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Cycling of lithogenic marine particles in the US GEOTRACES North Atlantic transect

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ABSTRACT

In this paper, we present, describe, and model the first size-fractionated (0.8–51 μm; > 51 μm) water-column particulate trace metal results from the US GEOTRACES North Atlantic Zonal Transect in situ pumping survey, with a focus on the lithogenic tracer elements Al, Fe and Ti. This examination of basin-wide, full-depth distributions of particulate elements elucidates many inputs and processes—some for bulk lithogenic material, others element-specific—which are presented via concentration distributions, elemental ratios, size-fractionation dynamics, and steady-state inventories. Key lithogenic inputs from African dust, North American boundary interactions, the Mediterranean outflow, hydrothermal systems, and benthic nepheloid layers are described. Using the refractory lithogenic tracer Ti, we develop a 1-D model for lithogenic particle distributions and test the sensitivities of size-fractionated open-ocean particulate Ti profiles to biotically driven aggregation, disaggregation rates, vertical sinking speeds, and dust input rates. We discuss applications of this lithogenic model to particle cycling in general, and to POC cycling specifically.

1. Introduction

In marine systems, lithogenic particles are refractory assemblages of crustally-derived minerals that transit the water column largely unaltered. Lithogenics are one of three overarching classes of particles present in marine systems, together with *biogenic particles* (living and dead organic matter and mineral skeletons) and other abiotically-derived *authigenic particles* produced and cycled in situ (e.g. Fe and Mn oxides, barite). Lithogenics, as a major class of particulate matter, are typically not a dominant component of marine vertical particle fluxes in much of the open ocean (Francois et al., 2002) far away from lithogenic inputs such as eolian dust and lateral transport of continental margin sediments. The subtropical North Atlantic, however, is heavily influenced by mineral dust deposition (Mahowald et al., 2005): lithogenics account for between 40% and 72% of the vertical sediment trap flux at productive margin systems between the Cape Verde Islands (CVI) and Cape Verde, Senegal (Ratmeyer et al., 1999), compared to typically less than 20%, and frequently less than 5%, at open ocean stations distant from eolian dust sources (Francois et al., 2002). The North Atlantic, where 43% of annual dust deposition is estimated to occur (Jickells et al., 2005), thus provides an opportunity to examine lithogenic particle distributions and behaviors in a basin dominated by lithogenic inputs.

Each year, large quantities—1 Pg (Ginoux et al., 2004; Mahowald et al., 2009)—of crustally-derived particles cycle through the world oceans. Although most of this material settles or sinks through the water column unchanged, it participates in the biogeochemical cycling of many trace elements by acting as a source of dissolved trace elements from dissolution, a scavenging surface for trace metals, and a ballasting agent for marine aggregates. Long-range eolian and subsurface lateral (Moore and Braucher, 2008; Lam and Bishop, 2008) inputs of lithogenics are of special importance due to their ability to deliver bio-limiting micronutrients directly to productive surface ocean ecosystems.

In this paper we present, examine, and model the first basin-wide, full-depth zonal transect of marine lithogenic material. We differentiate this material from other particulate analytes through principal component analysis (PCA) of a large multi-element dataset, then examine three elements—Al, Fe, and Ti—that act predominantly as tracers of lithogenic particles. Concentration distributions of these three elements provide information about eolian, lateral/margin, bottom resuspension, and hydrothermal

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inputs, which are major controls on the basin's total metal fluxes. Elemental ratios provide further insight into element-specific alteration processes and site-specific inputs.

The refractory nature of particulate Ti and its dust-dominated input to the surface of the subtropical gyre presents an opportunity to model vertical particle distributions and underlying dynamic processes using a passive tracer. We present a 1-D model that qualitatively describes the distributions of refractory particulate metals in marine systems, and perform sensitivity tests on how variations in aggregation, disaggregation, and sinking rates may affect size-fractionated field data.

2. Methods

2.1. Study region

Particulate samples were collected at 22 stations across the subtropical N. Atlantic during US GEOTRACES North Atlantic Zonal Transect cruises KN199-04 and KN204-01 aboard the R/V *Knorr* (Fig. 1). Cruise KN199-04 in October 2010 occupied stations 10-01 through 10-12 in the eastern basin, including key stations (Fig. 1, annotations) 10-01 near Lisbon and within influence of the Mediterranean outflow, 10-09 located 200 km west of the Mauritanian shelf break, and 10-12 at the Cape Verde Ocean Observatory (CVOO, formerly known as TENATSO) time series site 70 km NE of the Cape Verde Islands. Cruise KN204-01 in October–November 2011 occupied stations 11-01 through 11-24 from Woods Hole to Cape Verde, including seven in situ pumping stations along Line W between Woods Hole and Bermuda at the BATS site (stn. 11-10); stn. 11-16 at the TAG hydrothermal site along the mid-Atlantic ridge (TAG/MAR); and a KN204/KN199 crossover station at the CVOO site.

The meridional component of the cruise (stations 10-01 to 10-09) is characterized by North Atlantic Central Water (i.e., relatively warm and salty waters between 20–30 °W and 30–35 °N that characterize the North Atlantic subtropical thermocline) in the upper 500 m, high salinity Mediterranean Outflow Waters between 500 and 1500 m, and North Atlantic Deep Water with some Antarctic Bottom Water below that (Jenkins et al., 2015). The zonal portion of the transect can be separated into three sections. From west to east, these are: the Line W section between Woods Hole, MA and Bermuda (stations 11-01 to 11-10), the oligotrophic open ocean section between Bermuda and Cape Verde Islands (stations 11-10 to 11-24), and the Mauritanian Upwelling section between Cape Verde and the Mauritanian coast (stations 10-12 to 10-09). North Atlantic Central Water dominates the thermocline (upper ≈600 m) in the Line W and oligotrophic sections, whereas Atlantic Equatorial Water (i.e., fresher and cooler thermocline waters at 20–40 °W, 5–10 °N) is more important in the thermocline of the Mauritanian Upwelling part of the section (Jenkins et al., 2015). Northern sourced Upper and Central Labrador Seawater are the dominant intermediate water masses along Line W, whereas southern sourced Antarctic Intermediate Water and Upper Circumpolar Deep Water dominate in the Mauritanian upwelling section, with a mixture of northern and southern sourced intermediate waters in the oligotrophic section. A similar pattern of more northern sourced waters in the west and more southern sourced waters in the east characterizes the deep waters of the zonal section (Jenkins et al., 2015).

2.2. Particle sampling

The dataset described herein comprises 17 elements (Ag, Al, Ba, Cd, Co, Cu, Fe, Mn, Nd, Ni, P, Pb, Th, Ti, V, Y, Zn) and two particulate size classes (0.8–51 μm, and > 51 μm), though we focus here on the predominantly lithogenic tracers Al, Fe, and Ti. Particles were collected via in situ battery-powered pumps (McLane WRT-LV), in a modified dual-flow configuration described in (Cutter et al., 2010; Lam and Morris, 2013).

Twenty-two stations were sampled, typically at sixteen-point depth resolution over two casts within ca. 24 h: a shallow cast during which eight depths were sampled in the upper 1000 m, including four depths in the upper 200 m, and a deep cast during which eight pumps were sampled between 1000 m and the ocean floor. During the 2011 cruise, a 12 kHz pinger at the bottom of the hydrowire allowed closer sampling of near-bottom depths and benthic nepheloid layers when conditions permitted. Pumps were deployed on a trace-metal hydrowire (Hytrel-jacketed Vectran) and operated for four hours at initially programmed pumping speeds of 8 L/min. Each pump was configured with two parallel flowpaths ("QMA" and "Supor") each of which filtered first through a 51 μm polyester pre-filter (hereafter the "large size fraction" or LSF: particles > 51 μm), and then through either paired 0.8 μm polyethersulfone Supor™ filters (hereafter: "small size fraction" or SSF: particles 0.8–51 μm), or paired quartz fiber Whatman QMA filters (not discussed here). Both QMA and Supor flowpaths were independently flow-metered to determine volume filtered. Combined flowpath outflow was metered separately to ensure volume determination in the event of a single flowmeter failure. Typical total volumes filtered were 1500–1700 L, with 30% of volume (median: 461 L) passing via the Supor flowpath and the rest (median: 1167 L)

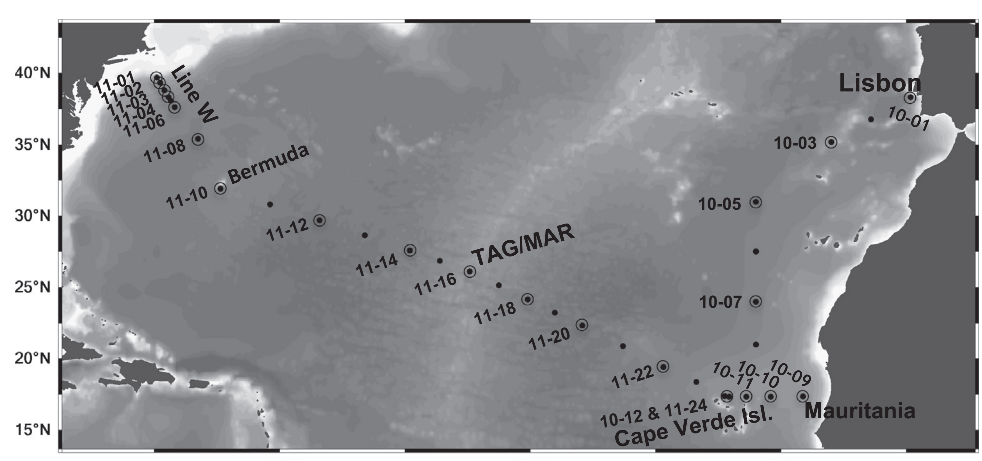

Fig. 1. Oceanographic stations from *R/V Knorr* cruises KN199-4 in October 2010 (stations 10-xx) and KN204-1 in November-December 2011 (stations 11-xx) where particulate samples were collected (circles and annotations). TAG is the TAG hydrothermal site along the mid-Atlantic Ridge (MAR).