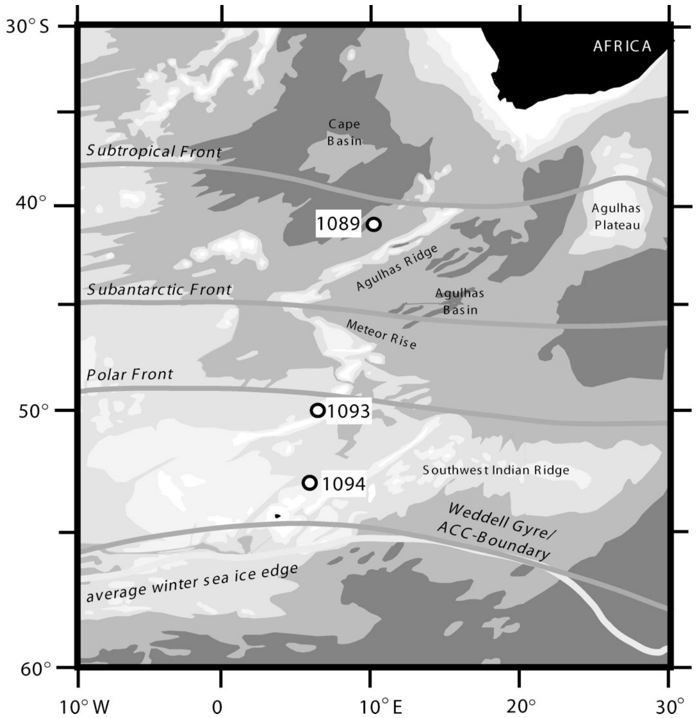

Figure 1. Study site locations in southeastern Atlantic Ocean, modified from Gersonde et al. (1999). Site 1089 (4620 m, 41°S, 9°E) is located in southern Cape Basin, Site 1093 (3626 m, 50°S, 5°E) is located north of Shona Ridge, and Site 1094 (2807 m, 53°S, 5°E) is north of Bouvet Island. ACC—Antarctic Circumpolar Current.

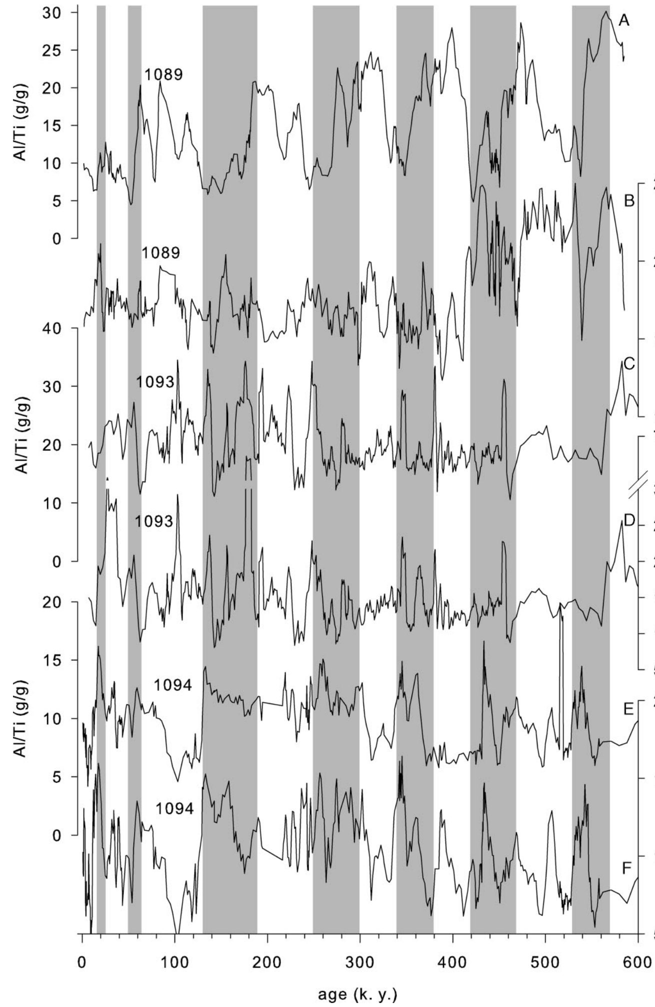

Figure 2. Downcore Al/Ti and Fe/Ti ratios for study sites. All data have been smoothed using 5-point moving average. Gray bars approximate timing of glacial intervals. Average continental crust has Al/Ti = 15.8, upper continental crust has Al/Ti = 26.8, and basalt has Al/Ti ratio ≤10 (Taylor and McLennan, 1985).

thermore, the northernmost and southernmost sites have geochemically dissimilar sources that are distinguishable from that of dust found in Antarctic ice cores for the past 30 k.y., reinforcing the importance of surface and deep currents in the transport and deposition of detrital components.

RESULTS AND DISCUSSION

The downcore trends in Al/Ti and Fe/Ti ratios (Fig. 2; also see Data Repository Tables DR1 and DR2[1], and supplemental material) suggest that terrigenous provenance varied significantly over the past 600 k.y.; however, each site has a unique history of provenance changes. The downcore Al/Ti ratios (Fig. 2) support the suggestion that the terrigenous sediments are a mix of continental crust and basalt sources with variable influence from dust, hemipelagics, and ice-rafted debris. Volcanic sources, such as the South Sandwich Islands and various volcanic sources in South America and Antarctica (Basile et al., 2001), may also influence the study sites. For example, Site 1089 has high Al/Ti ratios during interglacial intervals that decrease through the glacial, with minimum values near glacial terminations. At Site 1089, similar downcore variability in clay mineralogy is observed, which was also interpreted as a reflection of changes in provenance (Kuhn and Diekmann, 2002). In contrast, Site 1093 Al/Ti ratios oscillate between relatively high and low values regardless of climate state and often multiple times within any given glacial or interglacial interval. Site 1094 displays long intervals of relatively low variability in the Al/Ti ratios, for example between 300 and 130 ka. The Fe/Ti ratios (Fig. 2) for the study sites illustrate similar downcore variability. The Fe/Ti and Al/Ti ratios at Sites 1093 and 1094 have very similar downcore records, suggesting that Fe, Al, and Ti within each site have similar provenance, although there is variability between sites. The Fe/Ti ratios at Site 1089, however, do not mimic the trends observed in the Al/Ti ratios. The Fe/Ti ratios at Site 1089 have more variability than observed in the Al/Ti ratios, and the Fe/Ti ratios do not contain a clear glacial-interglacial pattern. The dissimilarity of the Al/Ti and Fe/Ti ratios suggests that there are multiple sources of terrigenous material with different amounts of Al and Fe relative to Ti reaching Site 1089. After 400 ka there is a permanent decrease in the Fe/Ti ratios. This shift possibly reflects a major and permanent change in either atmospheric circulation, hydrography, or bottom current strength associated with the transition from marine isotope stage (MIS) 12–11, and is also observed in the Vostok ice core as increased atmospheric temperatures (δD) (EPICA Community Members, 2004).

The bulk elemental ratios suggest temporal variability in provenance, but provide a nonunique solution to source identification. For this reason, Nd and Sr isotopic data and Sm/Nd ratios for samples from Sites 1089 and 1094 (Fig. 3A) representing the past ~30 k.y. were generated. The Nd and Sr data illustrate that Sites 1089 and 1094 have geochemically distinct terrigenous sources. This observation is further supported by comparison of the ε_{Nd} and Sm/Nd ratios for the two sites (Fig. 3B) that plot in distinct geochemical fields. However, the same

[1]GSA Data Repository item 2006106, Table DR1, elemental data for Site 1093; Table DR2, elemental data for Site 1094; Table DR3, radiogenic isotope data from Sites 1089 and 1094; and supplemental material containing the methodology, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

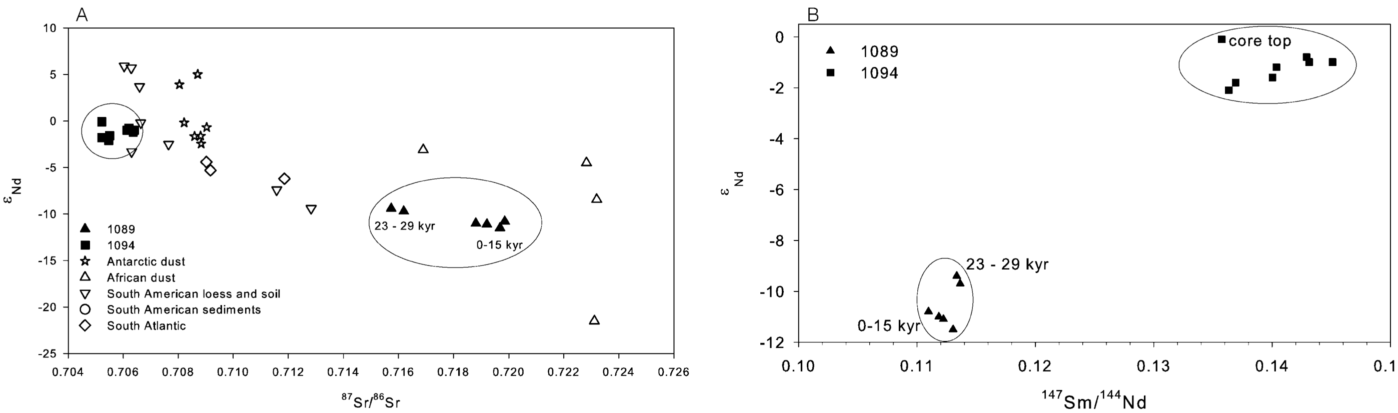

Figure 3. A: ε_{Nd} vs. $^{87}Sr/^{86}Sr$ for selected samples representing Holocene and last glacial interval from Site1089 (filled diamonds) and Site 1094 (filled squares). Also plotted (open symbols) are data from Grousset et al. (1992), Basile et al. (1997), Walter et al. (2000), and Delmonte et al. (2004). Data demonstrate that two study sites are geochemically distinguishable and that samples are likely mix of multiple sources. Dust in Antarctic ice cores has Patagonian provenance (Grousset et al., 1992; Basile et al., 1997; Delmonte et al., 2004). Site 1089 is strongly influenced by South African sources, and provenance at Site 1094 is more similar to South American sources, although Site 1094 was at least intermittently covered by sea ice during full glacial conditions, suggesting that either seasonal sea-ice melting or bottom currents are controlling isotopic signatures. Data from RC11–83, which is located near Site 1089 in Cape Basin, have similar Sr isotope ratios (Rutberg et al., 2005). B: ε_{Nd} vs. Sm/Nd ratios for Site 1089 (filled diamonds) and Site 1094 (filled squares). Data further demonstrate that two sites are geochemically distinguishable.

variability seen in the bulk elemental ratios is not seen in the Nd data for Site 1094. Whereas the 1094 Sr and Nd data plot near the South American sources, the data for Site 1089 appear to be dominated by sources in southern Africa. This is further supported by clay mineralogical data that suggest that potential South American and Antarctic terrigenous sources have a greater influence on Site 1089 during glacial intervals (Kuhn and Diekmann, 2002). Figure 4 illustrates how dissimilar the ε_{Nd} data are for the two sites. It also demonstrates that there is statistically significant separation between the data sets, and that there is some temporal variability.

There is some observable temporal variability in the Sr and Nd isotopic data (Fig. 3; also see Table DR3 [see footnote 1]) at Site 1089 that corresponds to the variability seen in the Al/Ti ratios (Fig. 2). The Agulhas Current is responsible for bringing material into the Cape Basin from South Africa and the Indian Ocean, as has been observed previously (Flores et al., 1999; Kuhn and Diekmann, 2002; Rutberg et al., 2002, 2005; Sachs and Anderson, 2003). Rutberg et al. (2002, 2005) and Flores et al. (1999) demonstrated this using Sr isotopes and nannofossil assemblages, and suggested that the Agulhus Current was stronger and influenced the Cape Basin to a greater extent during interglacial intervals. The Sr and Nd isotopic data support these results, suggesting that during glacial intervals terrigenous provenance was influenced to a greater extent by South American sources relative to interglacials. However, this South American terrigenous material minimally contributes to the isotopic signatures. In contrast, Site 1094 has ε_{Nd} and $^{87}Sr/^{86}Sr$ values more similar to South American sources, and although not plotted may be influenced by volcanics associated with the South Sandwich Islands. Because Site 1094 was south of the maximum sea-ice extent during the last glacial maximum (Crosta et al., 1998; Gersonde and Zielinski, 2000), it is likely that Site 1094 was at least intermittently covered by ice, which would prevent direct deposition of dust onto the sea surface, although seasonal sea-ice melting could have contributed dust that would influence the provenance signal. However, it seems plausible that terrigenous sediments at Site 1094 were strongly influenced by the strength of the ACC. Risso et al. (2002) demonstrated that volcanic material from the South Sandwich Islands in the Scotia Sea region can be transported long distances (>20,000 km) by the ACC (Risso et al., 2002). Furthermore, these results reinforce the suggestion that the surface currents and the ACC are vital to the transport and deposition of terrigenous material in the southeastern Atlantic Ocean.

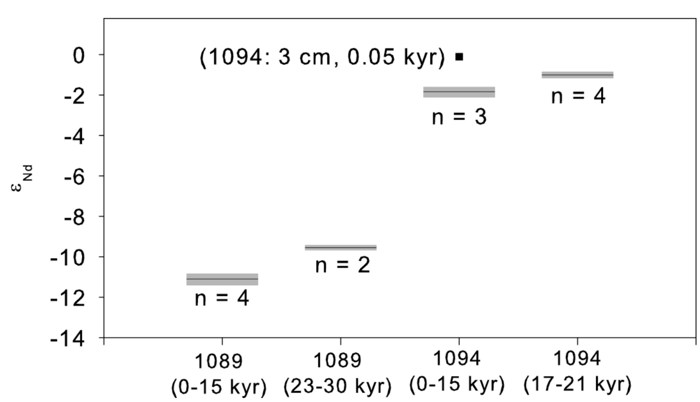

Figure 4. ε_{Nd} data for study sites. Data illustrate statistical differences between study sites and show that there is measurable temporal variability.

CONCLUSIONS

The data suggest that provenance is highly variable on glacial-interglacial time scales and that different transport mechanisms are responsible for the eventual sedimentation of detrital material delivered to the southeastern Atlantic Ocean. While all of the study sites have considerable temporal variability, each site has its own unique downcore trends based on the Al/Ti and Fe/Ti ratios. The Fe/Ti ratios at Site 1089 also suggest a major change in atmospheric circulation, hydrography, or bottom current strength during the MIS 12–11 transition. The Nd and Sr isotopes suggest that Sites 1089 and 1094 are both influenced by sediment originating in South America, whereas Site 1089 is more strongly influenced by south African sources and the strength of the Agulhas Current as it varied on glacial-interglacial time scales. The isotopic data and the Sm/Nd ratios highlight the fact that these two sites are geochemically distinct, and a comparison of the ε_{Nd} values in the sediments with ice core dust samples supports a more hemipelagic-dominated system rather than eolian-influenced system. Further work needs to investigate how sources varied in the past with changes in the strength of ocean currents, including the Agulhas Current, but also North Atlantic Deep Water and the ACC, as well as how glacial-interglacial variability in the position of major frontal zone and sea-ice extent affected terrigenous delivery to the Southern Ocean.

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