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Sediment waves on the Conrad Rise, Southern Indian Ocean: Implications for the migration history of the Antarctic Circumpolar Current

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ABSTRACT

The Antarctic Circumpolar Current (ACC) is the worlds longest and largest current system; therefore, it plays a prominent role in the global distribution of heat, nutrients and greenhouse gasses. While past changes in the ACC have been reconstructed by a number of studies using sedimentary records in the Southern Ocean, a detailed understanding of the relationship between its temporal and spatial variability and the changes in the Earths climatic system remains unclear. In this study, we conducted multibeam bathymetry, multi-channel seismic reflection, and sediment coring surveys on the Conrad Rise, located in the southern Indian Ocean sector of the ACC. These data reveal large scale sediment wave structures with continuous and parallel reflectors that have low to moderate reflection amplitudes in the upper part of the seismic section (Unit A). These phenomena are most likely formed by bottom current interactions with the sea-floor and sediment transport under the ACC. The basal age of Unit A is estimated to be younger than Pliocene/Pleistocene boundary based on the extrapolation of sedimentation rates from a shallow sedimentary core. The lower part of the section (Unit B) is characterized by moderate to high amplitude sub-horizontal to horizontal reflectors that are interpreted as pelagic sedimentation with stronger current influence to the upper part of the unit. Based on the correlation with ODP sites in the Southern Ocean, we estimate that the upper part of Unit B mainly comprises calcareous ooze. Though the age of the change in the sedimentary environment from seismic Units B to A is not specified, it is thought to be caused by a northward shift of the ACC.

1. Introduction

The Southern Ocean has a profound influence on the world's ocean and climate (e.g., Carter et al., 2009). Based on its salinity and temperature structure, the Southern Ocean has several latitudinal zones (Pollard et al., 2002). The Subtropical Front (STF), Subantarctic Front (SAF), Polar Front (PF), and the southern boundary of the ACC (SB) separate the Subantarctic Zone (SAZ), Polar Frontal Zone (PFZ), and Antarctic Zone (AAZ), respectively (Fig. 1). The ACC is enclosed between the SAF and SB (Fig. 1), and the mean position of the ACC "axis" is given by the locus of the PF (Barker and Thomas, 2004). The ACC is also the most prominent current in the Southern Ocean, and it flows through three major ocean basins. The eastward flow of the net current of the ACC extends from the surface to the bottom of the ocean, and its path is guided by the seafloor topography (Orsi et al., 1995). The ACC is also responsible for the inter-basin exchange of heat, salinity, nutrients, and gasses, and it contributes to the thermohaline circulation (e.g., Rintoul, 2009). Furthermore, the ACC inhibits meridional transport of water, which causes thermal isolation of the Antarctica from the warm waters distributed to the north of the current (e.g., Rintoul, 2009). Therefore, the past variability of the ACC has a large impact on environmental change in the Southern Ocean and Earth's climatic system. Thus the establishment of ocean gateways and fluctuation of the ACC have been discussed in relation with the cooling of the Antarctica for example at the Eocene/Oligocene boundary (e.g. Exon et al., 2000; Barker and Thomas, 2004; Bijl et al., 2013), but these are also disputed (e.g. DeConto and Pollard, 2003; Huber and Nof, 2006).

The ACC plays an important role in the zonation of the biogeochemical features and processes in the Southern Ocean (e.g., Pollard et al., 2002). Production of diatoms is greatly subordinate to other phytoplankton north of the PF due to the limitation of temperature and nutrients (e.g., Burckle and Cirlli, 1987; Zielinski and Gersonde, 1997; Nelson et al., 2001), resulting in a predominance of carbonate sediments (Hutchins et al., 2001). In contrast, diatoms are a dominant primary

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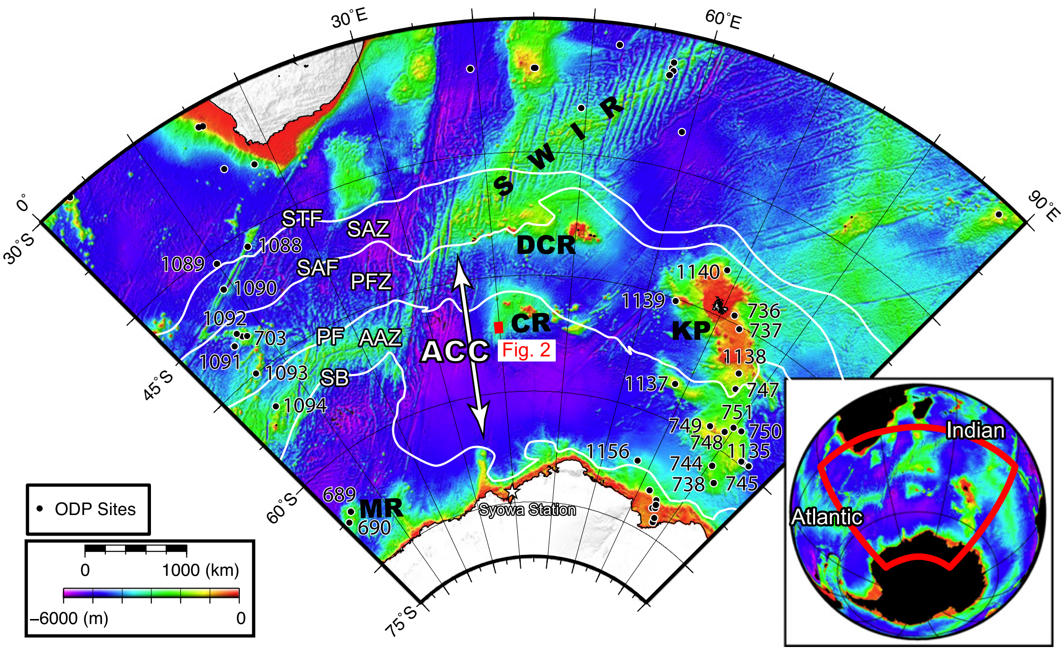

Fig. 1. Bathymetric and oceanographic map of the Indian and Atlantic sector of the Southern Ocean. Topographical features are labeled. SWIR: Southwestern Indian Ridge, DCR: Del Caño Rise, CR: Conrad Rise, KP: Kerguelen Plateau, MR: Maud Rise. Oceanic fronts are shown in white lines. STF: Subtropical Front, SAF: Subantarctic Front, PF: Polar Front, SB: Southern Boundary of ACC. Oceanic zones are also indicated. SAZ: Subantarctic Zone, PFZ: Polar Front Zone, AAZ: Antarctic Zone. Positions of the oceanic fronts and zones are based on Sokolov and Rintoul (2009a, b). ODP Site numbers are leveled.

producer south of the PF and account for up to two-thirds of the total global silica input to the deep oceans (Tréguer et al., 1995; DeMaster, 2002; Cortese et al., 2004). These characteristics make it possible to reconstruct past fluctuations of the ACC associated fronts, and water masses using geological, geophysical, and geochemical analyses of the Southern Ocean sedimentary archives and to evaluate their response to changing climate (e.g., Howard and Prell, 1992; Barron, 1996; Bohaty and Harwood, 1998; Becquey and Gersonde, 2002; Diekmann and Kuhn, 2002; Whitehead and McMinn, 2002; Gersonde et al., 2005; Flores and Sierro, 2007; Marino et al., 2009; Kemp et al., 2010; Williams et al., 2010; Etourneau et al., 2012).

The meridional migration of zonal westerly winds and Southern Ocean fronts in response to global climate events, such as the late Pliocene global cooling, mid-Pleistocene transition, and mid-Brunhes event, has been proposed by several studies (e.g., Bard and Rickaby, 2009; Kemp et al., 2010; McKay et al., 2012). McKay et al. (2012) suggest that major ice expansion on Antarctica and sea-surface ocean cooling began at approximately 3.3 Ma, followed by a stepwise expansion of sea ice between 3.3 and 2.5 Ma. Based on the AND-1B sediment record from the Ross Sea and deep ocean drill core records from the global ocean, McKay et al. (2012) hypothesize that the northward migration of westerly winds and ocean fronts potentially reduced the Atlantic Meridional Overturning Circulation (AMOC) by restricting the surface water connectivity between the ocean basins. Kemp et al. (2010) highlighted a stepwise northward migration of the locus of the PF in the early to mid-Pleistocene based on the change of diatom ooze distribution. A key feature of these hypotheses is the northward migration of the ACC that restricts interconnectivity of subtropical gyres between ocean basins and, specifically, heat transport from the Indian Ocean to the Atlantic Ocean, which could potentially weaken the global ocean circulation. However, these paleoceanographic inferences are made based on a limited number of records. In this study, we provide direct evidence of migration of the ACC and associated oceanic fronts in the Indian Ocean. The depositional units we describe hold a record of the relationship of change in the ACC to global cooling events that is accessible through scientific drilling.

The Conrad Rise is an intra-plate aseismic topographic high located between 50°S and 55°S in the Indian sector of the Southern Ocean, and it is presently situated in the AAZ near the PF (Fig. 1). The ACC is unrestricted in the region and bifurcates at the western side of the Conrad Rise, forming jets along the 3500 m isobaths to the north and south, and it converges again on its eastern side (Ansorge et al., 2008). This oceanographic setting is suitable for addressing the past fluctuations of the ACC and its associating oceanic fronts. However, the sedimentary history of the Conrad Rise remains poorly understood because of very limited geological and geophysical data from the region. In this study, we interpret a northward shift of the paleo-ACC based on seismic reflection configuration and facies, swath bathymetry, and sediment coring from the Conrad Rise. This first report of the long-term sedimentary history from the Conrad Rise is correlated with ODP sites in the Kerguelen Plateau and southeastern Atlantic, and provides a direct record of Late Neogene ACC variability and new insights into the evolution of the Southern Ocean.

2. Methods

We conducted swath bathymetric surveys, seismic reflection, and sediment coring in the southwestern slope of the Conrad Rise. Surveys were undertaken during two cruises in 2008 and in 2010-2011 using the Research Vessel (R/V) *Hakuho-Maru* from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC).

Swath bathymetric data were obtained using a SeaBeam 2120 echosounder system along the ship's tracks (Fig. 2). 150 beams and a swath width of 120° were used for data collection. The raw data were edited to remove outlying depth values. The sea-floor gradient was calculated from the grid data spacing and the differences in elevation.

We collected a sedimentary core (COR-1bPC) at 54° 16′ S, 39° 46′ E on the southwestern slope of the Conrad Rise, where the water depth was 2828 m (Fig. 2). The length of the core was 10.5 m. Color reflectance was measured at 1 cm resolution on the surface of split cores (Fig. 3). The Minolta CM-2002 photospectrometer was used to measure the hue and chroma attributes of the sediments, as well as the reflected