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研究課題名（英文）Indonesian Throughflow variability and its influence on global climatic events during the Pliocene and Pleistocene

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研究成果の概要（和文）：本研究は，インドネシア通過流水（ITF）が過去のインド洋の気候にいかに変化をもたらしたかを理解することに焦点を当てた。ITFは世界の海洋循環に重要な役割を果たし，気候に変化をもたらす。ITFがどのように変化するかを理解するために，本研究では国際深海底掘削計画(IODP)の第356次航海で得られた堆積物試料を用いた。この堆積物は，オーストラリア西岸に沿って南流するルーウィン海流中で形成されたものである。当海流はITFによって直接供給され，その変化を記録している。本成果はインドネシア列島のテクトニクスの変化，特に世界的な海水準の変化がITFの動態を変化させてきたことを示している。

研究成果の学術的意義や社会的意義
本研究の成果は，過去500万年にわたるITFの詳細な歴史を明らかにした。330万年前の氷期イベントは，現在の地球温暖化の最も良い例と考えられている。他方，中期更新世移行期（MPT）は，外部フォーシングに対する気候の応答の本質的な変化の一例である。こういった時代の研究は，私たちの地域的・全球的な気候変動に関する理解を増進させる。それは現在の地球温暖化のインパクトを予測するために用いられるコンピューター・モデルを改良するのに必須の知見である。本研究は，高解像度データとモデルの相互比較のために利用しうる貴重な基礎データを供給する。

研究成果の概要（英文）：The project focused on understanding how changes in the Indonesian Throughflow (ITF) impacted climatic conditions in the Indian Ocean and the worlds global climate in the past. Today the ITF is an important part of the global ocean circulation. Changes in its flow have consequences to ocean circulation and in turn our climate. To better understand how changes in the ITF can affect the Indo-Pacific region we studied samples recovered during International Ocean Discovery Project (IODP) Expedition 356 ‘Indonesian Throughflow’. These sediments were deposited within the path of the Leeuwin Current a warm tropical currented flowing southward along the western coast of Australia. The Leeuwin current is directly fed by the ITF and records changes in its flow. The results show that both tectonic changes of the Indonesian Archipelago, as well as changes in global sea level can change the behavior of the ITF. We show how sensitive ITF was to past climate change, especially to sea level changes.

研究分野：Paleoceanography, Paleoclimatology, Paleoecology

キーワード：Indonesian Throufhflow　MPT　M2 glacial event　Nannoplankton　Pliocene　West Pacific Warm Pool　Leeuwin Current　Australian Climate

１．研究開始当初の背景

The Indonesian gateway is the last remaining of tropical ocean passageways (Figure 1). The opening and closing of such gateways was previously associated with major reorganizations in global ocean circulation, as shown by the closure of both the Tethys and Panama gateway (Kuhnt et al., 2004).

As the last remaining tropical gateway connection to major ocean basins the Indonesian Gateway plays a major role in the Earth’s climate today. Particularly, the heat transport from the West Pacific Warm Pool (WPWP) into the Indian Ocean via the Indonesian Throughflow (ITF) is recognized as an important part of the oceanic thermohaline circulation (Godfrey, 1996; Godfrey & Mansbridge, 2000; Jochum et al., 2009; Kuhnt et al., 2004; Schneider, 1998)). Although modeling studies do suggest a significant influence of ITF variability on heat distribution in the oceans (Jochum et al., 2009), its exact influence on global climate, in both modern times and the geological past, is difficult to resolve. (Kuhnt et al., 2004).

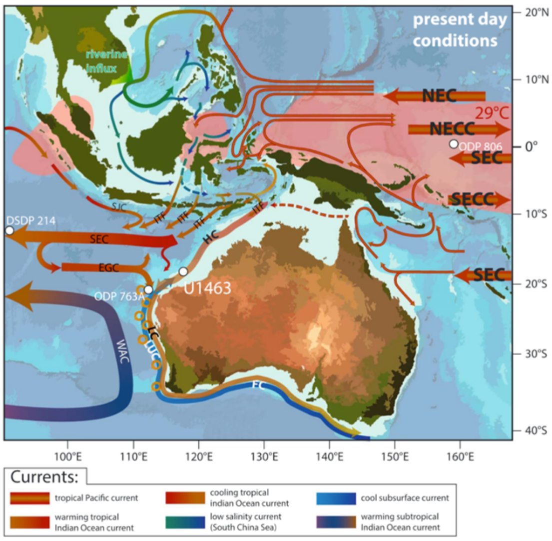

Figure 1: Map showing the position of Sites U1463, Ocean Drilling Program (ODP) 763A, ODP 806, and Deep See Drilling Project (DSDP) 214 (white dots) in relation to the major current paths of the Indonesian Throughflow (ITF) and the eastern Indian Ocean. Colors on land approximate current vegetation cover in Australia and the maritime continent from satellite images. Base map and satellite images used to generate this figure were generated in GeoMapApp (http://www.geomapapp.org). Pacific currents: North Equatorial Current (NEC), North Equatorial Counter Current (NECC), South Equatorial Current (SEC), and South Equatorial Counter Current (SECC). Indian Ocean currents: Indonesian Throughflow (ITF = dominant outflows from the Indonesian Archipelago), South Java Current (SJC), South Equatorial Current (SEC), East Gyral Current (EGC), Holloway Current (Wilson, 2013), and Leeuwin Current (LC), which are considered as one current system in this work, Leeuwin Undercurrent (LUC), West Australia Current (Schott et al., 2009).

The complex tectonic history of the Indonesian archipelago that lead to ongoing ITF restriction also makes it difficult to obtain tectonically undisturbed records of the ITF directly within the Indonesian archipelago. Conversely, the effects of its evolution during the late Neogene and Quaternary are currently poorly constrained (Kuhnt et al., 2004). The best areas to investigate ITF history are thus downstream in the Indian Ocean, either in the deep ocean away from strong tectonic deformation or along proximal passive margins that are directly influenced by the ITF, or are under the influence of offshoot currents fed by the ITF. The Leeuwin-Holloway current system, a shallow (< 200m water depth) current flowing along the western Australian margin, is of particular interest in this context (Figure 1). Today, the Leeuwin current (LC) is highly influenced by the Southern Oscillation, indicating that warmer (La Niña phases) conditions in the WPWP enhance Leeuwin-Holloway current strength while years with a colder WPWP (El Niño phases) significantly reduce the southward warm water transport within the current (Lenanton et al., 2009).

２．研究の目的
The aim of this project was to understand the ITF variability and its influence on the west Australian shelf and by extend global climate, we studied study two short (~500 kyr) intervals in the geological record, that contain episodes of intense climatic shifts:
(1) An interval from 3.0 to 3.5 Ma at Site U1463, which encompasses the so-called M2-event at ~3.3, representing an intense cooling event related to tectonic restriction of the ITF (De Schepper et al., 2014).
(2) An interval from ~1.1 - 0.6 at Site U1460 focused on the early-middle Pleistocene Transition, including the ~900 ka event, which represents the transformation in the Earth's climate state from the 41-kyr paced Pliocene to the quasi-100-kyr paced glacial Pleistocene (Head & Gibbard, 2015).

３．研究の方法
Our research focused on surface water productivity to reconstruct oceanographic and by extend paleoclimatological conditions in the Indian Ocean during these critical time intervals. To achieve this goal e implemented a multiproxy approach, using paleobiological (calcareous nannofossil assemblages and absolute abundance counts) and geochemical (total organic carbon, uranium, sulfur and alkenone concentrations), as well as geophysical (XRF, and natural gamma log measurements) proxies, to fully reconstruct the surface water conditions during the M2-event at Site U1463 and the EMPT at Site U1460.

４．研究成果
Research results for U1463 (M2-event study) performed in FY2017 are summarized in Auer et al. (2019) and revolve around these major conclusions (Figure 2,3):
Our sub–Milankovitch scale calcareous nannofossil and geochemical records from IODP Site U1463 combined with existing Indo–Pacific data (De Vleeschouwer et al., 2018; Karas et al., 2009; Wara et al., 2005) enabled us to reconstruct the timing and pacing of tectonic ITF restriction during the Pliocene (3.66-2.97 Ma). The position of IODP Site U1463 within the upper branch of the
LC provides new insights into Pliocene ITF dynamics between 3.66 and 2.97 Ma, allowing us to distinguish changes caused by tectonic ITF restriction from those imparted by global sea level variability, along the NWS:
(1) The dominant equatorial connection between the Indo–Pacific Warm Pool and the Indian Ocean via the Indonesian Gateway had already ceased ~3.54 Ma, as shown by a distinct shift in nannofossil assemblages at Site U1463. These changes are in line with cooling equatorial Indian Ocean temperatures at Site 214, pinpointing the switch to dominant northern Pacific ITF sources for the first time.
(2) Nannofossil assemblages provide detailed insights into how initial ITF reorganization after 3.5 Ma led to fundamental changes in paleoenvironmental conditions along the NWS and altered LC dynamics: The northern mode ITF led U1463 to reflect a more open Indian Ocean signal, which became especially pronounced during a long–term sea level lowstand between 3.4 and 3.2 Ma.
(3) The MIS M2 glaciation at 3.3 Ma was amplified by a significant reduction in equatorial heat exchange between the Pacific and Indian Ocean after 3.5 Ma. During MIS M2 sea level driven ITF restriction further enhanced the observed thermal isolation of Antarctica (De Vleeschouwer et al., 2018; Patterson et al., 2014) leading to the irreversible cooling of the eastern Indian Ocean (Karas et al., 2009; 2011) and Antarctica from 3.3 Ma onward.
(4) Nannofossil assemblage and δ13CT. sacculifer data show that the Pliocene sea level lowstand culminating in MIS M2 likely established an early form of the Sahul–Indian Ocean Bjerknes mechanism leading to upwelling along the NWS (Di Nezio et al., 2016). This mechanism also enhanced seasonality and aridification on the Australian Continent after 3.3 Ma, by establishing a more seasonally variable LC.
(5) The permanently tilted thermocline by 3.3 Ma and heightened glacial/interglacial LC variability after ~3.2 Ma resulted in oceanographic conditions along the NWS that were much closer to their Pleistocene configuration characterized by a weaker (stronger) LC during glacials (interglacials) (Gallagher et al., 2009; Spooner et al., 2011). These insights also illustrate the significant role eastern Indian Ocean surface water conditions played during the inception of the Australian Transitional Interval (Christensen et al., 2017).

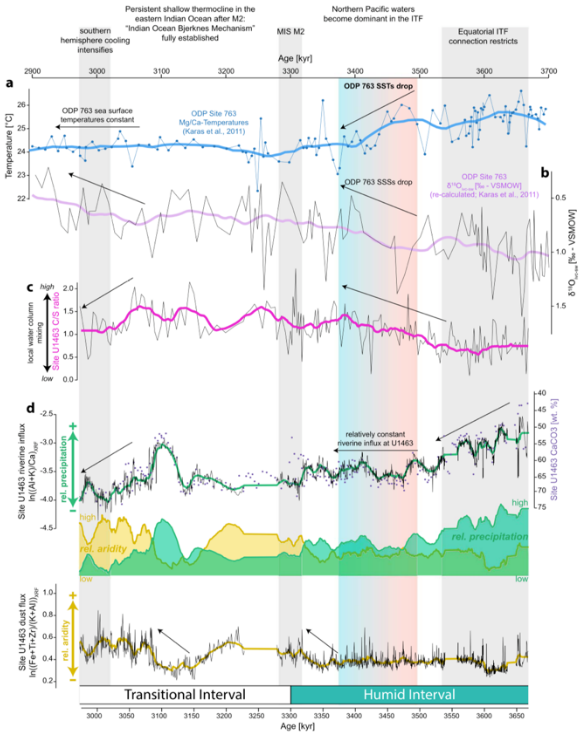

Figure 2: Long‐term oceanographic trends between 3.56 and 2.97 Ma along the northwest shelf at sites 763A (Karas et al., 2011) and Site U1463 with climatic conditions in the Australian hinterland (Christensen et al., 2017; De Vleeschouwer et al., 2018; this study): (a) Site 763A Ca/Mg temperature record (Karas et al., 2011), showing SSTs decreasing south of Site U1463 shortly after the assemblage shift ~3.54 Ma (black arrow); (b) recalculated $\delta^{18}O_{ivc-sw}$ (Karas et al., 2011) showing two intervals sea surface water freshening at Site 763A; (c) C/S ratio showing bottom water oxygenation as a proxy for water column mixing at Site U1463. (d) X‐ray fluorescence (XRF) elemental ratios ln((K + Al)/(Ca)) (= riverine influx) and ln((Fe + Ti + Zr)/(Al + K)) (= dust flux) are shown with their long‐term trends (21 pt. running mean). Discrete measurements of calcite equivalent calcium carbonate content (wt.%; blue dots) are shown in conjunction with the ln((K + Al)/(Ca)) record. The running means of the XRF records were superimposed to show relative changes in precipitation (riverine influx) versus aridity (windblown dust) at Site U1463. Tansition between humid and transitional intervals (after Christensen et al., 2017); MIS = marine isotope stage; ITF = Indonesian Throughflow

This study thus provided a unique time series of Pliocene paleoenvironmental conditions along the northwest shelf of Australia while linking them with long‐term changes in Australian climate. The observed local paleoenvironmental and paleoclimatological changes corroborate well‐established conceptual models of Indian Ocean and Australian Climate dynamics. Combined, this resulted in a robust model tying local environmental changes on the NWS to global Pliocene climatic trends. Our results also provide strong support for the interhemispheric teleconnection proposed by Sarnthein et al. (2017). We show the direct effect of changing ITF dynamics, especially in relation to changing sea level, had on past Australian and also global climatic changes.

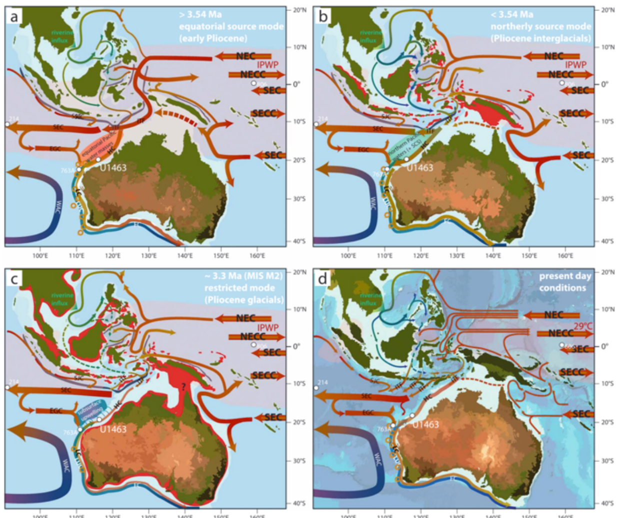

Figure 3: Tectonic and oceanographic change throughout the studied interval between 3.65 and 2.97 Ma (Hall, 2002). Current abbreviations follow the same scheme as in Figure 1. (a) Map showing the proposed open equatorial connection between the Pacific and the Indian Ocean. The extent of northern vegetation is inferred from Krebs et al. (2011); (b) configuration with landmasses potentially above sea level after 3.54 Ma (Molnar & Cronin, 2015) in red. Deep blue lines indicate subduction zones during the Pliocene. Uplift of Timor/Halmahera is implied by 3.5 Ma (Hall et al., 1988; Tate et al., 2017); (c) throughflow geometry with maximum emergent land during marine isotope stage M2 (assuming a sea level lowstand of −30 m); (d) modern configuration.

Major results for the EMPT study performed in FY2018 at U1460 are currently in the process of being published and support the following conclusions:
Sea level driven restriction of the ITF below a threshold of ~40‐50 m had a major impact on productivity and upwelling dynamics on the Australian shelf at Site U1460 (Figure 4). The 900-kyr-event lowstand thus led to a major reorganization of productivity patterns along the Australian Shelf.

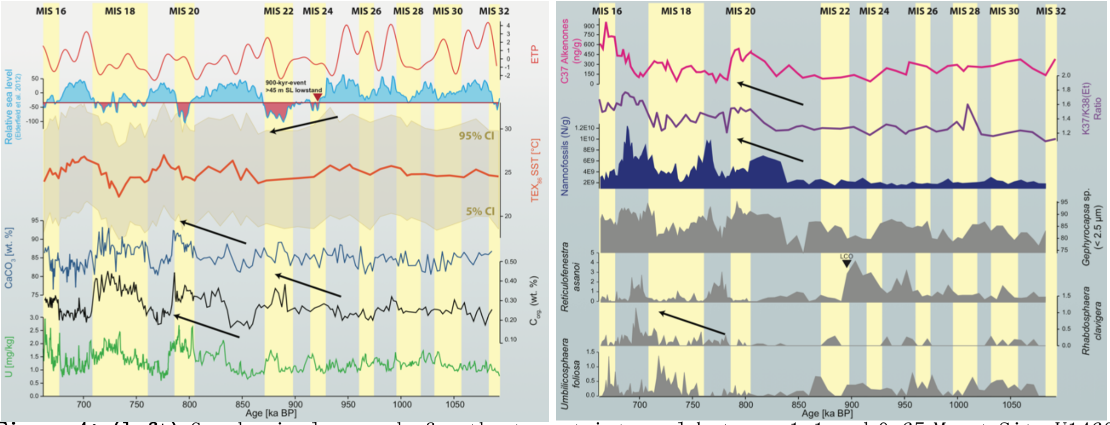

Figure 4: (left) Geochemical records for the target interval between 1.1 and 0.65 Ma at Site U1460 compared to the austral summer eccentricity-tilt-precession (ETP) composite, the sea level reconstruction of Elderfield et al. 2012 and the TEX86 BAYSPAR sea surface temperatures (SST) record of Petrick et al, 2018. Geochemical records shown are calcite equivalent carbonate (CaC03) content in weight percent (wt. %). Total organic carbon Corg. concentrations in wt. %, and ICP-MS calibrated Uranium (U) content in mg/kg derived from WRMSL natural gamma radiation counts measured during IODP Expedition 356. Note the close co-evolution of Corg., Uranium, and CaC03 after 840 kyr. **(right)** Long-chain C37 Alkenone concentrations and the K37/K38Et ratio compared to calcareous nannofossil assemblage data of the MPT target interval at Site U 1460. Shown are total nannofossil abundances as nannofossils per gram of sediment (N/gsediment) and relative abundances data of Gephyrocapsa sp. (< 2.5 µm), *Reticulofenestra asanoi* with its last common occurrence (LCO; black triangle) recorded ~895 kyr at Site U1460. The relative abundance of *Rhabdosphaera clavigera* commonly regarded as a oligotrophic warm water taxon and *Umbilicosphaer foliosa* (temperate, mesotrophic) illustrate changes in LC and LUC dynamics during the MPT.

Restricted ITF connectivity during the MIS 24 and MIS 22 sea-level-lowstands reduced Leeuwin Current (LC) strength and increased the upwelling of cool, well oxygenated and nutrient-rich Leeuwin Undercurrent (LUC) waters (Figures 4). Heightened southern hemisphere temperature gradients after the 900-kyr-event led to a stronger LUC, which affected nutrient availability and thus surface water productivity at Site U1460 by MIS 21 (~ 840 kyr). Heightened surface water productivity is reflected by a relative increase in organic carbon and Uranium content, as well as Alkenone concentrations and increased nannofossil abundances in the sediment.

MIS 20 marks the onset of Glacial/Interglacial (G/IG) cycles in all our productivity records, with strongest overall productivity occurring during glacials as indicated by high abundances of organic carbon, Uranium, calcium carbonate and Alkenone concentrations. Increased nutrient levels are also supported by increased abundances of *Umbilicosphaera foliosa* in MIS 18 and MIS 20. In summary the 900-kyr events seems to have disrupted the mid-Pleistocene LC/LUC system when sea levels fell below a threshold for an extended period of time, consequently altering ITF dynamics. Subsequently a distinct G/IG state established itself in the LC/LUC system at Site U1460 during MIS 21 and MIS 20 (Figures 4).

５．主な発表論文等

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６．研究組織

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