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Persistently strong Indonesian Throughflow during marine isotope stage 3: evidence from radiogenic isotopes

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A R T I C L E I N F O

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A B S T R A C T

The Indonesian Throughflow (ITF) connects the western Pacific Ocean with the eastern Indian Ocean, thus forming one of the major near surface current systems of the global thermohaline circulation. The intensity of the ITF has been found to be sensitive to changes in global ocean circulation, fluctuations in sea level, as well as to the prevailing monsoonal conditions of the Indonesian Archipelago and NW Australia. This study presents the first reconstruction of ITF dynamics combining radiogenic isotope compositions of neodymium (Nd), strontium (Sr), and lead (Pb) of the clay-size detrital fraction to investigate changes in sediment provenance, and paleo seawater Nd signatures extracted from the planktonic foraminifera and authigenic Fe–Mn oxyhydroxide coatings of the marine sediments focussing on marine isotope stage 3 (MIS3). Sediment core MD01-2378 was recovered within the framework of the International Marine Global Change Study (IMAGES) and is located in the area of the ITF outflow in the western Timor Sea (Scott Plateau, 13° 04.95′ S and 121° 47.27′ E, 1783 m water depth). In order to produce reliable seawater signatures, several extraction methods were tested against each other. The results of the study show that at this core location the extraction of surface water Nd isotope compositions from planktonic foraminifera is complicated by incomplete removal of contributions from Fe–Mn oxyhydroxides carrying ambient bottom water signatures. The bottom water Nd isotope signatures reliably obtained from the sediment coatings (average $\varepsilon Nd = -5.0$) document an essentially invariable water mass composition similar to today throughout the entire MIS3. The radiogenic Nd, Sr, and Pb isotope records of the clay-sized detrital fraction suggest that the Indonesian Archipelago rather than NW Australia was the main particle source at the location of core MD01-2378, and thus indicating a persistently strong ITF during MIS3. Furthermore, the variations of the detrital radiogenic isotopes are shown to be more sensitive to changes in circulation and document a somewhat enhanced ITF intensity during the early part of MIS3 until 47.4 ka compared with the remaining MIS3.

1. Introduction

The Indonesian Throughflow (ITF) defines the hydrographic gateway between the Pacific and Indian Oceans. Hence, it constitutes one of the key areas for present-day global ocean exchange processes (e.g., salinity, heat), as well as a sensitive location for climatic and environmental changes through time (Visser et al., 2003; Ruth et al., 2007).

The ITF current system forms a major part of the surface water pathways of the global thermohaline circulation and is characterized by low-salinity surface and intermediate waters from the western and northwestern Pacific Ocean flowing through the Indonesian Archipelago and entering the eastern Indian Ocean (Schmitz, 1995; Gordon, 2005; Xu et al., 2010). The Pacific surface and subsurface waters enter the Indonesian Archipelago south of the Philippines and pass the Celebes Sea and Makassar Strait southwards into the eastern Java Sea (Fig. 1). While a part of these

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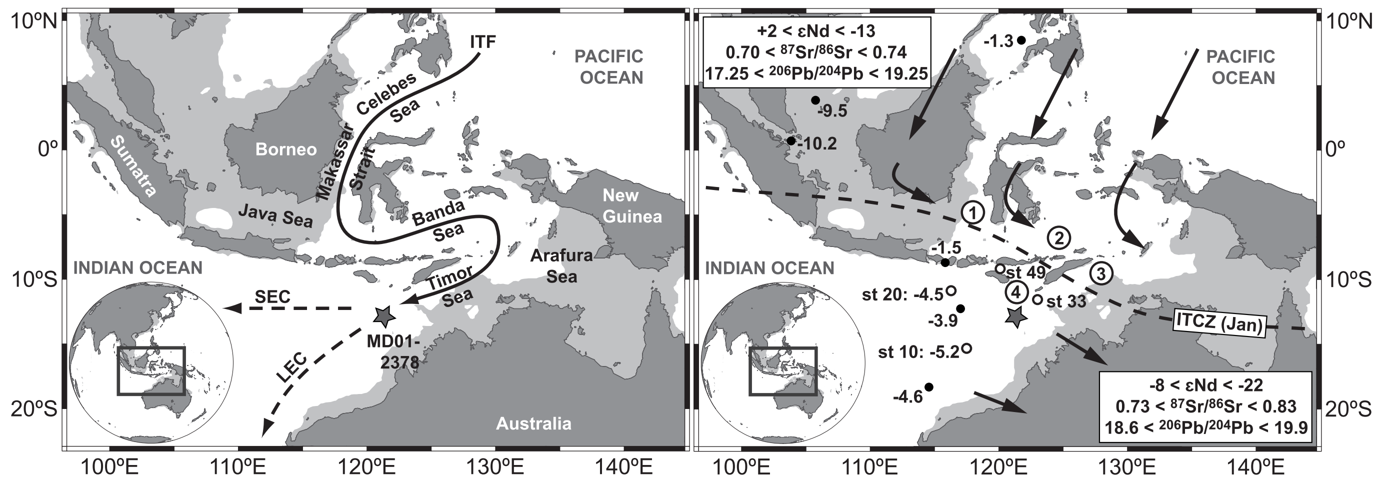

Fig. 1. (left): The Indonesian Seas with the main pathway of the Indonesian Throughflow (ITF) and proximal ocean currents, as well as the location of sediment core MD01-2378 (star symbol) in the western Timor Sea (modified from Godfrey, 1996; Spooner et al., 2005; Zuraida et al., 2009; SEC: South Equatorial Current; LEC: Leeuwin Current). The area shaded in grey denotes the coastline at a sea level 100 m lower than today corresponding to the minimum levels reached during MIS3. (right): Nd isotope compositions of surface (solid dots) and subsurface (open dots) waters (Jeandel et al., 1998; Amakawa et al., 2000), and the range of radiogenic Nd, Sr, Pb isotope compositions of Indonesian (upper left box) and NW Australian (lower right box) source rocks (Vroon et al., 1995). Numbers 1–4 refer to locations of surface sediments along the ITF pathway (Ehlert et al., 2011). Arrows indicate simplified wind trajectories during NW monsoon conditions in Austral summer, the dashed line shows the corresponding approximate position of the ITCZ in January (e.g., Gingele et al., 2002; Xu et al., 2008). Note: During Austral winter, the ITCZ is located at 10–15°N (outside the map margins) and easterly winds of the SE monsoon predominate in the Indonesian Seas.

waters exits directly southwards into the eastern Indian Ocean through the Lombok Strait, the main pathway of the ITF continues eastwards into the Banda Sea (Godfrey, 1996). In addition, there are some minor contributions of Pacific surface waters reaching the Banda Sea from the north through the Halmahera and Molucca Seas (Spooner et al., 2005). Regional excess of precipitation over evaporation, vertical mixing, as well as freshwater contributions from the South China Sea lead to a salinity decrease within the Banda Sea to levels lower than those of the Pacific source waters (Hautala et al., 1996; Tozuka et al., 2009). Finally, the modified ITF surface waters exit the Banda Sea into the eastern Indian Ocean via the Ombai and the Timor Straits of the Timor Sea.

The ITF waters branch out westwards and contribute to the South Equatorial Current (SEC), which crosses the Indian Ocean and has an impact on the strength and hydrographic properties of the Agulhas Current. A second branch of the ITF heads southwards to strengthen the Leeuwin Current flowing along the west coast of Australia (Godfrey, 1996). These large scale current systems directly respond to changes in ITF intensity, which itself is strongly influenced by the prevailing atmospheric conditions over Asia and Australia (Godfrey, 1996; Wijffels et al., 1996; Gordon, 2005; Spooner et al., 2005; Schott et al., 2009). Specifically, the intensity and volume flow of the ITF within the Indonesian Archipelago respond significantly to the regional monsoonal system. During Austral winter (May–September) when the Inter Tropical Convergence Zone (ITCZ) is located at about 10–15°N, westward blowing winds of the SE monsoon promote an intensification of the ITF accompanied by a shallowing of the surface mixed layer. In contrast, during Austral summer (November–March) the ITCZ shifts southward and eastward winds of the NW monsoon accumulate water in the Banda Sea resulting in a deepening of the thermocline, as well as in a decrease of ITF intensity (Wijffels et al., 1996; Gordon, 2005; Fig. 1).

The reconstruction of past variations in ITF intensity thus can serve to draw conclusions about regional and global oceanic and climatic conditions. Previous reconstructions of the Late Quaternary hydrographic and atmospheric variability in the ITF region were mainly based on clay mineral assemblages, stable isotope compositions ($\delta^{18}O$, $\delta^{13}C$) of planktonic and benthic foraminifera, as well as Mg/Ca thermometry (e.g., Gingele et al., 2001, 2002; Holbourn et al., 2005, 2011; Spooner et al., 2005; Xu et al., 2008; Zuraida et al., 2009).

This study focuses on marine isotope stage 3 (MIS3), which was characterized by rapid, millennial-scale climate variability, i.e., Dansgaard–Oschger interstadials and Heinrich stadials. Although these climate oscillations were most pronounced in higher latitudes of the northern hemisphere, they have also been observed in subtropical and tropical regions, as well as in the southern hemisphere (Voelker et al., 2002; Lynch-Stieglitz, 2004; Huber et al., 2006; Piotrowski et al., 2008). In addition, this period of time was characterized by significant sea level changes ranging from 40 to 100 m below the present level (Siddall et al., 2003), which would have resulted in exposure of large parts of the shelf of the Indonesian Archipelago, and significantly affected ITF current pathways (in analogy to the sea level changes during the LGM; De Deckker et al., 2002).

Based on analyses of foraminiferal assemblages and stable isotopes ($\delta^{18}O$, $\delta^{13}C$), a generally drier climate over the Indonesian Archipelago has been suggested for MIS3 due to the ITCZ being permanently located to the north of the Banda Sea (Spooner et al., 2005). In analogy to modern observations, this atmospheric setup would have resulted in constant 'SE monsoon'-like conditions accompanied by a thinner mixed layer and an intensified throughflow. On shorter millennial to centennial time-scales within MIS3, the variability of the ITF intensity has been found to respond to variations in global oceanic circulation, sea level changes, as well as orbitally driven monsoon fluctuations (Holbourn et al., 2005; Dürkop et al., 2008; Zuraida et al., 2009; these authors used sediments of core MD01-2378 as well). According to these studies lower sea levels during stadial periods (i.e., Heinrich events) were associated with slowdowns of the ITF.

This study aims to investigate past environmental changes within the western ITF and their controlling factors focussing on marine isotope stage 3 (MIS3). We combine the evidence provided by independent approaches of analysing radiogenic isotope compositions (i.e., neodymium, strontium, lead) of the detrital clay size