Multi-proxy study of the Leeuwin Current System evolution along the Western Coast of Australia during the Middle Pleistocene Transition

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The Middle Pleistocene Transition (MPT) stands out in Earth's climatic history as a significant reorganisation in the glacial/interglacial rhythmicity, representing a switch from obliquity-dominated glacial/interglacial patterns towards the quasi-periodic 100 kyr cyclicity. This fundamental rearrangement in the climatic response to orbital forcing occurred without comparable changes in the astronomical rhythms before or during the MPT, suggesting a drastic change within the climate system. Although the MPT has been intensively studied, the main causes and the components of the climate system involved remain poorly understood.

High-resolution studies from the equatorial to mid-latitude shelf regions are to date rarely investigated. Thus, we analysed an expanded MPT section recovered at Site U1460A (eastern Indian Ocean, 27°22.4949′S, 112°55.4296′E, 214.5 mbsl), during International Ocean Discovery Program (IODP) Expedition 356.

We compare high-resolution records of shallow marine productivity and organic matter flux (Auer et al., 2021) to new benthic and planktonic foraminifera datasets. This multi-proxy approach aims to better define the response of the Leeuwin Current System during the MPT on tropical shelf regions.

Benthic foraminifera assemblage and plankton/benthos (P/B) ratio at Site U1460A will be used to understand the bottom water community response to the Leeuwin Current System variations during the MPT and to constrain the local impact of sea-level changes in a highly dynamic shelf setting, respectively.

Shallow coastal areas are highly useful to record glacial/interglacial alternance connected sea-level oscillations. The variations in the P/B ratio allow to obtain a preliminary overview of local sea-level changes along the Australian shelf. Particularly, higher and lower values in this ratio indicate highstand and lowstand phases, correspondingly. In this respect, foraminifera data will be combined with a multi-proxy dataset (Auer et al., 2021) to obtain important knowledge on local sea-level-driven environmental changes during the MPT. This, in turn, will allow to untangle the impact of local versus global climatic change over the MPT.

Finally, the presence of *Globorotalia tosaensis* was recorded at the top of our studied interval (Sample U1460A-14F-3W, 20-24 cm; 61.72 mbsf), which extended the local biostratigraphic range of this marker to Core 14. The continuous presence of this taxon indicates an age older than 0.61 Ma (Gradstein et al., 2020), reconfirming the most recent age model provided for this site by Auer et al. (2021).

Analysis of Pleistocene planktonic and benthic foraminifera assemblages from Fantangisña seamount in the NW Pacific Ocean (IODP Expedition 366)

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The Mariana forearc, in the NW Pacific Ocean, represents the southern sector of the Izu-Bonin-Mariana (IBM) trench-arc system (12° N to 35° N). It is considered the only setting where active serpentinite mud volcanism occurs. Several large serpentinite mud volcanoes are located on the forearc, between the trench and the Mariana volcanic arc. Among them, Fantangisña seamount was drilled during International Ocean Discovery Program (IODP) Expedition 366. Cored lithologies include serpentinite mud with lithic clasts from the subducting Pacific Plate, forearc crust and mantle overlain by pelagic sediments containing few ultramafic clasts. Additionally, nannofossil-bearing pelagic sediment and volcanic ash/tephra layers were recovered at the base of the seamounts.

Fantangisña serpentinite mud volcano is situated in the tropical Pacific region, at low latitudes (16° N) within the latitudinal range of the North Equatorial Current (NEC). The NEC represents a warm and oligotrophic water mass, moving westward in the tropical Pacific Ocean due to trade winds.

We performed benthic and planktonic foraminifera analyses at Site U1498A, situated on the southern, more stable flank of Fantangisña seamount. Previous biostratigraphic analyses on this site indicated that most of our studied interval covers the Early to Late Pleistocene.

Cluster analyses on Pleistocene planktonic foraminifera resulted in two sample groups based on the ratio of thermocline-dwelling species to mixed-layer dwellers. These groups suggest fluctuations in the depth of the thermocline (DOT) during the Pleistocene. We retained that the variations of the DOT can be linked to changes in the intensity of the NEC. Specifically, our results indicated a deep and stable thermocline with a strong NEC in the Early-Middle Pleistocene (during the Early-Middle Pleistocene Transition or EMPT). Conversely, a weaker thermocline and NEC were recorded during the Middle-Late Pleistocene (following the EMPT).

The intensification/weakening of the NEC could be related to ENSO climate phases (El Niño/La Niña).

In addition, planktonic foraminifera diversity data showed that the serpentinite mud vulcanism in the area did not affect the distribution of the planktonic community. Interestingly, our results suggest that rapid burial from serpentinite mud flows could enhance the preservation of the planktonic tests.

Benthic foraminifera exhibited high diversity before and after the serpentinite mudflow activity and suggest oligotrophic and oxic bottom-water conditions. Conversely, benthic taxa severely suffered during the volcanic activity due to serpentinite mud flows and gas exhalations.

The promise and achievements of multi-proxy biomarker reconstructions from the margins of the Indian Ocean

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The organic fraction of marine sediments contains a wealth of information about ocean and atmospheric conditions, aquatic communities and in marginal settings about terrestrial ecosystems and environments (Inglis et al., 2022). Solvent extraction of marine sediments yields a total lipid extract that can be purified into a variety of compound classes, and analytical target molecules can be identified, quantified and analyzed isotopically. Whether generalist markers for plants, archaea or specific to a species, these biomarker molecules carry ecological and environmental proxy information. In a series of projects in marine marginal settings from DSDP Site 231 (Gulf of Aden) (Feakins et al., 2005; Feakins et al., 2007; Feakins, 2013; Feakins et al., 2013; Liddy et al., 2016), IODP Site 1457 (Indus Fan) (Feakins et al., 2020; Tauxe and Feakins, 2020), transects of sites in the Bengal Fan including IODP Site 1451 (Hossain et al., 2022; Lee et al., 2019), adjacent to Sumatra (Niedermeyer et al., 2014) and in the Indian Ocean sector of the Southern Ocean ODP Site 739 (Prydz Bay) (Tibbett et al., 2021) my goal has been to reconstruct terrestrial ecosystems and the related oceanic and climatic conditions that determine terrestrial environments. Plant wax biomarkers record C3 to C4 transitions in tropical grasslands, an important plant evolutionary step captured by marine sedimentary archives. These biomarker reconstructions of vegetation change can be combined with microfossil evidence (e.g., pollen, charcoal) to achieve robust reconstructions of ancient ecosystems and agents of change, like fire. Biomarkers can also carry signals of precipitation and runoff from land, including the evidence for fluvial erosion in the presence of wood or lignin, and the brGDGTs from terrestrial soils, and they may carry signals of rainwater isotopes within the hydrogen isotopic composition of plant waxes. Temperatures on land and in the oceans are key complements that organic proxies can offer – some have proven especially helpful at high temperatures. Existing reconstructions from four corners of the Indian Ocean have revealed changes in vegetation, temperature change, revealed episodic events that have persisted over millions of years as well as directional change that altered the global climate state. Past climate offers many lessons and tests of system response to large changes that can help inform our understanding of future change, including proxy-model comparisons for training and testing climate models (Tibbett et al., 2022). The biomarker toolkit offers approaches to reconstruct, temperature, rainfall and ecosystem change to address three 2050 Science Framework strategic objectives: Earth's climate, feedbacks and tipping points. Further, biomarkers will specifically contribute to knowledge of the geographic patterns of future rainfall and vegetation response to future temperature rise, that can be tested on major transitions of the past – as part of the flagship initiative of ground-truthing future climate change.

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Dust deposited in the Western Arabian Sea during the warm Pliocene originates from the Arabian Peninsula

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Mineral dust is a major contributor to atmospheric aerosol loading and plays an important role in Earth's climate system. The Arabian Peninsula is the world's second largest dust producing area contributing over 10% of total annual global dust emissions. It is generally agreed that West Asia will become warmer (by up to 4°C average annual temperature above pre-industrial levels by the end of the century). But the response of rainfall to warming in this region is much less well understood. Geological data from past warm intervals can provide valuable context. While terrestrial records provide evidence of past humid intervals, they are less useful in documenting palaeoaridity. The sediments of the Arabian Sea archive long continuous records of continental climate, carried by the windblown dust and riverine material derived from its encircling land masses. But the classic published records of this type are associated with considerable uncertainties. We present new high-resolution data sets (elemental composition derived from XRF core scanning, grain size distributions and radiogenic Nd and Sr isotope composition on the terrigenous fraction) from classic drill sites from ODP Leg 117 (Sites 721/722) for the warm Pliocene (from 3.9 to 3.4 Ma). We compare our records to published palaeo data sets and maps of modern-day dust activation to assess variability in continental rainfall climate with changes in global climate state.

Multiproxy paleoceanography from Broken Ridge pinpoints the onset of Tasman Leakage at 6.6 Ma

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Inter-basinal heat and water exchange play a prominent role in driving global climate change on astronomical timescales, as part of the global thermohaline circulation. Tasman Leakage connects the Pacific and Indian Oceans at an intermediate water depth, south of Australia. Therewith, Tasman Leakage advects heat toward the Indian Ocean, and ultimately toward the Agulhas system. Hence, Tasman Leakage constitutes a non-negligible part of the present-day thermohaline circulation. The onset of Tasman Leakage likely occurred sometime in the Late Miocene (Christensen et al., 2021), but a precise geochronology for the establishment of this inter-basinal connection is still lacking. Moreover, Tasman Leakage sensitivity to astronomical forcing remains to be constrained in detail. To understand Tasman Leakage on astronomical timescales, we present a new Miocene-to-recent multi-proxy dataset from Ocean Drilling Program (ODP) Sites 752 and 754, cored on Broken Ridge (30°53.475'S), southeastern Indian Ocean.

The dataset consists of new X-ray Fluorescence (XRF) core scans that provide element contents for 18 different elements, along with benthic carbon and oxygen stable isotopic records at 4 cm resolution. The XRF-derived Ca/Fe record is paced by 405-kyr eccentricity between 22 Ma and 13 Ma (early-middle Miocene), but then becomes more sensitive to obliquity and precession forcing. The new high-resolution benthic $\delta^{13}C$ record confirms the onset of Tasman Leakage in the Late Miocene, more specifically at 6.6 Ma. This is when the Broken Ridge benthic $\delta^{13}C$ signature no longer reflects an Antarctic Intermediate Water signal. The benthic $\delta^{18}O$ record shows a strong ~110-kyr eccentricity imprint, indicating that Tasman Leakage might be most sensitive to this astronomical parameter. We conclude that the Neogene nannofossil oozes, preserved on Broken Ridge, constitute an excellent paleoceanographic archive that allows us to fingerprint Tasman Leakage sensitivity to astronomical forcing.

Variability of the Indonesian Throughflow and Australian monsoon dynamism across the Mid Pleistocene Transition (IODP 363, Site U1483)

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The Mid Pleistocene Transition between ~1200 and ~800 ka represents a major shift in global climate, as it was marked by a change from ~41 to ~100 kyr glacial/interglacial periodicity, resulting in higher amplitude sea-level variations and intensified glacial cooling. The Indonesian Throughflow (ITF), which controls the exchange of heat between the Pacific and Indian Oceans, is a major component of the global climate system. Indeed, the heat transported by the ITF is related to the Asian-Australian Monsoon dynamics and the strength of the warm surface flow and cool thermocline is controlled by the seasonal reversal of monsoonal winds. Recent studies showed that changes in sea-level also influence the ITF because most of the seas feeding the ITF are very shallow. Therefore, reconstruction of ITF variability during the MPT has the potential to clarify the impact of glacio-eustatic sea-level and monsoonal climate dynamics on the hydrology of Northwest Australia. The International Discovery Program (IODP) Expedition 363 retrieved at Site U1483 drilled on the Scott Plateau, off Northwestern Australia, an extended, continuous hemipelagic sediment succession spanning the past two million years. In addition, core top samples were obtained along the Northwest Australian Margin during RV “Sonne” Expedition 257 in summer 2017.

In this study, we analyzed radiolarian assemblages in core top samples retrieved during Sonne 257 and downcore samples from IODP Site U1483 to monitor the variability of regional sea surface temperatures (SSTs) during the MPT and to determine ITF dynamics in relation to glacio-eustatic sea-level variations and tropical monsoon strength. We suggest the glacio-eustatic sea-level variations are the key factor influencing changes in SSTs at Site U1483 because the ITF is the main current controlling regional SSTs and the latter is formed in a complex area of shallow sea highly sensitive to glacio-eustatic sea-level variation. Based on comparison with SSTs data from the mid latitudes off Northwest Australian and the South China Sea, we suggested that temperature at Site U1483 to be highly dependent on the ongoing climate changes in the northern hemisphere U1483 because of the domination of the ITF, which is originated in the Northwest Pacific marginal seas and thus it is probable that there is a decoupling in the ocean/atmospheric response to the MPT off the northwest Australian margin at low latitude. In addition, comparison of radiolarian total abundances with XRF-scanning elemental data suggested that until the onset of the MPT (~1200 ka), radiolarian productivity is higher during intervals of strong summer monsoon during interglacial probably because of the high riverine runoff generated by heavy summer monsoonal precipitations. However, since ~900 ka, it is likely that there is a shift in the radiolarian productivity mode with having an increase in radiolarian productivity during glacial periods when nutrients are mainly delivered by dust deposition due to strong trade winds and mixing of the shallow water, which fertilised the deposited dust.

Utilizing IODP 356 Sea Surface Temperature Transect for proxy development and large-scale circulation changes.

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In 2015 IODP Expedition 356 took 6 cores from a transect from the west and northwest Australian shelf. The goal was to track changes in the warm southward flowing Leeuwin current, which is sourced directly from the Indonesian Throughflow (ITF). All the cores were taken on carbonate shelves which is not the typical environment for many climate reconstructions. Although using biomarkers to do SST reconstructions is not a new method, most of the work has focused on deep water sediments. This is because of a combination of a lack of expeditions to these environments as well as potential issues with sedimentation, alteration, and low TOC. Despite this, in Expedition 356 we managed to get multiple multi-million-year records from cores shallower than 300 m using TEX86 SST proxy for four sites (U1459, U1460, U1461, U1463). Together these sites cover a period from 0-6.5 Ma. There has been a debate about the accuracy of TEX86 records with many researchers suggesting that they represent sub-surface temperatures. However, our records show that the SSTs records are if anything too warm compared to the expected SST. This seems to be a combination of the depth of the Leeuwin current, the lack of terrestrial input, and the season when the TEX86 is being produced which happens to be when the Leeuwin is strongest. Interestingly the other major SST proxy UK37' does not preserve decent records for reasons that will be explored in more detail. It highlights the importance of multi-proxy studies and understanding the sources of the biomarkers. Finally, we plan to use the combined SSTs records to understand the drivers of changes across the entire Leeuwin Current. While the Leeuwin current is seen across the entire 6.5 Ma records there is evidence of a stronger Leeuwin current after 1.5 Ma. We will discuss whether these changes are a result of changes in sea level, changes in global wind circulation patterns, or a combination of both.

Exploring Linkages between Southern Hemispheric Climate and South Asian Monsoon Variability

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The southern hemisphere's influence on South Asian monsoon (monsoon hereafter) variability on millennial and longer timescales is poorly studied even though summer monsoon wind originates from there. A few recent studies, though, have tried to remedy it. For example, Kumar et al., 2021 (10.1029/2020PA004139) have shown that cold (warm) SST in the southern mid-latitude region of the Indian Ocean since MIS 3 were associated with intense (weak) summer monsoon intervals on the millennial timescale. They proposed that instead of solely ascribing all the millennial-scale variability to the influence of northern high latitude climate, we should consider it in the context of bipolar coupling facilitated by thethermohaline circulation. This coupled climatic anomaly is transferred to the southern midlatitude region, which also possesses independent regional climatic changes. The combined effect is then propagated northward to the Mascarene High region and the northern Indian Ocean, which affects the cross-equatorial pressure gradient and the millennial-scale monsoon variability. Tiwari et al., 2021 (10.1016/j.polar.2021.100739) also show that Antarctic temperature variability plays an important role in governing summer monsoon precipitation with weaker monsoon observed during warm episodes in Antarctica. Another study (Sarathchandraprasad et al., 2021, 10.1016/j.palaeo.2021.110447) based on IODP Expedition 355 shows that during the Mid Pliocene Warm Period (MPWP), the Indian monsoon precipitation enhanced. Additionally, it finds that the tectonically driven Indonesian Throughflow variability plays a major role in governing monsoon intensity by changing the source water and subsequently the temperature in the southern equatorial Indian Ocean, which can affect the cross-equatorial pressure gradient. Based on the same expedition, Behera et al. (under review) have found that stronger SAsM corresponds to lower Arctic sea ice extent during the late Pliocene. The longest record of denitrification since the late Miocene (Tripathi et al., 2017, 10.1038/srep43056), and a high-resolution resolution record of productivity and denitrification for the last 600 Kyrs (Tripathi et al., 2020, 10.18520/cs/v119/i2/282-290) and Mid-Pleistocene Transition (Tripathi et al., under review) have also been reconstructed based on samples obtained during IODP 355 Expedition. Such studies make it clear that the changes in the southern hemisphere affect the monsoon significantly via various mechanisms involving intermediate and deep water circulation (oceanic tunnels) and atmospheric bridges. But the existing studies exploring the teleconnections between the southern hemispheric climate variability and the monsoon are mostly limited to the last interglacial with no information beyond it. Using meridionally placed IODP drill sites, it is important to understand how the climate, specifically temperature, variability in various regions of the Southern hemisphere has influenced the monsoon since its origin and specifically during periods such as early Miocene, Mid-Miocene Climatic Optimum, late Miocene, MPWP, MPT, and so on.

When eastern India oscillated between desert versus savannah-dominated vegetation

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During the last glacial period, the tropical hydrological cycle exhibited large variability across orbital and millennial timescales. However, the response of the Indian summer monsoon (ISM), its related impact on terrestrial ecosystems, and associated forcing mechanisms remain controversial. Here we present a marine record of pollen-inferred vegetation changes based on marine sediments from IODP Site U1446 in the Bay of Bengal suggesting that eastern India shifted from woody-savanna mosaics during Marine Isotopic Stage 3 to grasslands during the Last Glacial Maximum resulting from large-scale drying. Our data shows that ISM maximum is in phase with obliquity and precession maxima suggesting a dominant role of the Indian Ocean interhemispheric temperature gradient on glacial ISM variability. Persistent and abrupt dryland expansions of varying magnitude suggest rapid-scale onset of aridity during Heinrich Stadial events and during the Toba eruption. We propose that the amplitude of ISM drought events is initiated by high latitude and volcanic forcings, although modulated by precession.