15. **Scientific Ocean Drilling: Driving Questions from a Swiss Prospective**

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Global size evolution of the planktonic foraminifera *Globorotalia menardii* during the last 8Ma: Synthesis of 23 years of research

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In 23 years of evolutionary prospection of menardiform planktonic foraminifera, morphometric data of more than 35,000 specimens were collected from 192 deep sea sediment samples (Knappertsbusch, 2007, 2011, 2016, manuscript in preparation; Friesenhagen, in preparation a and in preparation b). They allow an unprecedented insight into the tempo and mode of evolution of our model lineage *Globorotalia menardii* since the late Miocene. Speciation and evolutionary trends are investigated by comparing changes in the test morphology for the last eight million years and between the Atlantic Ocean (DSDP Site 502, ODP Site 667A, ODP Site 925B), the Pacific Ocean (DSDP Site 503, ODP Site 806C), and Indian Ocean (IODP Site U1476A).

Intact tests were picked from the >63µm fraction and standardly mounted on Plummer Cells in keel position. Specifically for this enterprise two automated orientation, imaging and measurement systems (AMOR 1 & 2) were developed over the years (Knappertsbusch et al., 2009 and manuscript in preparation). Based on the collected images, measurements of different morphometric parameters were performed employing own-developed software programmed in *Fortran* and LabView (Knappertsbusch, 2015).

Evolution in menardiform globorotaliids is strongly manifested in size evolution of the shell. The speciation mode of cladogenesis (splitting) and subsequent morphological divergence could be observed in the menardiform lineage, but despite the large number of specimens investigated it is visibly expressed to a less prominent degree than it was originally expected for a speciation event.

The comparison of the test size evolution between the sites shows striking differences. While an almost gradual test size evolution is observed in the Pacific and the Indian Ocean sites, the Atlantic Ocean reveals several phases of size fluctuations. A distinct event is developed at the time interval between 3.2-2Ma. In the eastern tropical Atlantic Site 667A the axial length (max δY) significantly decreases from 875µm during the Mid-Pliocene Warmth period (3.2Ma) to 520µm at end of Pliocene (ca. 2.6Ma). This time interval coincides with the onset of the Northern Hemisphere Glaciation. It is followed by an interval of test size increase. Until ca. 2Ma, the size more than doubles (ca. 1200µm) to a size which has never been observed before. The occurrence of giant menardiforms was also observed in the western tropical Atlantic Site 925B and the Caribbean Sea (Site 502), although 0.1Ma and 0.4Ma later, respectively. The comparison with Indian Ocean specimens suggests episodic dispersal of a giant form from the Indian Ocean into the Atlantic Ocean, which we tentatively explain by an episodic phase of strengthening of Agulhas Faunal Leakage.

This “new” giant *G. menardii* form occurs at almost all sites within this time interval. Its predominant coiling direction is sinistral, while the ancient, smaller morphotype occurred in predominantly dextral coiling. This observation suggests that a new morphotype/subspecies replaced the old incumbent type between 2.5 and 1.7Ma at the six investigated sites.

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Export production and oxygen bottom conditions in the Eastern Equatorial Pacific during the Mid-Pleistocene Transition

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We present new high-resolution microfossil and geochemical records at Ocean Drilling Program Site 1242 located in the deep East Equatorial Pacific (EEP). We reconstruct the export production and the oxygen conditions in the deep ocean between 760 and 1040 ka using benthic foraminifera assemblages and redox-sensitivity elements (see Diz et al 2020a; 2020b for details). Benthic fauna two major shifts related to changes the nature of the organic carbon arriving at the seafloor. During marine isotopic (MIS) 23 the increased influence of the open ocean upwelling of the Costa Rica Dome caused an increase in the seasonality of the organic carbon flux. Another change occurred at MIS 19 coinciding with the disappearance of mainly elongated benthic foraminifera (Extinction Group) suggesting a link between both events. Geochemical and microfossil data indicate the development of suboxic bottom conditions during MIS 23 and 22, suggesting capture and storage of respired carbon. Re-oxygenation of the deep ocean started during the MIS 22/21 deglaciation, and it was accomplished during full interglacial conditions at MIS 21. This pattern pattern, describe as “less complete deglacial ventilation”, differs from the Mid-to-Late Pleistocene Pacific deep ocean ventilation patterns, dominated by 100kyr climate cyclicity. We suggest that deep-ocean carbon sequestration beyond deglaciation might have contributed to the development of the 100kyr variability.

REFERENCES
15.3

Microbial alkalinity production and clay mineral alteration in marine methanogenic zones: implications for carbonate diagenesis

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Methanogenic zones in marine sediments are commonly attributed with very high alkalinity and local production of diagenetic carbonates. It is not clear whether these effects are mainly a result of microbial metabolic activity or of interaction with silicate minerals. A numerical reaction transport model was developed to simulate the effects of microbial activity and mineral reactions on the composition of the porewater in a 150-m-thick sedimentary interval drilled in the Peruvian deep-sea trench (Ocean Drilling Program, Site 1230). This site shows a zone of intense methanogenesis below 10 m sediment depth. The simulation shows that microbial activity accounts for most alkalinity production of up to 150 mmol/l, while the excess of CO2 produced during methanogenesis causes a strong acidification of the porewater. Ammonium production from organic matter degradation significantly contributes to alkalinity production, whereby ion exchange was simulated to compensate for hidden ammonium production not otherwise accounted for. Although clay minerals are reacting far too slowly to equilibrate with the porewater over millions of years, additional alkalinity is provided by slow alteration of chlorite, illite, and presumably volcanic glass. Overall, alkalinity production in methanogenic zones is sufficient to prevent dissolution of carbonates and to induce carbonate formation either continuously as disseminated (cryptic) dolomite or episodically as hard lithified beds along a supersaturation front. The simulation presented here provides fundamental insight into the diagenetic effects of the deep biosphere and may also be applicable for the long-term prediction of the stability and safety of deep CO2 storage reservoirs.
15.4
The Maldivian archipelago: Past, present and future climatic and oceanographic insights using foraminiferal proxies

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Coral reefs are sensitive to climatic perturbations, and as such, a major concern for the Maldivian archipelago, in the equatorial Indian Ocean, is the future response of the seasonally reversing South Asian Monsoon (SAM) to increasing global temperatures. The SAM governs the climate across the entire northern Indian Ocean and furthermore, drives the regional surface ocean currents. This work uses planktonic and benthic foraminiferal geochemical measurements (n = 5067) to better understand past SAM processes and forcing mechanisms, and its influence on the physicochemical properties and thermocline of the Maldives Inner Sea. Particular emphasis is given to the interval encompassing Marine Isotope Stage (MIS) 11 (ca 410 kyr BP), a recognised analogue for the current Holocene. Insight gained from the warmer MIS11 allows a better comprehension of possible future SAM scenarios, in a world with rapidly increasing sea surface temperatures (SSTs), and the associated impacts on the shallow, tropical Maldivian ecosystems.

To reconstruct past SAM dynamics, high-resolution geochemical records (δ¹⁸O, δ¹³C, Mg/Ca) are compiled for multiple foraminiferal species (n = 15) for the top ~1800 kyrs (60 mcd) of International Ocean Discovery Program (IODP) Expedition 359 Site U1467, drilled within the drift deposits of the Maldives Inner Sea. Notwithstanding the apparent diagenetic influences on the foraminiferal geochemistry within this shallow carbonate setting, absolute reconstructions of seawater temperatures, salinity and δ¹⁸Osw are still deemed viable for at least the top ~627.4 - 790.0 kyr (24.7 - 28.7 mcd) of the records. Multi-species geochemical data across the MIS10-13 interval, together with data from the modern core-top and extremes of the Last Glacial Maximum (LGM), MIS11 and MIS12 all confirm discrete glacial-interglacial thermocline and SAM dynamics. Overall, the summer SAM is found to be in-phase with insolation and atmospheric CO₂. Similar to present observations there was a strong summer SAM during the interglacials, which resulted in large basin-wide salinity gradients whereas; at the glacial maxima, it was weaker with subsequently more homogenous basin-wide surface waters. A deeper, warmer SML together with a stronger thermocline and more stratified water column is observed for the interglacial maxima with a cooler, shallower SML and comparatively weak thermocline during the glacial maxima. Overall, based on the assumption that future conditions could present with similarities to the warmer MIS11 maximum (+0.30 - 0.41 °C from modern SSTs), it is shown that in comparison to the present, there was a stronger summer SAM control with a more prominent Arabian Sea Oxygen Minimum Zone extent in the Maldives region.

As opposed to the traditional ‘pooled’ foraminiferal geochemical measurements, which provide a mean signal from the measured population, supplementary individual foraminiferal analysis (IFA) datasets allow insight into the relative frequency (skewness) and magnitude of periodic warm events. In this respect, our IFA datasets, of the shallow-dwelling species Globigerinoides ruber (white) and Trilobatus sacculifer, show that in conjunction with elevated SSTs during MIS11 the respective IFA datasets are skewed towards higher temperatures with coral bleaching thresholds exceeded more frequently (two-fold). Alarming, this region has already experienced three El Niño related mass-bleaching events over recent years. All of these events led to widespread mortality of corals and symbiont-bearing larger benthic foraminifera (e.g., Amphistegina), both of which represent important reef constituents. Based on the reality that current warming (anthropogenically driven) is much faster than seen during MIS11, more extreme as well as more frequent El Niño events are anticipated in the future which would place the world’s coral reef ecosystems under increasing strain.

This research confirms the strength of an integrated multi-species foraminiferal geochemical study to link both present and past oceanographic and SAM processes, which is particularly important in light of the current anthropogenic warming trends. A future increase in SSTs together with a stronger summer SAM control and more prominent low oxygen/high nutrient intermediate waters might push the tropical Maldivian coral and benthic shoal ecosystems closer or even beyond their ecological and thermal limits. Importantly, these ecosystems have proven to be resilient in the past and thus, it remains to be seen if they can continue to recover and adapt to future climatic perturbations.

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15.5 Distribution and sources of carbon at the Atlantis Massif (IODP Expedition 357)

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Serpentinization is a fundamental process that has significant consequences for geochemical cycles and microbial activity in a variety of environments. IODP Expedition 357 used seabed drills to core 17 shallow holes at nine sites across the Atlantis Massif (30°N, MAR) to better understand the role of serpentinization in driving hydrothermal systems, in sustaining microbiological communities, and in the sequestration of carbon in ultramafic rocks. On-going active serpentinization is evident by in-situ gas release and elevated concentrations CH₄ and H₂ over several sites. Our study aims to evaluate abiotic vs biotic carbon in this serpentinizing environment. Petrological and stable isotope studies allow us to track abiotic vs biotic carbon and to characterize the speciation and source of carbon as well as the distribution of carbonates in the drill cores.

Serpentinites from the central part of the massif closest to the Lost City hydrothermal field have higher total carbon concentrations, in general, related to higher carbonate contents. Total organic carbon contents range between 46 ppm and 800 ppm with isotopic composition between -28 ‰ to -20 ‰. The carbonate phases at the southern wall of the Atlantis Massif record multiple episodes of fluid movement through the detachment fault and secondary faults that cut the detachment. Total inorganic carbon isotopic composition varies over a broad range from -14.1 ‰ to +2.4 ‰. The carbon isotopic signature of carbonate veins lies on a mixing line between the Lost City hydrothermal fluid and seawater (d¹³Cveins = -3.0 ‰ to +2.3 ‰). The measurements of multiply substituted carbonate isotopologues (clumped isotopes) allow us to reconstruct formation temperatures of the carbonates without considering the isotopic composition of the related fluid; instead, it even allows us, using different calibrations, to calculate d¹⁸Ofluid. Carbonate phases at the AM include aragonite, calcite, dolomite, and magnesite, whereas the latter two are restricted to high-temperature phases with up to 188°C. Based on carbon and oxygen isotopic composition, two types of carbonates can be distinguished. Type I carbonates show a more rock dominated signatures (d¹³C < -2.1 ‰, Td > 50°C) and type II resemble formation from a seawater dominated endmember hydrothermal fluid (d¹³C > -0.5 ‰, Tclumped isotopes = 4 - 7°C). Carbonates in general, occur in the basement as interstitial carbonates, carbonates replacing fully serpentinized olivine cores and as carbonate veins. Until today magnesite within oceanic peridotites have only been reported in a few studies (Gablina et al., 2006), even though magnesite is a ubiquitous phase in ultramafic outcrops on land, and thermodynamic studies predict that magnesite should form during the reaction of oceanic serpentinite and CO₂-bearing aqueous fluids (e.g., Grozeva et al., 2017; Klein and Garrido, 2011). The underlying mechanisms controlling the transformation of CO₂ to carbonates in ultramafic-hosted hydrothermal systems remain incompletely understood. A long-term laboratory experiment was conducted at 300 °C and 35 MPa to investigate serpentinization and carbonate formation pathways during hydrothermal alteration of peridotite. Powdered harzburgite was initially reacted with a Ca-rich aqueous fluid for 14,592 h (608 days).

Our data indicate that carbonate precipitation in the footwall of the oceanic detachment fault at the Atlantis Massif depends on multiple geochemical mechanisms including fluid flux intensity, the concentration of SiO₂(aq) and CO₂(aq), the location relative to mafic intrusions, and temperature. Based on our results, we argue that three primary carbon sources affect the system: (i) reduced carbon from hydrothermal degradation of organic matter; (ii) mantle carbon trapped as volatiles in fluid inclusions; and (iii) dissolved inorganic carbon from the seawater.

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15.6

Morphological and geochemical characterisation of seep carbonates in the southeastern Mediterranean Sea (Palmahim Disturbance and Levant Basin)

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Seep carbonates were recently discovered in the Levant Basin and Palmachim Disturbance (SE Mediterranean Sea) during the EUROFLEETS 2 SEMSEEP expedition aboard the RV AEGEO in September 2016 offshore Israel. Methane-derived authigenic carbonates are often used to identify the methane source and the timing of the seepage. Here, we try to reconstruct the past seepage activity in the Eastern Mediterranean Sea using sediment petrography, XRD and stable isotope analysis of different seep carbonate morphologies.

Three different seep carbonate morphologies (chimneys, crusts and pavements) were found in the Palmachim Disturbance (PD), the Levant Channel (LC) and the Nile Fan (NF). The combination of X-ray computed tomography and sedimentary petrography highlight recurrent cements. X-Ray Diffraction analyses indicate the presence of high-magnesium calcite, as well as aragonite, dolomite and low-magnesium calcite.

The chimneys consist mostly of high-Mg calcite and botryoidal and fan-shaped growing aragonite. Furthermore, Fe-Mn phases were often found at the boundaries of the aragonitic cements and barite crystals within the high-Mg calcite and aragonite.

The carbonate crusts show a high amount of high-Mg calcite with low content of aragonite. The carbonate pavements evidence in contrast to the crusts and chimneys high amounts of micritic dolomite within a low-Mg calcitic matrix. The aragonite content in the carbonate pavements change throughout the sample, but is always less than ~10%.

Stable carbon isotope data reveal three different clusters, resp. (1) one highly depleted cluster (~35 to – 50‰), (2) one cluster with values around 0‰ and (3) one mixing phase respectively.

The occurrence of different cement generations indicate changing seep activity conditions through time in the Eastern Mediterranean Sea.
P 15.1
Insights from the study of morphological evolution of menardiform globorotalids at Western Pacific Warm Pool ODP Hole 806C (Ontong-Java Plateau)

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The morphological evolution was investigated in the tropical Neogene planktonic foraminiferal lineage *Globorotalia menardii*, *G. limbata* and *G. multicamerata* during the past 8 million years at ODP Hole 806C (Ontong-Java Plateau, Western Pacific Warm Pool WPWP). This research is an extension of a series of previous studies about the morphological evolution in this group from the Caribbean Sea, the tropical Atlantic and the Eastern Equatorial Pacific (Knappertsbusch, 2007; Mary and Knappertsbusch 2015; Knappertsbusch, 2016; Friesenhagen and Knappertsbusch, 2020). The goal is to find empirical and quantitative confirmation for morphological speciation – splitting or phyletic gradualism – in planktonic foraminifera with the above lineage as model objects. A major question was whether a conspicuous time-transgressive shell size-increase of menardiforms, that was observed in several tropical Atlantic sites during the Late Pliocene, is also present in the tropical Pacific Ocean. The Atlantic size evolution pattern is currently thought to reflect a peripheral influence from Agulhas Current Faunal Leakage of Indian Ocean or even remote Pacific menardiform faunas into the South Atlantic (Knappertsbusch, 2016), but accelerated evolution may come as an alternative explanation as well. The present study from ODP Hole 806C, which is outside the reach of the Agulhas Current System, thus serves as a test to discriminate between these scenarios.

In the WPWP, stable tropical environments prevailed back to Pliocene times, and potential influences of Northern Hemisphere Glaciation are thought to bear less severely on shell size evolution than in the Atlantic Ocean. Hence, a slow and gradual pattern of shell size increase is expected in the western tropical Pacific, in contrast to the intermittent rapid menardiform shell size increase during periods of intensified formation of warm water eddies in the southern to tropical Atlantic.

For this study >5250 specimens comprising *G. menardii*, *G. limbata* and *G. multicamerata* from 33 stratigraphic levels extending over the past 8 million years were morphometrically investigated using imaging- and microfossil orientation robots AMOR and System AMOR2, that were both especially developed for such purposes (Knappertsbusch et al. 2009, Knappertsbusch et al. 2019). Special attention was given to trends of spiral height (dX) versus axial length (dY) in keel view, for which bivariate contour- and volume density diagrams were constructed to visualize speciation and evolutionary trends.

The investigation at Hole 806C showed, that *G. menardii* evolved in a more gradual manner than in the Atlantic. Plots of dX versus dY reveal bimodality between 3.18 Ma – 2.55 Ma with a dominant branch consisting of smaller *G. menardii* (dX<~300 μm) persisting until the Late Quaternary, and a less dominant branch of larger *G. menardii* (dX>~300 μm) until 2.63 Ma. There is evidence for cladogenesis – splitting with subsequent morphological divergence in the Late Pliocene *G. menardii-limbata-multicamerata* lineage, albeit the divergence was less clearly expressed than originally expected for such a speciation event. Up-section, bimodality vanished but *G. menardii* populations shifted towards extra large shells between 2.19-1.95 Ma supporting the possibility of long-distance inter-oceanic dispersal of giant menardiforms.

In summary, the morphological evolution of Pacific menardiform globorotalids contrasts the one observed in the Atlantic realm. Seen together this inter-oceanic asymmetry is indication of possible long-distance dispersal of *G. menardii*, at least during intermittent phases. Implications for biostratigraphic applications are, that in planktonic biostratigraphy correlation events may be based more often than previously thought on large scale environmental perturbations with local morphological ecophenotypic adaptations and nuances.

REFERENCES


MORE INFO:
https://www.micropal-basel.unibas.ch/
https://www.micropal-basel.unibas.ch/Research/Evolut.html
Looking to the Future of Scientific Ocean Drilling from a Swiss Prospective

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In 2018, the Earth science community celebrated the 50th anniversary of scientific ocean drilling. From the early beginnings of the Deep Sea Drilling Program (DSDP) to the current International Discovery Program (IODP), numerous Swiss scientists have been actively involved and have contributed to the success of this ongoing and evolving program. Now, 52 years after the first official expedition was conducted, organized scientific ocean drilling is still going strong with continued Swiss participation to many drilling programs, e.g., from drilling the Atlantis Massif to study serpentinization and associated microbial life (IODP Exp. 357) to probing into “Iceberg Alley” to study Subantarctic ice and ocean dynamics (IODP Exp. 382). Looking to define the challenging directions of the post-2023 drilling program, a large and diverse international multidisciplinary science community has compiled an extensive document entitled “Exploring Earth by Scientific Ocean Drilling”, which aims to provide a 2050 Science Framework to make new discoveries about Earth’s past, present, and future. In presenting the content of this new document from a Swiss prospective, we ask Quo Vadis?