Universität Bremen

The Ocean Floor – Earth's Uncharted Interface

Full Proposal for a Cluster of Excellence

marum
Center for Marine Environmental Sciences
| Research Faculty |

Cluster of Excellence

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The Ocean Floor – Earth's Uncharted Interface

University of Bremen

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Universität Bremen

CONTENTS

LIST OF ACRONYMS AND ABBREVIATIONS

aDNA	Ancient deoxyribonucleic acid
AMAR	AWI-MARUM Alliance
ANTARES	ANTARES Datensysteme (Company developing wireline logging tools, Stuhr, Germany)
ArcTrain	Processes and impacts of climate change in the North Atlantic Ocean and the Canadian Arctic, DFG International Research Training Group, University of Bremen
AtlantOS	Optimising and enhancing the integrated Atlantic Ocean observing systems (EU Project)
AUV	Autonomous underwater vehicle
AWI	Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research, Bremerhaven
BCR	Bremen Core Repository
BMBF	Federal Ministry of Education and Research
BMWi	Federal Ministry for Economic Affairs and Energy
BPP	Benthic primary production
BYRD	University of Bremen Graduate Center, Bremen Early Career Researcher Development
CCD	Carbonate compensation depth
CCSM	Community climate system model
CE	Common Era
cGENIE	Grid enabled integrated Earth system model
CliCCS	Climate, Climatic Change and Society, Cluster, Univ. of Hamburg
COOPEUS	Strengthening the cooperation between the US and the EU in the field of environmental research infrastructures (EU project)
CPT	Cone penetration testing
CPU	Central processing unit
DCO	Deep Carbon Observatory, international initiative, supported by A. P. Sloan Foundation
DeepMIP	The Deep-Time Model Intercomparison Project
DFG	Deutsche Forschungsgemeinschaft (German Research Foundation)
DKK	Deutsches Klima-Konsortium (German Climate Consortium)
DOI	Digital object identifier
DOM	Dissolved organic matter
DSDP	Deep Sea Drilling Project (1968–1983)
ECORD	European Consortium for Ocean Research Drilling
ECR	Early career researchers
EMSEA	European Marine Science Educator Association
EMSO	European Multidisciplinary Seafloor and water-column Observatory
ERC	European Research Council
ETH	Eidgenössische Technische Hochschule (Swiss Federal Institute of Technology), Switzerland
EU	European Union
EuroGOOS	European Global Ocean Observing System
FAIR	Data principles (Findable, Accessible, Interoperable, Re-usable)
FCSP	Fucose-containing sulfated polysaccharides

FLOCS	Flow-through osmo colonization system
FOKUS	Fraunhofer Institute for Open Communication Systems, Berlin
FP7	7th Framework Programme of the EU
FRAM	Frontiers in arctic marine monitoring, Ocean observing system (AWI)
FTICR-MS	Fourier-transform ion cyclotron resonance mass spectrometry
FTIR	Fourier-transform infrared spectroscopy
FZT	Research center funded by the DFG
GC-MS	Gas chromatography-mass spectrometry
GC-TOF-MS	Gas chromatography time-of-flight mass spectrometry
Geomil	Geomil equipment (company for cone penetration testing technology / equipment, Moordrecht, The Netherlands)
GEOTRACES	An international study of the marine biogeochemical cycles of trace elements and their isotopes (SCOR project)
GFZ	Helmholtz Centre Potsdam – GFZ German Research Centre for Geosciences
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit (German development agency)
GLOMAR	Global Change in the Marine Realm (International Graduate School for Marine Sciences, University of Bremen)
GOOS	Global Ocean Observing System (Program executed by the Intergovernmental Oceanographic Commission of UNESCO)
HIFMB	Helmholtz Institute for Functional Marine Biodiversity at the University of Oldenburg
HPLC	High-performance liquid chromatography
ICP-MS	Inductively coupled plasma mass spectrometer
ICSU	International Council for Science
Ifremer	Institut français de recherche pour l'exploitation de la mer, Brest, France
iGSI	International Geospatial Services Institute GmbH, Emden
IMBeR	Integrated Marine Biosphere Research (Project of SCOR and Future Earth)
INTERCOAST	Integrated Coastal Zone and Shelf-Sea Research, DFG International Research Training Group, University of Bremen
IODP	Integrated Ocean Drilling Program (2003 – 2013) International Ocean Discovery Program (since 2013)
IPCC	Intergovernmental Panel on Climate Change
JAMSTEC	Japan Agency for Marine-Earth Science and Technology, Yokosuka
JPI Oceans	Joint Programming Initiative Healthy and Productive Seas and Oceans (EU Intergovernmental Platform)
KDM	German Marine Research Consortium
LGM	Last Glacial Maximum
MALDI	Matrix-assisted laser desorption / ionization
MAPPA	Underwater glider (MARUM)
MARGO	Multiproxy Approach for the Reconstruction of the Glacial Ocean surface
MARUM	Center for Marine Environmental Sciences, Bremen
MBARI	Monterey Bay Aquarium Research Institute, Moss Landing, USA
MeBo	Meeresboden-Bohrgerät, Sea-Floor Drill Rig (MARUM)
MICADAS	Mini carbon dating system
MIT	Massachusetts Institute of Technology, Cambridge, USA
MITgcm	MIT general circulation model
MPI-MM	Max Planck Institute for Marine Microbiology, Bremen
MS	Mass spectrometer

NanoSIMS	Nanoscale secondary ion mass spectrometry
NGO	Non-governmental organization
NIOZ	Royal Netherlands Institute for Sea Research, Texel and Yerseke
NMR	Nuclear magnetic resonance
NOC	National Oceanography Centre, Southampton, UK
NSERC	Natural Sciences and Engineering Research Council of Canada
ODP	Ocean Drilling Program (1983–2003)
OGC	Open Geospatial Consortium
ONC	Ocean Networks Canada
ONI	Oceanic Niño index
OOI	Ocean Observatories Initiative (USA)
ORCID	Open researcher and contributor ID
PAGES	Past Global Changes (Core Project of Future Earth)
PANGAEA	Data Publisher for Earth & Environmental Science (AWI and MARUM)
PAP	Porcupine abyssal plain observatory
pCO_2	Partial pressure of carbon dioxide
PETM	Paleocene-Eocene thermal maximum
PI	Principal investigator
PLOCAN	La Plataforma Oceánica de Canarias, Telde, Gran Canaria, Spain
PMIP	Paleoclimate Modelling Intercomparison Project
POM	Particulate organic matter
QUEST	Remotely operated vehicle (MARUM)
RCT	Research Unit REACTOR
REC	Research Unit RECORDER
ROMS	Regional oceanic modeling system
ROV	Remotely operated vehicle
RV	Research vessel
RVR	Research Unit RECEIVER
SCOR	Scientific Committee on Oceanic Research
SDG	Sustainable Development Goal (of the United Nations)
SEAL	Autonomous underwater vehicle (MARUM)
SGN	Senckenberg at the Sea, Wilhelmshaven
SQUID	Remotely operated vehicle (MARUM)
SST	Sea-surface temperature
SWE	Sensor web enablement
TEX_{86}	Tetraether index of 86 carbon atoms (temperature proxy)
TIMS	Thermal ionization mass spectrometry
UN	United Nations
UPLC-MS	Ultra performance liquid chromatography mass spectrometer
WDS	World Data System
WHOI	Woods Hole Oceanographic Institution, Woods Hole, USA
WSS	Werner Siemens-Foundation, Zug, Switzerland
XRF	X-ray fluorescence
ZMT	Leibniz Centre for Tropical Marine Research, Bremen

1 GENERAL INFORMATION

Title in German and English
Der Ozeanboden – unerforschte Schnittstelle der Erde
The Ocean Floor – Earth's Uncharted Interface

Applicant university	Location
University of Bremen (Univ. Bremen)	Bremen

Names of spokespersons
Michael Schulz, Nicole Dubilier, Kai-Uwe Hinrichs

Principal investigators (women)	Function / Contract type	Location / Institution
Antje Boetius	Professor (W3), Director AWI[1]	Bremerhaven, Bremen / AWI, Univ. Bremen
Nicole Dubilier	Professor (W3), Director MPI-MM	Bremen / MPI-MM, Univ. Bremen
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Gesine Mollenhauer*	Professor (W2)	Bremerhaven, Bremen / AWI, Univ. Bremen
Juliane Müller*	Head Junior Research Group (Tenure Track)	Bremerhaven, Bremen / AWI, Univ. Bremen
Marta Pérez-Gussinyé*	Professor (W3)	Bremen / Univ. Bremen
Monika Rhein	Professor (W3)	Bremen / Univ. Bremen
Ursula Röhl	Senior Scientist (permanent)	Bremen / Univ. Bremen
Hildegard Westphal	Professor (W3), Director ZMT	Bremen / ZMT, Univ. Bremen
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Thorsten Dittmar*	Professor (W3)	Oldenburg, Bremen / Univ. Oldenburg, MPI-MM
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Michael Schulz	Professor (W3), Director MARUM	Bremen / Univ. Bremen

Other participating institutions (higher education institutions, non-university research institutions)	**Location**
Carl von Ossietzky University Oldenburg (Univ. Oldenburg)	Oldenburg
Jacobs University Bremen (Jacobs Univ.)	Bremen
Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI)	Bremerhaven
Max Planck Institute for Marine Microbiology (MPI-MM)	Bremen
Senckenberg at the Sea (SGN)	Wilhelmshaven
Leibniz Centre for Tropical Marine Research (ZMT)	Bremen

Individuals as cooperation partners[2]	**Location / Institution**
Prof. Jack Middelburg	University of Utrecht, Utrecht, NL
Prof. Victoria Orphan	California Institute of Technology, Pasadena, USA
Prof. Eske Willerslev	University of Copenhagen, Copenhagen, DK

(*) Investigators who were not PIs in the proposal for the existing Cluster of Excellence.

[1] See front matter for list of abbreviations and acronyms.

[2] U Bremen Excellence Chairs

SUMMARY OF THE PROPOSAL IN GERMAN AND ENGLISH

Der Ozeanboden macht 71 % der festen Oberfläche der Erde aus und befindet sich im Mittel 3.700 Meter unter dem Meeresspiegel. Er ist schwer zugänglich und seine Untersuchung erfordert Schiffsexpeditionen und den Einsatz hochspezialisierter Unterwassertechnologien. Auch wenn bisher nur ein sehr geringer Teil des vermeintlich passiven Ozeanbodens erforscht werden konnte, ist bereits sicher, dass er eine wichtige, dynamische Schnittstelle mit weitreichenden Funktionen für das gesamte Erdsystem bildet. Am und im Ozeanboden wechselwirken geologische, physikalische, chemische und biologische Prozesse und beeinflussen so das Klimasystem, den globalen Kohlenstoffkreislauf und die biologische Produktivität des Weltozeans. Noch wissen wir zu wenig über diese Prozesse, um den Ozeanboden in globale Stoffbilanzen einbeziehen zu können.

Der Cluster setzt sich zum Ziel, ein neues Kapitel der Ozeanbodenforschung aufzuschlagen und die Austauschprozesse an dieser bedeutenden Grenzfläche und deren Rolle im Erdsystem zu quantifizieren. Dafür gilt es (i) zu entschlüsseln, welche Prozesse den Transport von biogenen Partikeln zum Ozeanboden und deren Umwandlung unter sich verändernden Umweltbedingungen steuern, (ii) den Transfer von Kohlenstoff und anderen Elementen zwischen Ozeanboden und Meerwasser zu bilanzieren, (iii) zu verstehen, wie Ökosysteme am Ozeanboden auf Umweltveränderungen reagieren, und (iv) aus den Klimaarchiven des Ozeanbodens mit Hilfe von Klimamodellen Szenarien für eine „wärmere Welt“ zu entwickeln. Diese wissenschaftlichen Aufgaben erfordern neuartige Technologien zur Beobachtung und Beprobung des Ozeanbodens, hochempfindliche analytische Methoden und eine Erweiterung numerischer Modelle. Aufgrund ihrer wissenschaftlichen und technologischen Komplexität können die genannten Ziele nur durch einen interdisziplinären Forschungsverbund erreicht werden.

Der Cluster wird an der Forschungsfakultät MARUM – Zentrum für Marine Umweltwissenschaften der Universität Bremen angesiedelt sein. Mit dem Cluster kann das Potenzial der Ozeanbodenforschung über alle beteiligten Partnerinstitutionen strategisch verknüpft und ausgeschöpft werden. MARUM verfügt als eines von etwa zehn Instituten auf der Welt über hochentwickelte Unterwasserfahrzeuge und -systeme und kann damit zum Ozeanboden in der Tiefsee vorstoßen, dort Daten gewinnen, Proben nehmen und Experimente durchführen. Für deren Auswertung steht ein weltweit einmaliges analytisches Methodenspektrum zur Verfügung.

Der Cluster setzt sich das verbindliche Ziel, den Anteil von Wissenschaftlerinnen zu erhöhen, und er wird zuverlässige und transparente Karriereperspektiven für den wissenschaftlichen Nachwuchs schaffen. Im Dialog mit der Öffentlichkeit wird der Cluster seine wissenschaftlichen Erkenntnisse an unterschiedliche Zielgruppen vermitteln und so wissensbasierte Entscheidungen zum Schutz der marinen Umwelt und zur nachhaltigen Nutzung der Ozeane unterstützen.

The ocean floor, which makes up 71 % of the Earth's solid surface, lies an average of 3,700 meters beneath the ocean surface. The difficulties related to accessibility necessitate ship expeditions and the use of highly specialized underwater equipment for its exploration. As yet, only a small fraction of the ocean floor has been scientifically investigated, but it is already known that this supposedly passive environment is an important interface with a wide range of functions that impact the entire Earth system. Geological, physical, biological and chemical processes interact at and within the ocean floor, thus influencing the climate system, the global carbon cycle, and biological productivity in the world ocean. We still know too little about ocean-floor processes to compile detailed global mass budgets.

The Cluster aims to initiate a new chapter in ocean-floor research by quantifying exchange processes at this significant boundary layer and their roles in the Earth system. This will be achieved by: (i) deciphering processes that control the transport of biogenic particles to the ocean floor and their transformation under changing climate conditions, (ii) balancing the transfer of carbon and other elements between the ocean floor and seawater, (iii) understanding how ocean-floor ecosystems react to environmental changes, and (iv) developing scenarios for a "warmer-than-present world" from ocean-floor climate archives with the help of climate models. These scientific tasks demand the use of novel technologies for ocean-floor observation and sampling, highly sensitive analytical methods, and an expanded application of numerical models. Because of their scientific and technological complexity, the stated goals can only be achieved through interdisciplinary research.

The Cluster will be hosted by the Research Faculty MARUM – Center for Marine Environmental Sciences at the University of Bremen. Through the Cluster, the potential for ocean-floor research among all of the participating partner institutes can be strategically linked and fully exploited. MARUM is one of about ten institutions in the world that possess highly advanced submersible vehicles and systems that are able to access the ocean floor in the deep sea, obtain data and samples, and carry out experiments there. For the subsequent investigations, a broad spectrum of analytical methodologies, unrivaled worldwide, is available.

The Cluster has binding target numbers for the recruitment of female scientists and their participation in decision-making bodies, and it will also develop reliable and transparent career prospects for early career researchers. In dialogue with the public, the Cluster will communicate its scientific findings to various target groups, thereby facilitating informed decision-making for the protection of the marine environment and sustainable use of the oceans.

2 OBJECTIVES OF THE CLUSTER OF EXCELLENCE

RESEARCH OBJECTIVES

<table>
<tr><th colspan="2">Objective</th><th>Success Measures</th></tr>
<tr><td>1</td><td>To understand the processes that transform the properties and fluxes of biogenic particles on their transit to the ocean floor under changing climate conditions.</td><td rowspan="6">• Outstanding scientific achievements at the highest level of impact
• Establishment of international leadership in comprehensive ocean-floor research
• Substantial methodological and technological innovation
• Contributions to IPCC, UN SDGs and other assessments and scientific contributions to interactions with stakeholders</td></tr>
<tr><td>2</td><td>To quantify fluxes of carbon and other elements to and across the ocean floor and estimate their budgets under current and past states of the Earth system.</td></tr>
<tr><td>3</td><td>To generate an in-depth understanding of how the structure and state of ocean-floor ecosystems are interrelated with local-scale biogeochemical processes and other environmental conditions.</td></tr>
<tr><td>4</td><td>To derive scenarios for “warmer worlds” through comprehensive decoding of environmental signals from past warm climate conditions as recorded in ocean-floor archives.</td></tr>
<tr><td>5</td><td>To design and implement novel methods and technology for ocean-floor observation and probing, ultra-sensitive chemical analyses, and an Earth-system modeling framework that includes ocean-floor dynamics.</td></tr>
<tr><td>6</td><td>To provide impartial knowledge of ocean-floor processes both to engage the public and to guide decision-making within the framework of environmental protection and sustainable use of the ocean.</td></tr>
</table>

STRUCTURAL OBJECTIVES

Objective		Success Measures
7	To exploit the full potential of ocean-floor research across the partner institutions.	Optimized strategies relating to science activities among partners, including training, hiring, infrastructure investment, and management of and access to research data
8	To obtain a more even gender balance across all staff levels.	Women comprising at least 33 % at senior scientist level (currently 21 %) and ~30 % at the professorial level (currently 25 %) by the year 2025 in marine sciences at the University of Bremen
9	To offer further career perspectives for outstanding researchers.	Employ at least 10 researchers with tenure-track option by the year 2025 at the Research Faculty MARUM

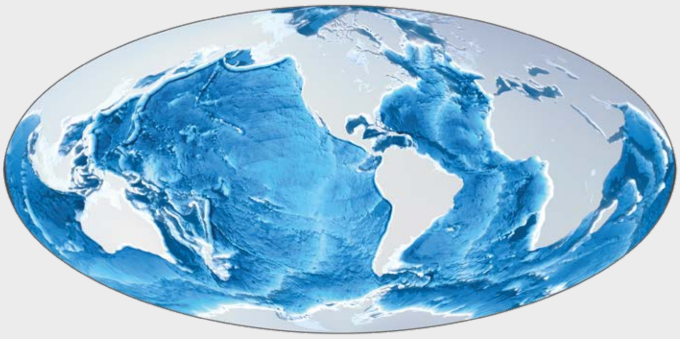
3 RESEARCH PROGRAM

3.1 RESEARCH OBJECTIVES, RESEARCH APPROACH AND POSITIONING WITHIN THE RESEARCH AREA

More than two-thirds of the Earth's surface is covered by the oceans. The submerged part of this surface – the ocean floor – remains largely unexplored, primarily due to enormous technical challenges. Plate tectonics is key to our understanding of how our planet works and it is on the deep ocean floor that most of the plate boundaries are found. Thus, to understand the Earth as a system, we have to understand the ocean floor. Geological processes shape the ocean floor and result in vastly different environments, including mid-ocean ridges where new ocean floor forms, subduction zones where old ocean floor is transferred back into the Earth's interior, cold seeps and hot vents, both of which release fluids and gases from within the ocean floor, and vast areas and volumes of sediment, which register the history of the ocean and climate. It is now evident that the ocean floor and its biological communities are anything but static. Life at and within the ocean floor is surprisingly diverse despite the absence of light and other energy limitations, but it is not easily observed nor probed. The ocean-floor ecosystems extend up to 2.5 kilometers beneath the seabed, and are fueled by inadequately explored metabolic processes. More than 80 % of volcanic activity on the Earth occurs on the ocean floor and the volume of seawater circulating through the ocean floor rivals the discharge of all the rivers on the planet. Therefore, the ocean floor is a major driver of our planet's global element cycles, biogeochemistry, and climate.

Many aspects of the ocean floor have been investigated in recent decades from a mono-disciplinary perspective; at the same time, the investigations have been limited by available techniques and technology for the acquisition of data and samples at the ocean floor. Given the key role of the ocean floor in regulating the cycles of carbon and other elements and its impact on global biogeochemical cycles and climate (Fig. 1), the time is ripe to quantify the impact of ocean-floor processes on element cycles at a global scale through an interdisciplinary research approach. Addressing this great challenge will profoundly expand the knowledge base for more reliable assessments of the potential effects of natural and human-induced perturbations at the ocean floor.

As one of the world's leading hubs for marine-based Earth-system research, we will apply our interdisciplinary expertise, technology and infrastructure to systematically explore the function of the ocean floor within the Earth system. We will characterize and quantify key processes that are responsible for the transfer of matter and its transformation, and use marine sediment archives to constrain the rates and sensitivities of these processes to global changes and perturbations.



THE GLOBAL OCEAN FLOOR

- ▶ Key interface of the global carbon and nutrient cycles
- ▶ Host to unique and vulnerable ecosystems
- ▶ Driver and archive of environmental and climate changes

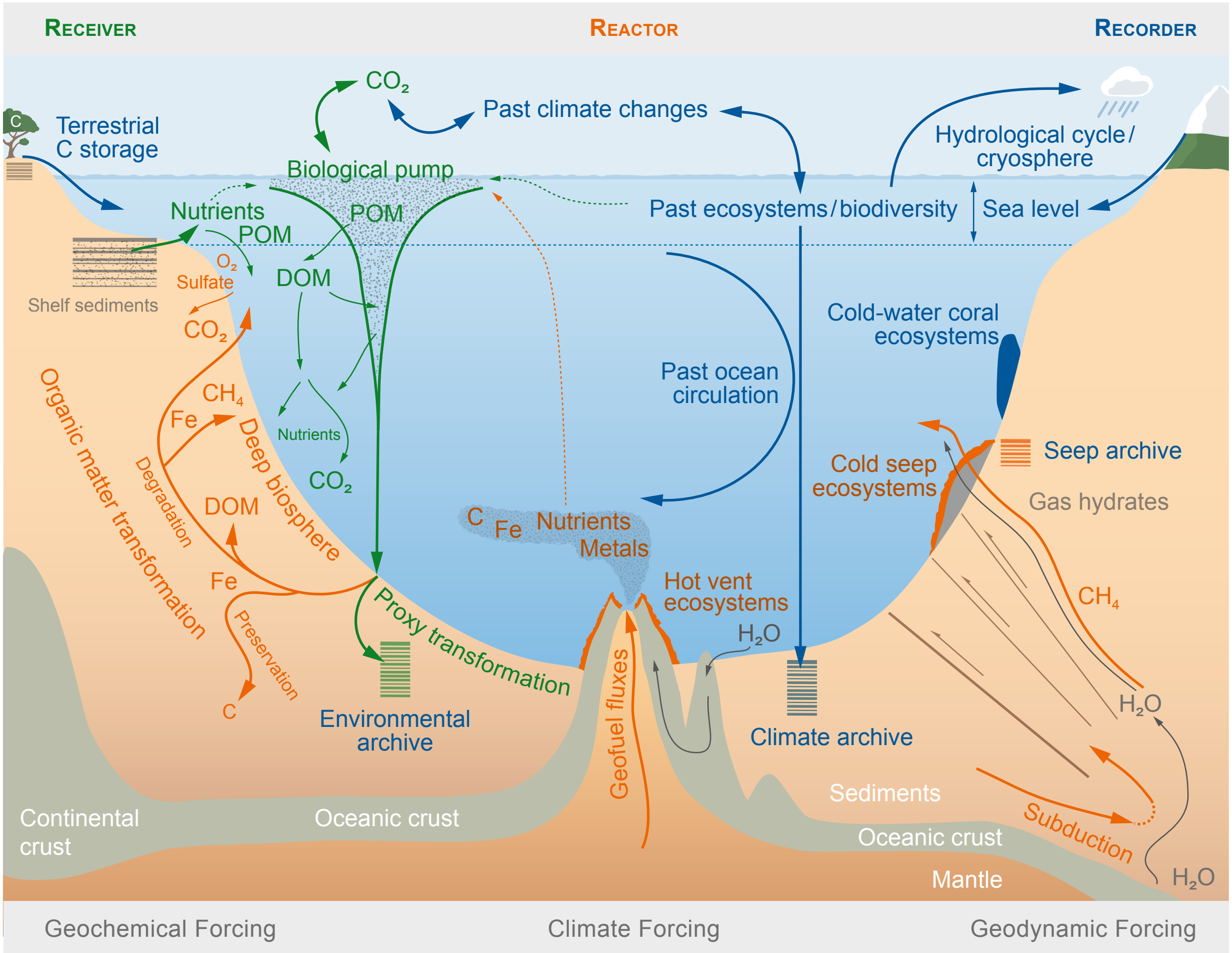


Figure 1 | Global relevance of the ocean floor (top) and key processes involving the ocean floor and their links to the Research Units of the Cluster (bottom): Biologically mediated transfer of carbon to and its transformation at the ocean floor, and exchange between the shelf and open ocean will be studied in the Receiver Unit (green), element fluxes and budgets across the ocean-floor / water interface in the Reactor Unit (orange), and information on warm climates and environmental conditions of the past in the Recorder Unit (blue) (DOM / POM: dissolved / particulate organic matter). The Cluster will generate a new understanding of how geochemical, climate, and geodynamic forcing affect ocean-floor processes and their connections to the Earth system.

Research in the proposed Cluster will address the following **overarching objectives**:

- **To understand the processes that transform the properties and fluxes of biogenic particles on their transit to the ocean floor under changing climate conditions:** The transfer of biogenic particles through the water column to the ocean floor and the partitioning of organic matter between the shelf and open ocean play a pivotal role in the climate system by affecting atmospheric carbon-dioxide (CO_2) content. The associated biological pump, that is, the rate of organic-matter transfer to the ocean floor, depends on the biological transformation during particle transit. Fundamental knowledge gaps regarding the transformation of biogenic particles result in grossly simplified representations of the biological pump in global biogeochemical models. The Cluster will significantly improve the understanding of how biogenic particles are transformed before and after reaching the ocean floor and will use this information to critically enhance global biogeochemical models.

- **To quantify fluxes of carbon and other elements to and across the ocean floor and estimate their budgets under current and past states of the Earth system:** Geodynamic and biogeochemical processes associated with oceanic plate boundaries and continental margins control the fluxes of biologically relevant elements across the ocean-floor interface on geological timescales. While many of the underlying mechanisms have been identified, a comprehensive picture of the interconnected element cycles and their feedbacks within the Earth system is only beginning to emerge. By acting globally, these processes ultimately also control the uptake of anthropogenic CO_2 by the oceans. The Cluster intends to provide pivotal knowledge towards the quantification of relevant element fluxes and to develop modeling frameworks that integrate multidisciplinary observations into a global synthesis over a wide range of timescales.

- **To generate an in-depth understanding of how the structure and state of ocean-floor ecosystems are interrelated with local-scale biogeochemical processes and other environmental conditions:** The ocean floor hosts diverse ecosystems, many of which occupy extreme environments. For example, hot vents and cold seeps support abundant chemosynthetic life at the ocean floor. Here, unique ecosystems are ultimately shaped by geological and tectonic processes. Microbial processes within the ocean floor are key drivers of biogeochemical element cycles. Neither the diversity nor the functioning of these ecosystems, nor their interactions with biogeochemical processes has yet reached a satisfactory level of quantitative understanding. Such an understanding is required to assess, for example, the potential impact of deep-sea mining on these ecosystems. Cold-water coral ecosystems, occurring at continental margins, are oases of life at the ocean floor. While these are globally threatened by human activities, e.g., by fishing, our knowledge about the environmental conditions that allow these ecosystems to thrive is far too limited to establish conservation concepts. The Cluster will greatly enhance the knowledge base related to these ocean-floor ecosystems, and facilitate a quantitative understanding of their role in shaping the ocean-floor environment at a global scale.

- **To derive scenarios for "warmer worlds" through comprehensive decoding of environmental signals from past warm climate conditions as recorded in ocean-floor archives:** Instrumental records alone cannot provide reliable information about the potential consequences of global warming because climate conditions such as those now projected for the near future have never been directly observed. Since warming by more than 2 °C by the end of this century cannot be ruled out, it is of utmost importance to provide scenarios for warm climate conditions (> 2 °C) that include threshold processes, which are only incompletely captured in state-of-the-art climate models. By making full use of environmental information from warm periods in the Earth's history, which is archived in ocean-floor sediments, the Cluster will inform climate models and deliver critical new knowledge about changes in ocean circulation, the hydrological cycle, biological productivity, and the state of the cryosphere (incl. sea level) during periods with warmer climate conditions. In combination with Earth-system models, this paleoclimate information will greatly improve the robustness of climate scenarios for the future.

Achieving these objectives will transform ocean-floor research from a largely disciplinary level to an integrative research field that will provide novel insights into the functioning and role of the largest solid interface on Earth and thus reveal important information about the Earth system and the sustainable use of the ocean and its resources. A further key objective is to enhance core underpinning methodologies that will enable us to reach our scientific goals. Innovative developments in the existing seagoing systems will enhance our capabilities for *in-situ* observation and sampling of particles in the water column, for example, or for conducting real-time 3D environmental mapping. The Cluster will also strive to develop novel analytical approaches to decode environmental information stored in organic molecules and in the isotopic compositions of matter at the ocean floor. Finally, model developments will target identified shortcomings regarding the representation of ocean-floor processes in existing modeling systems and provide the means for integrating local and regional information into a global framework.

Besides major scientific advances, the Cluster will generate services to society by providing impartial knowledge of ocean-floor processes, both to engage the public and to guide decision-making within the framework of environmental protection and sustainable use of the ocean. Because of its inaccessibility to humankind, the ocean floor is the last largely intact natural habitat on the planet. This situation is likely to change, with increasing pressure from climate change dynamics, resource extraction, pollution and ocean acidification impairing the integrity of ocean-floor ecosystems. In this regard, a basic knowledge of ocean-floor processes, dynamics and resilience is crucial in order to inform policy makers and to instill natural conservation values in future generations. Unlike the atmosphere and land surface, where the consequences of large-scale human intervention were recognized only after the harm was done, we still have a chance to understand the natural function of the ocean floor and its services, and to guide its sustainable use. Protecting the integrity of the ocean floor is important because of its ecosystem and climate services as well as its resources. Our intended ocean-floor research will fill major knowledge gaps and provide information for ocean governance within the framework of the United Nations Sustainable Development Goals and climate policies (see Box 1 "Societal Relevance of the Ocean Floor").

Box 1: Societal Relevance of the Ocean Floor

The world oceans drive global systems and play a key role in making the Earth habitable for humankind. Consequently, the United Nations has devoted one of its Sustainable Development Goals (UN SDG 14) specifically to the use of the oceans and their resources. Many aspects of the ocean's crucial role for humankind are linked to ocean-floor processes. For example, the transfer of carbon by the biological pump to the ocean floor and the chemical buffering effect by the ocean floor ultimately control the uptake of anthropogenic CO_2 by the oceans. Biogeochemical processes at the ocean floor affect the biological productivity of the world ocean, which, in turn, provides 17 % of the animal protein consumed by the world population (IPCC, 2014).

The ocean floor hosts important energy (oil and gas) and mineral resources. Several countries have plans to mine mineral resources (e.g., manganese nodules and massive sulfides) from the ocean floor in the deep sea. The potential impacts of deep-sea mining on marine ecosystems and their services remain largely unknown – simply because the great majority of species and their related ecosystem functions are still awaiting discovery (e.g., Mora et al., 2011).

The ocean floor also provides unique habitats that host microbes with high potential for biotechnological applications or human health. These areas include hot vents in the deep ocean, environments characterized by high temperature, high pressure, and corrosive conditions to which certain microbes adapt. The resulting enzymes catalyze biochemical reactions under unique conditions not found on land. This genetic potential has already led to discoveries of biotechnological relevance (Schwander et al., 2016).

Large uncertainties exist with regard to important aspects of future climate change beyond our century (IPCC, 2013), especially concerning the responses of ice sheets and the global water cycle to warmer-than-present climate conditions. Ocean-floor sediments provide unique and continuous climate archives that allow assessments of such climate conditions. This information provides test cases for our understanding of the climate system that will ultimately lead to improved projections of future climate.

Research approach

An interdisciplinary team of geoscientists, (micro)biologists, biogeochemists, and environmental physicists will jointly apply their expertise in combination with highly advanced research infrastructures to address the scientific challenges in ocean-floor research. By tightly linking sea-going expeditions with shore-based analyses, experiments, and numerical modeling, we will achieve significant advances in ocean-floor knowledge. We will focus our sea-going efforts on a few key regions that will serve as interdisciplinary field laboratories and bring together researchers from all programmatic themes and disciplines. Our world-class inventory of underwater equipment (see Box 2 "Underwater Technology and International Core Repository") will provide the means for sampling and observing the ocean floor.

Box 2: Infrastructure – Underwater Technology and International Core Repository

Because investigations using satellites are largely limited to the sea surface, applications of highly specialized technology are crucial to investigations of the ocean floor. Observations and measurements of the ocean floor must be carried out directly *in situ* using remotely operated and autonomous underwater vehicles, deep-sea drill rigs, ocean-floor landers, and other technological tools deployed from research vessels. There are only a few institutions in the world that possess a fleet of modern underwater instruments for ocean-floor research comparable to those at MARUM. With this capability, it has developed into a center of marine research technology and a highly desired partner in international cooperative projects targeting ocean-floor research. In 2003, MARUM became the first institution in Germany to operate a work-class **remotely operated vehicle** (ROV) for deep-sea research. Today, the underwater systems include two ROVs, for 4,000 and 2,000 m water depths, and one **autonomous underwater vehicle** (AUV) for deployment down to 5,000 m. Furthermore, MARUM has blazed a new trail in scientific ocean-floor drilling through the development of robotic **deep-sea drill rigs** (MeBo70 and MeBo200). The MeBo200 system can be deployed to depths of 2,700 m and can drill 200 m into the ocean floor. The backbone of the proposed fieldwork in the Cluster is provided by a team of 40 highly specialized technicians and engineers and the sophisticated instruments they operate. The seagoing equipment is also made available to other working groups in Germany and internationally, and the ROVs, the AUV, and MeBo have been deployed multiple times for external working groups (e.g., 40 % for the ROVs).


ROV


MeBo

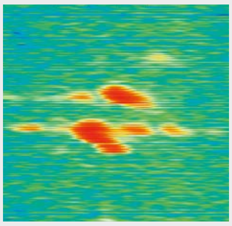

BCR

For more than two decades, MARUM has operated the **Bremen Core Repository** (BCR) of the International Ocean Discovery Program (IODP). It is one of the three IODP core repositories worldwide. The BCR houses more than 154 km of cores drilled on expeditions to the Atlantic and Arctic Oceans, Mediterranean, Baltic and Black Seas. Each year, approximately 200 international scientists visit the BCR for sampling of the cores. The BCR provides services to the international community through state-of-the-art curation and sampling procedures, and as science operator of the European Consortium for Ocean Research Drilling (ECORD). Multidisciplinary and multimedia data from all of these infrastructures are hosted by the central data platform PANGAEA – Data Publisher for Earth & Environmental Science.

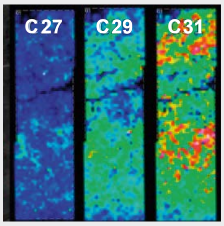
Box 3: Infrastructure – Analytical Facilities

The partner institutions and MARUM are home to a unique array of state-of-the-art analytical instrumentation that enables us to decode crucial information captured in organic molecules, minerals, and the isotopic compositions of organic and inorganic matter. These tools enable us to analyze samples such as single cells, animal tissue, calcareous fossils, rocks, sediments, and fluids. Through these analyses, we obtain insights into microbial communities, the types and rates of biogeochemical processes they are performing, the sources of various pools of organic matter, and environmental conditions and ecosystems of the past. The infrastructure for chemically examining marine samples includes several powerful major instruments and specialized laboratories that, in this combination, are internationally unique in the biogeosciences. These include: • **Metabolomics**: dissecting complex molecule mixtures in aqueous fluids, incl. marine dissolved organic matter, by ultra-high resolution mass spectrometry (FTICR-MS) • **Lipidomics**: comprehensive analysis of complex microbial lipids in marine samples • **Qualitative and quantitative analysis of a wide range of organic trace compounds**, ranging in size from C1 compounds to biopolymers • **Radiocarbon dating of biomarkers** with micro-scale accelerator mass spectrometer to study the carbon cycle • **Radiotracer tracking** of tracer incorporation into microbial biomarkers to determine metabolism and growth rates • **Stable and radiogenic isotopes:** multiple dedicated laboratories for high-precision isotopic analysis of light to heavy elements • **Molecular imaging:** ultra-high resolution temporal records of biomarkers in marine sediments and animal tissues • **µm-scale geochemical mapping** of element distributions in rocks and sediment records (X-Ray fluorescence, µ-computer tomography, laser ablation ICP-MS) • **Single-cell analysis:** determining the metabolism of marine microbes by NanoSIMS • **Atomic to nm-scale analysis** of mineral surface topography by Raman-coupled vertical scanning interferometry to study the kinetics of mineral dissolutions.

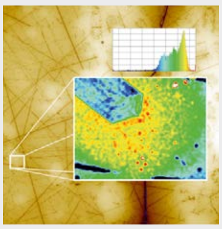
Lipidomics



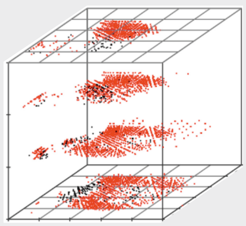
Molecular imaging



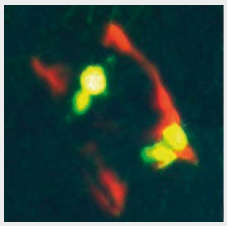
Mineral surface topography



Metabolomics



Single-cell analysis



The Cluster team will fully exploit the potential of the unique archive of sediment cores available in the international core repositories of the IODP, especially the one at MARUM (see Box 2). Shore-based work will make full use of a unique array of state-of-the-art analytical instruments that enable us to decode crucial information captured in organic molecules, minerals, and the isotopic compositions of organic and inorganic matter (see Box 3 "Analytical Facilities"). We will use numerical models at various levels of complexity to derive global matter and element budgets from experimental and observational data.

Positioning within the research area

We envision a transformation of the understanding of the ocean-floor processes that affect our planet through studies of matter fluxes as well as great progress in the analysis of climate and environmental changes archived in the sediments. Through our continued involvement in international programs and projects (e.g., International Ocean Discovery Program (IODP), European Consortium for Ocean Research Drilling (ECORD), Past Global Changes (PAGES), GEOTRACES, Integrated Marine Biosphere Research (IMBeR), Global Ocean Observing System (GOOS), Joint Programming Initiative Healthy and Productive Seas and Oceans (JPI Oceans)), our findings will be instrumental in shaping future research programs, which we expect, over time, to increasingly emphasize ocean-floor processes. Through the planned research, the Cluster will position itself internationally at the forefront in disciplines such as paleoclimate research, marine (bio)geochemistry and geobiology, as well as in integrating numerical modeling into Earth-system science at geological timescales.

Like space science, ocean-floor research has a high-risk potential, which is balanced by the prospect of scientific breakthroughs. On the one hand, the risks are an aspect of the technological challenges associated with observing and sampling the ocean floor in a hostile environment. On the other hand, the envisioned research program aims to achieve new levels of knowledge and understanding. This requires sample material of unprecedented quality to comprehensively decode the information on critical processes using our cutting-edge analytical facilities. However, relying on our long-standing experience in marine research, we expect the risk to be minimized.

The three proposed Clusters of Excellence in Bremen, Hamburg ("CliCCS"), and Kiel ("Future Ocean Sustainability") will be highly complementary to each other. While our research focus relates to the influence of the ocean floor on global element fluxes as well as the analysis of climate records archived in the sediments, "Future Ocean Sustainability" will focus on integrated science from ocean discovery to sustainable ocean development, and "CliCCS" will examine the future of the climate system and its interaction with society. One exemplary area of collaboration among the three Clusters is the marine carbon cycle, which takes advantage of the different timescales and approaches used in the Clusters. Other areas of collaboration are envisioned in the fields of the global hydrological cycle and climate sensitivity.

Preliminary work on which the Cluster is based

The Cluster will greatly benefit from the fact that MARUM has positioned itself internationally at the forefront of science in several interdisciplinary research areas, including the subseafloor biosphere, processes underlying natural climate variations, the role of microbial processes in shaping biogeochemical cycles, formation and disintegration of gas hydrates, and submarine geohazards, as well as the integration of numerical modeling into Earth-system science.

The scientific advances achieved by the Research Faculty MARUM are documented by 230 peer-reviewed publications per year (5-year average). In the field of sediment-related research in the Earth sciences, MARUM, Utrecht University, and Woods Hole Oceanographic Institution (WHOI) are the three most productive single-site institutions worldwide (Niu et al., 2014). Another indicator of our scientific impact is that 10 % of our publications appeared in journals with an impact factor greater than nine (based on Web of Science). In the ranking of Clusters of Excellence in Germany with respect to clear linkages between high-quality science and collaborations across borders, our current Cluster (see Appendix A6) is the only one in the field of Earth Sciences among the top ten clusters (Nature Index 2015; doi: 10.1038/527S80a). Over the past six years, the proportion of MARUM publications with international collaborators has increased from 60 % to 77 %, with the largest shares from Europe and North America (45 % and 36 %, respectively in 2017). Another sign of international visibility is the high response in applications we receive for advertised positions. Of 15 professorships the University has opened in the field of marine sciences since 2001, eight were filled with researchers from abroad (four from the USA, three from the UK, and one from Canada). About 40 % of the postdoc positions and 31 % of the PhD student positions at MARUM are filled by persons from abroad.

The planned research program will greatly profit from the fact that MARUM is one of about ten institutions worldwide that operate and develop large, high-technology underwater equipment, and it provides key infrastructure to the international scientific community. For more than a decade, the integration of science and technology under the MARUM umbrella has led to groundbreaking technological advances that are driven by scientific needs (see Box 2 "Underwater Technology and International Core Repository"). Major scientific advances have also been made possible through a unique set of analytical instruments at MARUM and its partner institutions (see Box 3 "Analytical Facilities"). In a pioneering effort, MARUM and its Helmholtz partner AWI established "PANGAEA – Data Publisher for Earth & Environmental Science", which is a nationally and globally leading open-access repository and data publisher and is a member of the International Council for Science (ICSU) World Data System (WDS). PANGAEA will form the backbone of research-data management in the Cluster (see Section 4.3) and is an asset in the growing field of data science.

Scientific achievements are closely related to advances in the training of early career researchers, equal opportunity measures, public engagement and governance. In these areas, MARUM has provided strategic momentum and has set standards for the University of Bremen during the past decade (cf. Appendix A7).

3.2 STRUCTURE OF THE RESEARCH PROGRAM

The research program is organized into three closely intertwined Research Units that examine the ocean floor from different perspectives (Fig. 2): (i) *the Ocean Floor as Receiver* approaches the ocean floor with a downward view through the water column, investigating how matter is being partitioned between the shelf and open ocean, transferred and transformed on its journey to the ocean floor, and how today's oceanic system properties are embedded in the sedimentary record;

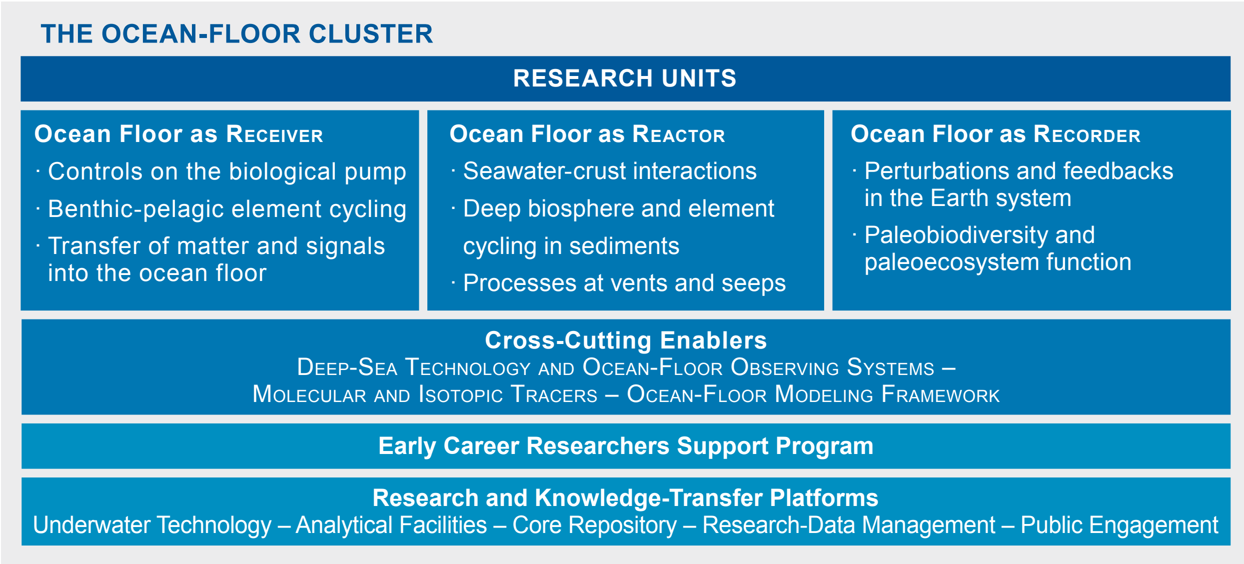


Figure 2 | Structure of the proposed Cluster.

(ii) *the Ocean Floor as Reactor* centers on geochemical and biogeochemical reactions at and within the ocean floor, their relationships to biological communities exploiting these reactions in a wide range of habitats, and fluxes of matter into and out of the overlying ocean; (iii) *the Ocean Floor as Recorder* will look into the past and decode proxy information stored in sedimentary records in order to elucidate the three-way relationships between physical climate processes, perturbations of the Earth system, and marine ecosystems, to provide a better understanding of the climate system and enable more robust projections of future climate change.

Enabling technology and methods will be developed across the Research Units. These cross-cutting enablers include innovative Deep-Sea Technology and Ocean-Floor Observing Systems (Technology), Molecular and Isotopic Tracers (Tracers), and a Framework for Ocean-Floor Modeling (Modeling). The expected advances in knowledge will be made possible by a unique combination of expertise in Research and Knowledge-Transfer Platforms (Fig. 2)

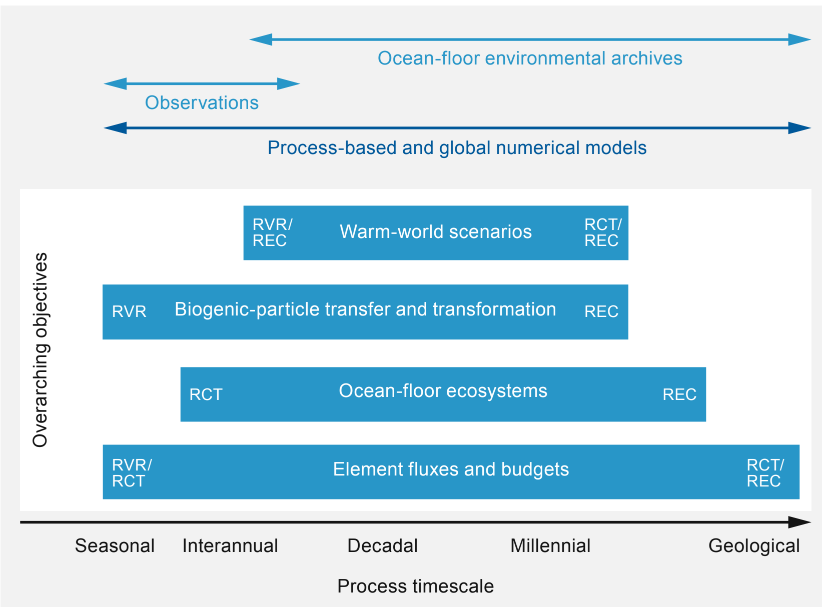


Figure 3 | Ocean-floor processes addressed in the overarching research objectives cover seasonal to million-year ("Geological") timescales and will be studied across the three Research Units Receiver (RVR), Reactor (RCT), and Recorder (REC). The Cluster will build on instrumental observations, as well as on information from ocean-floor archives and numerical models to integrate information across time-scales.

that include state-of-the-art analytical capabilities and provide direct access to the ocean floor by means of cutting-edge underwater technology. A further cross-cutting activity is the support of early career researchers (see Section 4.1).

The three Research Units are organized according to commonalities in underlying approaches and methods. At the same time, each Research Unit addresses several of the overarching objectives, ensuring integration of research across the Research Units. This research strategy will allow us to address the wide range of timescales associated with the overarching research questions and to combine instrumental observations with information from ocean-floor archives (Fig. 3).

3.3 STAFF AND INSTITUTIONAL COMPOSITION OF THE CLUSTER OF EXCELLENCE

The principal investigator (PI) group comprises the quality and diversity of talent, specialization and expertise that are required to meet the overarching goals of the Cluster. Many PIs and other involved researchers have already cooperated in previous research projects, and many will contribute to more than one Research Unit or cross-cutting Enabler, which strengthens the links within the Cluster.

Novel insights into the transfer and transformation of biogenic particles on their way to the ocean floor will result from the combined expertise in marine (micro)biology (T. Dittmar, J.-H. Hehemann, M. Iversen, M. Kučera, K. Zonneveld), biogeochemistry (A. Boetius, K.-U. Hinrichs, M. Kuypers, G. Mollenhauer), and transport mechanisms (D. Hebbeln, M. Iversen, G. Mollenhauer, M. Rhein). Other key researchers (see RECEIVER Section 3.4.1) will contribute specific knowledge on numerical modeling, inorganic and isotope geochemistry, and environmental geophysics. Fluxes and budgets of elements processed in the ocean-floor reactor will be studied by linking geology and geodynamic modeling (W. Bach, G. Bohrmann, M. Pérez-Gussinyé) with geochemistry (T. Dittmar, K.-U. Hinrichs, A. Koschinsky) and microbial ecology (A. Boetius, N. Dubilier, M. Friedrich). Other involved researchers (see REACTOR Section 3.4.2) will add key expertise in geochemistry, microbiology, mineralogy, geophysics, and physical oceanography. Scenarios for warm worlds will be based on information from ocean-floor archives that reflects changes in the physical and chemical environment (M. Kučera, J. Müller, U. Röhl), past variations in ecosystem structure and biodiversity (A. Freiwald, H. Hillebrand, M. Kučera, H. Westphal), and numerical Earth-system modeling (G. Lohmann, H. Pälike, M. Schulz). Other key researchers (see RECORDER Section 3.4.3) will provide expertise from paleoceanography and paleoclimatology as well as the physics of the climate system.

Three outstanding international scientists will be included in the Cluster as *U Bremen Excellence Chairs* (see Section 3.4.7) to systematically strengthen our research profile. They were selected based on their highly complementary expertise with regard to goals of the Cluster in the fields of biogeochemical element cycling and modeling (J. Middelburg), geomicrobiology (V. Orphan), and analysis and application of ancient DNA (aDNA; E. Willerslev).

The three cross-cutting Enablers (Sections 3.4.4 – 3.4.6) will benefit not only from the experience of the PIs but also from a range of other highly experienced researchers and engineers, who will provide the methodological backbone of the planned developments in these areas.

Overall, 31 professorships with their working groups will contribute to the Cluster (women are underlined): 16 of the University of Bremen (W. Bach, R. Bachmayer, G. Bohrmann, T. v. Dobeneck, M. Friedrich, D. Hebbeln, K.-U. Hinrichs, K. Huhn-Frehers, S. Kasemann, A. Kopf, M. Kučera, A. Lüttge, H. Pälike, M. Peréz-Gussinyé, M. Rhein, M. Schulz), 3 of the University of Oldenburg (T. Dittmar, H. Hillebrand, K. Pahnke), 2 of Jacobs University (A. Koschinsky, F. Maurelli), 5 of AWI (A. Boetius, S. Kasten, G. Lohmann, G. Mollenhauer, R. Tiedemann), 3 of MPI-MM (R. Amann, N. Dubilier, M. Kuypers), 1 of SGN (A. Freiwald), and 1 of ZMT (H. Westphal). Additional expertise at the University of Bremen will be included through a new professorship in sedimentology (as part of a national program to create new professorships across all disciplines) to be filled in 2019 / 2020 and a professorship in ocean-floor geology included in this proposal to be filled in 2019.

Two PIs of the University of Bremen will reach their retirement age during the term of the Cluster (G. Bohrmann and M. Rhein). The university will offer both of them an extension option for their professorships to carry out their work in the Cluster as planned, and will fill both positions with a comparable disciplinary orientation.

The Cluster will be hosted by the Research Faculty MARUM – Center for Marine Environmental Sciences at the University of Bremen. The partner institutions of the Cluster have research profiles that are highly complementary to each other in terms of their geographic and thematic foci. In the State of Bremen, where most of the partner institutions are located, this is due to long-term strategic planning in marine research (see Section 5.4 and Appendix A7). The Cluster will make it possible to develop the full potential in ocean-floor research among the involved partners by building on a foundation of unique complementary expertise, long-term cooperation, and world-class analytical facilities and research infrastructures. The Cluster will allow the University of Bremen to strategically align excellence in research, training, and research-and-information infrastructures with the partners of the Cluster (Univ. Oldenburg, Jacobs Univ., AWI, MPI-MM, SGN, and ZMT), establishing an exceptional center to attract outstanding international students and faculty.

3.4 DETAILED DESCRIPTION OF THE RESEARCH PROGRAM

3.4.1 Research Unit – Ocean Floor as RECEIVER

Principal investigators: T. Dittmar, M. Iversen, K. Zonneveld (coordinators), A. Boetius, D. Hebbeln, J.-H. Hehemann, K.-U. Hinrichs, M. Kučera, M. Kuypers, G. Mollenhauer, M. Rhein
Other key researchers: R. Amann, S. Bühring, G. Fischer, A. Gärdes, M. Holtappels, K. Huhn-Frehers, S. Kasemann, M. Könneke, S. Mulitza, K. Pahnke, F. Wenzhöfer, C. Wienberg
Excellence Chair: J. Middelburg

Importance: Half of the Earth's primary production occurs in the ocean's surface waters where large amounts of atmospheric CO_2 are fixed into organic matter. While sinking through the water column or being transported laterally, biogenic materials are transformed and to a large extent degraded. Thus, only a fraction of the biomass produced reaches the ocean floor where it has the potential to be sequestered over long timescales. Understanding the processes determining this burial flux is crucial for establishing the budgets of carbon and other elements across the ocean-floor interface. We will qualify and quantify the key processes controlling this biological pump and track the associated signatures preserved in the sedimentary record. Our **main objectives** / **expected achievements** are:

- To investigate the controlling mechanisms of the biological pump and its interaction with changing global biogeochemical cycles → we will develop a mechanistic understanding of how matter is transferred and transformed during its journey to the ocean floor.
- To quantify the impacts of continental-shelf processes on open-ocean biogeochemistry → we will reveal how the ocean floor on continental shelves acts as a buffer between land and the open ocean by filtering and transforming carbon and nutrients.
- To develop quantitative models determining the origin, trajectory, and age of organic and inorganic matter that reaches the ocean floor → we will examine the connectivity between surface-ocean conditions and the signatures received and integrated at the ocean floor.
- To trace how ocean conditions are preserved in the ocean floor as geological archives → we will establish novel and improve existing indicators (proxies) for reconstructing key parameters and processes in the ocean system.

Contribution to the overall objectives of the Cluster of Excellence

The RECEIVER will advance our understanding of the transfer of matter to the ocean floor, and how it is affected by climate change and recorded in the sedimentary record (Fig. 4), which is key for unraveling the processes and records to be studied by the REACTOR and RECORDER. Focusing on three Themes, the planned work will address fundamental gaps in knowledge with respect to the mechanisms of formation and transformation, translocation, degradation, and preservation of biogenic particles within the water column and at the ocean floor – collectively controlling the efficiency of the biological pump in the ocean.

Receiver Theme 1 – *The transfer and transformation of sinking particles* will strive to increase our mechanistic understanding of a key process in marine biogeochemical cycling. Combining challenging *in-situ* observations and innovative modeling approaches, we will unravel the controls on particle formation and sinking, including the role of marine life. Microbial transformation of the particle flux makes the ocean a "gigantic heterotrophic digester" that converts organic matter into CO_2 through respiration. Moreover, the water depth at which mineralization of organic carbon to CO_2 occurs determines the efficiency of the biological pump and its role in the global carbon cycle. As it is unclear how microbes achieve this transformation of matter, we will track the alteration of representative organic molecules through the water column to their incorporation in the sediments.

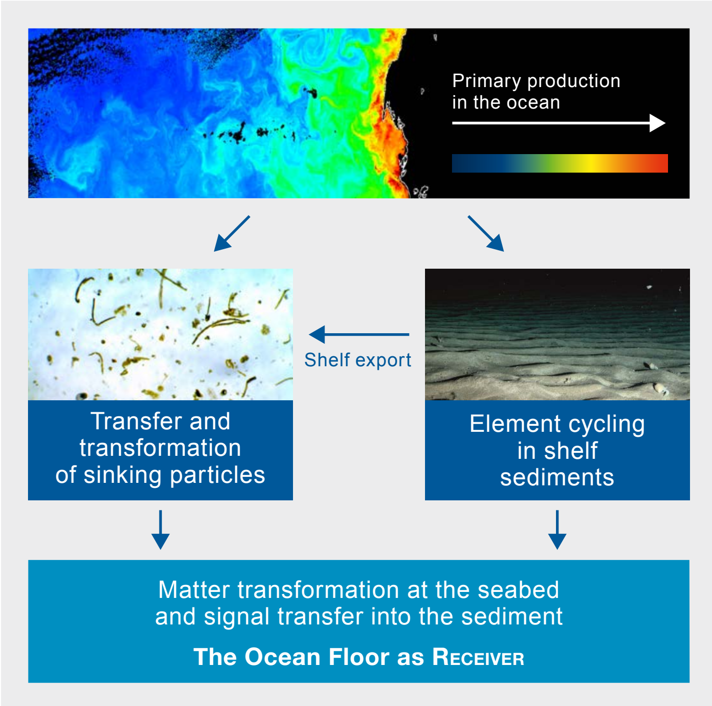


Figure 4 | The ocean floor receives matter, chemical energy, and information resulting from various processes in the water column, including the biological pump, which is a key control of atmospheric CO_2 concentration.

Receiver Theme 2 – *The role of continental shelves in nutrient cycling and organic-matter transformation* will investigate the exchange of matter between predominantly sandy shelf sediments and the overlying productive shelf waters to quantify transformation and lateral translocation rates of organic matter and nutrients, and to assess their impacts on global biogeochemical cycles. We will fill significant knowledge gaps related to the retention, transformation, and re-suspension of organic matter and nutrients in permeable shelf sediments, and elucidate how these processes influence the quantity and type of organic matter that is transported laterally toward the open ocean and subsequently sequestered. We will determine how degradation and removal of organic matter and nutrients within the sediment influence primary production and nitrogen budgets on the continental shelves, and eventually mitigate anthropogenic nitrogen inputs into coastal ecosystems.

Receiver Theme 3 – *The transfer of matter and signals into the ocean floor* will track physical, chemical and biological parameters related to key aspects of, for example, export production and preservation of carbon in ocean-floor sediments that leave measurable signatures in the composition and properties of pelagic and benthic particles and organisms. Such signals, also known as proxies, preserve an imprint of the prevailing conditions during particle formation as well as of the processes associated with particle transformation in the water column and at the ocean floor. We will use these proxies to extract quantitative information about the oceanic carbon pump, and apply them to suitable high-resolution archives bearing the potential to reconstruct past ocean conditions on sub-decadal and shorter timescales.

The RECEIVER team will (i) determine the fluxes and fate of carbon and other elements to and at the ocean floor, both on the shelf and in the deep sea, (ii) gain process understanding of feedbacks between the marine biosphere and climate, and (iii) advance our ability to quantify the role of the biological pump for different Earth-system states (Fig. 5). To achieve these three goals, close cooperation with the RECORDER, the REACTOR, and the Enablers will be essential (Table 3.4.1). This will be achieved by applying novel laboratory methods and innovative sea-going technology combined with state-of-the-art numerical modeling.

Pathways for impact

Projecting the impact of ongoing anthropogenic CO_2 emissions depends on the realistic assessment of major CO_2 sinks in the Earth system. Our research will improve knowledge about the regulation and efficiency of the biological pump as a sink for atmospheric CO_2, both for past and future Earth-system states, thereby contributing to the assessment of the capacity of the biological pump in future scenarios. As a part of this effort, we will elucidate major microbial transformation processes that directly affect the biological pump. By uncovering new genes and enzymes, we will provide data with a high potential for use in biotechnological developments. Processes that limit or accelerate organic-matter degradation in the ocean might inform industrial applications in the efficient transformation of plant biomass into useful products. As human activities disproportionately impact the continental shelves, our research on shelf sediments will help to assess

Table 3.4.1 | Overview of the Research Unit RECEIVER, its linkages within the Cluster and to its overarching objectives (see Section 2), study sites, and major disciplines involved.

RECEIVER	**Theme 1**	**Theme 2**	**Theme 3**
Research focus, spatial	Water column	Water column, sediment-water interface	Water column, sediment-water interface, surface sediments
Contributions to overarching objectives (Obj.) of the Cluster	Biogenic-particle transfer and transformation (Obj. 1); element fluxes and budgets (Obj. 2), and warm-world scenarios (Obj. 4)		
Most important links within the Cluster (T = Theme)	Transformation of biogenic particles (REACTOR T2), reconstructing carbon fluxes (RECORDER T1), upscaling from fluxes to budgets (Enabler MODELING)	Lateral biogenic-particle input from the shelves (REACTOR T2); *in-situ* analyses, seabed exchanges (Enabler TECHNOLOGY)	Biogeochemistry feedbacks (RECORDER T2), proxy signals to inform warm-world scenarios (RECORDER T3), signal transformation (Enabler TRACERS)
Key study sites	Mauritanian upwelling system, Irish margin, North Sea, Fram Strait	Mauritanian upwelling system, Irish margin, North Sea	Mauritanian upwelling system, Irish margin
Joint study sites	— NW African margin, NE Atlantic —		
Disciplines	Biogeochemistry, organic geochemistry, microbial ecology, physical oceanography	Biogeochemistry, organic geochemistry, microbial ecology, physical oceanography, sedimentology	Biogeochemistry, organic and inorganic geochemistry, microbial ecology, micropaleontology, sedimentology

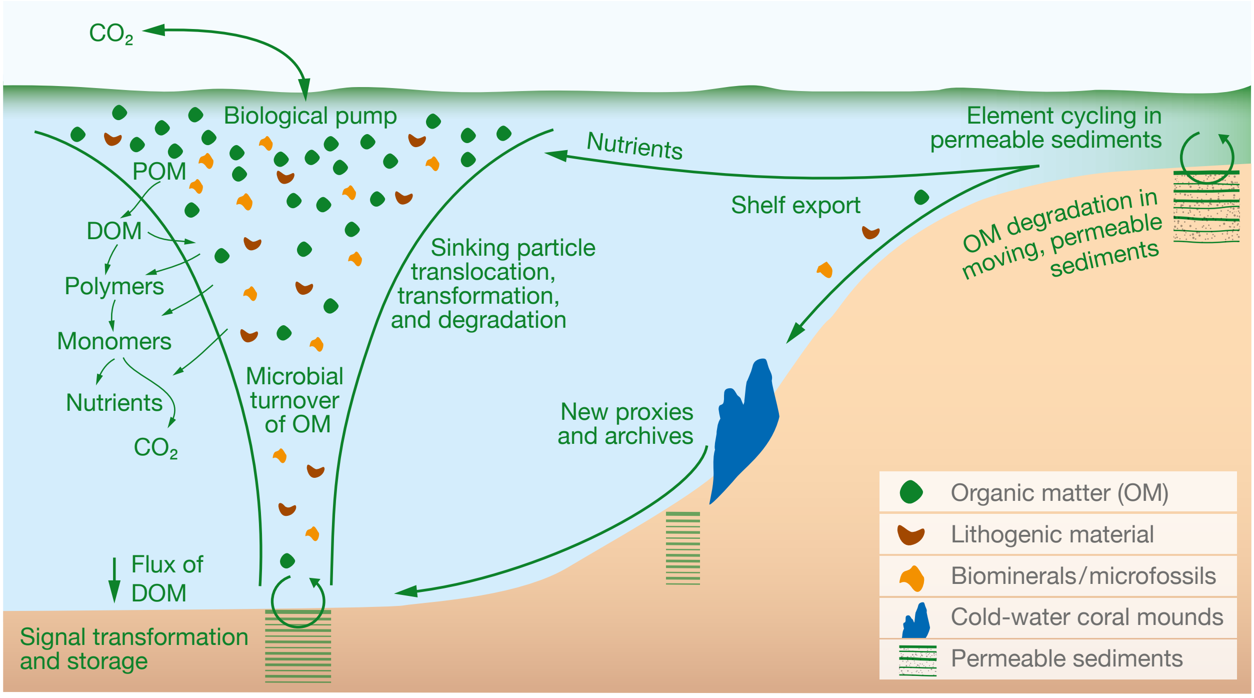


Figure 5 | Schematic overview of the research topics within the RECEIVER Research Unit. Research activities will primarily focus on the water column in the open ocean and on the shelf, and in the uppermost sediments. We will investigate processes associated with particle production, transformation and degradation, and the corresponding cycling of elements that ultimately controls the biological pump. Tracing the signals resulting from these processes into the sedimentary archive will support the RECORDER Research Unit in quantifying past states of the biological pump. An organizational overview of the program is provided in Table 3.4.1.

anthropogenic nutrient input into coastal ecosystems. We will improve the understanding of processes that regulate the removal of nutrients and organic matter, and evaluate their potential to mitigate anthropogenic pressure on the ocean system.

Current state of research (own publications underlined)

Sinking particles control the transfer of carbon and connected elements from the ocean surface to the ocean floor. Understanding the nature of the vertical flux of biogenic particles in the ocean, commonly referred to as the biological pump, remains a key goal of oceanography because this flux is a driver of important biogeochemical processes in the ocean. The magnitude of organic- and inorganic-matter transfer depends on how the particles are transformed as they sink. The key controls on the vertical and horizontal transport of material through the water column are still poorly constrained (Dall'Olmo et al., 2016).

Intriguingly, the amounts of primary production and export flux are not directly related. Instead, export flux is influenced by remineralization rates, which depend on the characteristics of the phytoplankton assemblages (Guidi et al., 2016). Variable remineralization is also due to the inherent chemical complexity of organic molecules, and to the kinetics of both transportation and transformation of biogenic particles. Furthermore, although aggregated material sinks faster, it is more likely to be rapidly remineralized than are small, dissolved molecules (Walker et al., 2016). We recently showed that biodiversity in surface waters and dominance of large zooplankton determine flux attenuation in the upper water column, while microbial communities largely determine the fate of sinking particles in the subsurface ocean (Iversen et al., 2017). However, the efficiency of carbon export varies both regionally and seasonally where particular events such as dust storms and sea-ice melting can result in high carbon export (e.g., Boetius et al., 2013).

The dissolution of aggregating macromolecules is catalyzed by microbes, whose evolution is accelerated by horizontal gene transfer, encoding enzymes that actively degrade organic matter (Hehemann et al., 2016). During microbial degradation, organic matter is molecularly diversified, resulting in very low concentrations of individual dissolved organic molecules in the deep ocean (Arrieta et al., 2015). The accumulation of dissolved organic matter (DOM), the largest and oldest pool of organic carbon in the ocean, over large spatial and temporal scales poses a conundrum, because it occurs under environmental conditions that should favor its heterotrophic consumption. We have recently suggested that the turnover of DOM is attenuated by the low concentration of individual molecules (Arrieta et al., 2015). There is a continuous exchange of matter between particles and aqueous solution, and some of the most recalcitrant forms of DOM may be removed from solution via adsorption to sinking particles (Hansell and Carlson 2013). Overall, our understanding of the processes and rates of organic-matter transformation and transport in the water column is fragmented.

Apart from the water column, where the processes controlling biological export production take place, **continental shelves play an important role in global cycles of carbon and nitrogen,** and are increasingly impacted by anthropogenic activities (Bauer et al., 2013). Particularly little is known about the transformations of carbon and nitrogen in the predominantly sandy sediments covering most continental shelves. Although shelves make up less than 10 % of the ocean floor, they account for about 30 % of the global marine primary production due to high, partly anthropogenic nutrient inputs. Much of the resulting organic matter reaches the shallow ocean floor but very little accumulates. This low accumulation is mainly due to the predominance of permeable sands on continental shelves; these sandy zones are characterized by intense biogeochemical cycling and contain only about 0.1 % organic carbon (Huettel et al., 2014). Previous work on continental shelves has focused largely on muddy sediments, partly due to the obstacles associated with working in the highly permeable, organic-lean sands. Consequently, the fate of organic matter that reaches the sandy seabed via the biological pump has been largely neglected, and little information is available to inform models of global ocean biogeochemistry. Recently, however, sandy continental-shelf sediments have been hypothesized to be sites of intense cycling of organic matter and nutrients (Bourke et al., 2017).

Our work has indicated that advection within continental-shelf sands increases the input of organic matter and nutrients to the sediment, whereupon they are subsequently degraded or, in the case of nitrogen, removed as dinitrogen gas (Sokoll et al., 2016), potentially mitigating anthropogenic N inputs (Marchant et al., 2016). The continental shelves thus form a buffer between the terrestrial realm and the open ocean, representing a zone of intense biogeochemical cycling, where organic matter and nutrients are transformed, reworked, and / or removed (Ahmerkamp et al., 2017; Marchant et al., 2017). Furthermore, the efficient remineralization in continental-shelf sediments prevents carbon burial in these areas, suggesting that only organic matter transported laterally to the open ocean has the potential to be sequestered and leave traceable imprints in the deep ocean floor (Zhang et al., 2016). Methodological and technological breakthroughs made by the RECEIVER proponents have enabled the realization of intricate biogeochemical studies on the continental shelves. Therefore, we are now in a position to study the impact of continental-shelf sediments on organic-matter transformation and to investigate why these sediments are such effective nitrogen sinks.

Much of our knowledge about the past ocean has been gleaned from geochemical signals preserved in the sedimentary record (e.g., Hain et al., 2014). Nevertheless, the opportunities to identify new informative approaches to reconstruct the **transfer of matter and to mechanistically understand the integration of signals into the ocean floor** have not been exhausted; the RECEIVER program is poised to make important contributions to this endeavor by identifying novel signals and / or archives and decoding their stored information. For example, polysaccharides, accounting for ~50 % of algal organic matter, can preserve valuable information regarding past CO_2 concentrations (Lee et al., 2016). On an organismic level, the intrinsic chemical properties of polysaccharide-based cell-wall biopolymers are opening attractive avenues for proxy development (Fig. 6). For example, the relationship between sedimentary concentrations of highly degradable heterotrophic dinocysts composed of nitrogen-rich polysaccharides, and concentrations of extremely resistant species composed of nitrogen-depleted polysaccharides, is dependent on ambient oxygen concentrations in the sediment (Gray et al., 2017). While the underlying structural differences explaining this selective degradability are not yet understood, the potential for exploiting these patterns for the quantitative reconstruction of past O_2 concentrations in ocean-floor settings, which is a property sensitive to the efficiency of the biological pump, is apparent.

Tracking the transfer of signals related to physical, chemical and biological properties of the ocean into the sedimentary archives is difficult. For example, the top centimeter of the sediment typically integrates ocean conditions on the order of decades to centuries – a fact that severely complicates the calibration of signals in ocean-floor archives against instrumental data. We have recently overcome this difficulty with the development of a methodological breakthrough that will enable us to decipher the molecular biomarker record preserved in ocean-floor archives at µm-scale resolution (Wörmer et al., 2014), in particular in non-bioturbated sediments. The approach will facilitate the calibration of biomarker signals with instrumental time series and allow the establishment of paleo-time series with temporal resolutions rivaling those of instrumental records (Fig. 7). In addition, new paleoarchives emerging from up to 300-m or higher mounds formed by cold-water corals (Cyr et al., 2016) provide access to ultra-high temporal resolution records. While the corals preserved in the widespread cold-water coral mounds can potentially record environmental information on annual to decadal timescales, this paleoarchive is still largely unexplored (Robinson et al., 2014).

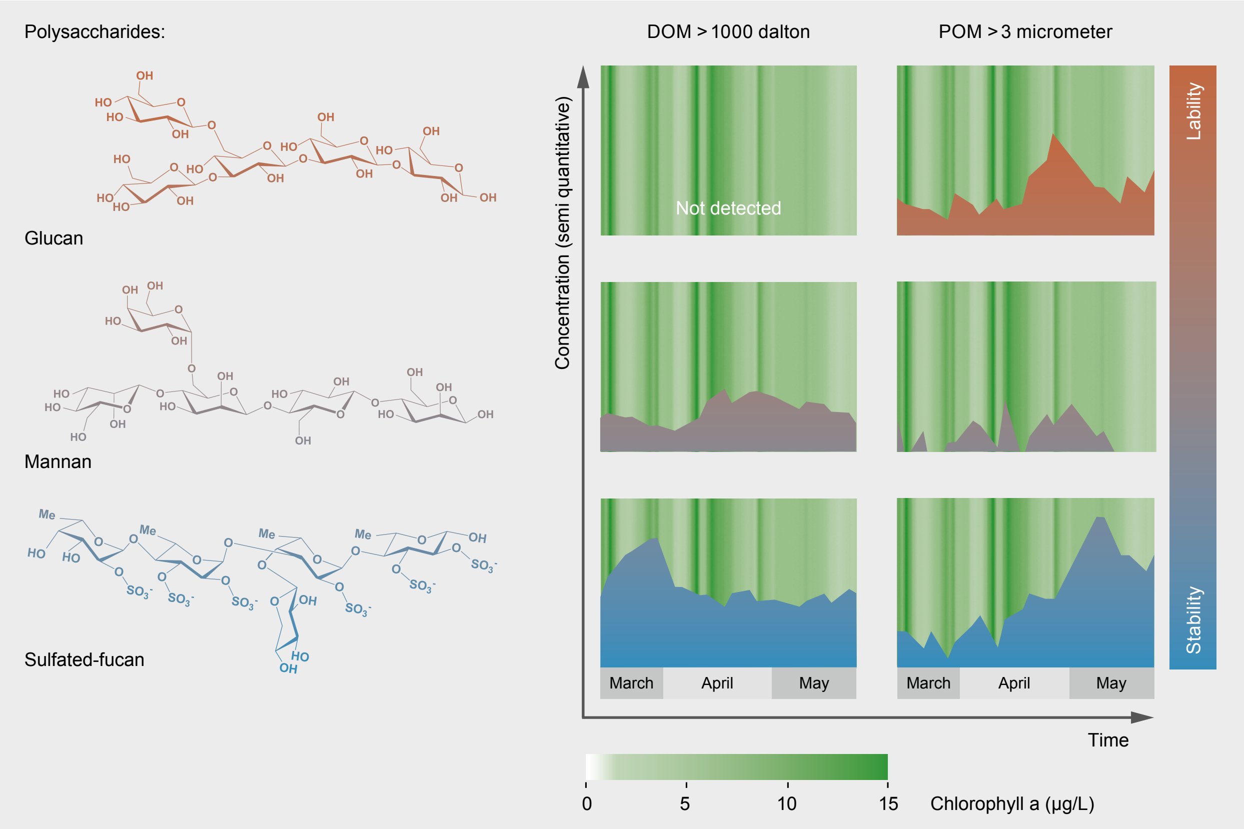


Figure 6 | Introducing immunological technologies in marine science to track diatom polysaccharides and thereby elucidate their carbon storage and nutrient potential. Dissolved and particulate organic matter was analyzed during a diatom bloom using microarrays and immunological detection with antibodies (specific for the structures on the left). Only the FCSP (Fucose-Containing Sulfated Polysaccharides) (blue) that are secreted by diatoms accumulated during the bloom. Therefore, the FCSP-formed particles may have the highest potential for transporting carbon and physiological signals into marine sediments (Hehemann et al., unpubl. data). The polysaccharide structures presented are models; the structural elucidation of the actual diatom polysaccharides is underway.

We recently demonstrated the potential of metalloid stable isotopes in marine carbonates for recording ancient ocean acidification (Clarkson et al., 2015), and will expand and validate this approach to the increasing number of cold-water coral-mound provinces being discovered.

Preliminary work

The RECEIVER team has extensive experience in applying state-of-the-art and innovative technology to the study of water-column and benthic processes. Using sediment-trap moorings, we have obtained one of the longest particle-flux time series in the ocean (Fischer et al., 2016), which forms a backbone of the work planned here. Combining sediment-trap studies with *in-situ* camera observations (infrared camera, Bio-Optical Platform) has opened a new window through which aggregate dynamics can be investigated throughout the water column. Novel *in-situ* lander technology, including the autonomous ocean-floor observatories LanceAlot, SedOBS, and a lander for measuring eddy covariance, has been developed, e.g., for the combined *in-situ* measurements of bedform migration and O_2 distribution within sediments (Ahmerkamp et al., 2017). Targeted ROV sampling of living cold-water corals from many sites around the Atlantic in recent years has provided a unique sample set, enabling the screening of these carriers for potential new proxies, such as the one achieved with neodymium isotopes (Dubois-Dauphin et al., 2017), to facilitate the exploitation of this very promising, yet largely unexploited new paleoarchive.

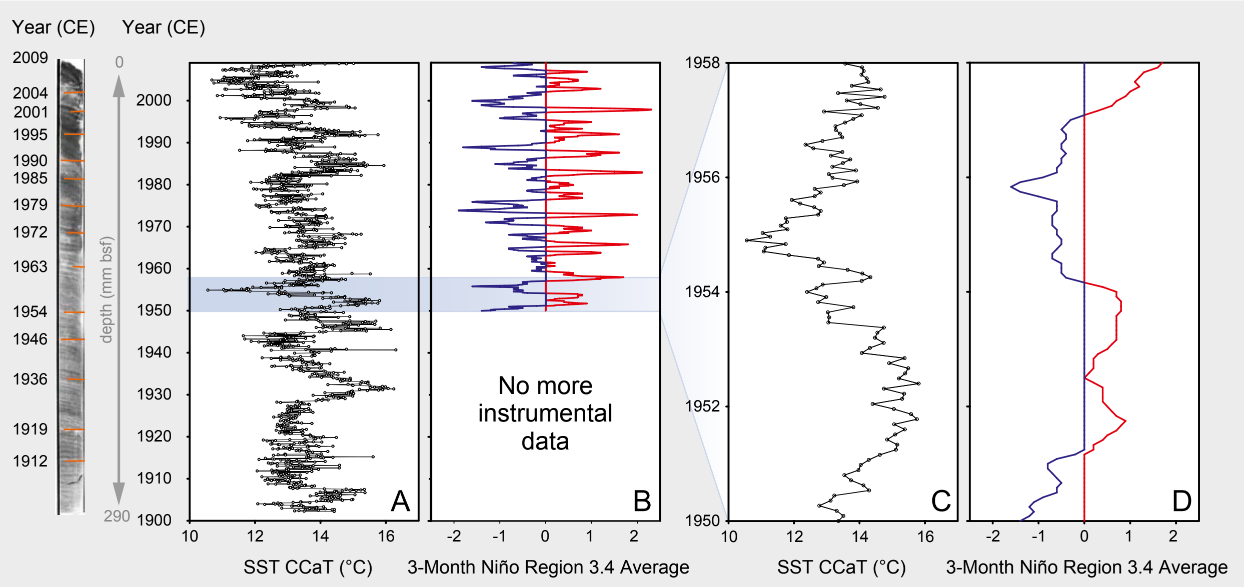


Figure 7 | New analytical approaches developed at MARUM: Ultra-high resolution molecular imaging of sediments will enable the reconstruction of biological, chemical, and physical oceanographic conditions at unprecedented resolution beyond the instrumental period. Exemplarily shown here is a sea-surface temperature (SST) record from the upper ~30 cm of laminated sediments from the Santa Barbara Basin, corresponding to the period of ~1900 to 2009 CE (core SPR0901-02BC, panel A), comparison to instrumental data (panel B) and zoom-in (panels C and D). SST reconstruction is based on the Crenarchaeol-Caldarchaeol tetraether (CCaT) ratio of two major archaeal lipids (Wörmer et al., 2014). Three parallel sediment slices were subjected to laser-desorption-ionization with 200 µm resolution resulting in ~130,000 individual CCaT values. Values from coeval laminae were averaged into a single data point; the resolution is approximately monthly. Panels B and D show the instrumental Oceanic Niño Index (ONI, www.cpc.ncep.noaa.gov) featuring temperature anomalies in a defined area of the Equatorial Pacific. The preliminary age model was obtained by correlating distinct laminae with a composite dated radiographic record (A. Schimmelmann, Indiana University); unpublished dataset by Alfken, Schimmelmann, Wörmer, Hinrichs.

Furthermore, our team has developed novel molecular techniques for the quantification of specific polysaccharides, the major building blocks of particulate organic matter (Becker et al., 2017). We have recently set up a geobiomolecular imaging lab for the analysis of molecular biomarkers in sedimentary matrices at µm-scale resolution (Box 3). This approach opens a new era in molecular stratigraphy with a vastly improved information density attainable from sedimentary records. To examine the molecular composition and age of organic matter we rely on a unique analytical infrastructure, including an advanced radiocarbon-dating laboratory and an ultra-high-resolution mass-spectrometry facility for molecular analysis of complex mixtures (Zark et al., 2017). Overall, the combination of analytical infrastructure and associated scientific expertise here represents a unique combination of facilities, technology and skills in the marine sciences (see Box 3 and Enabler TRACERS below).

Work program

RECEIVER Theme 1: Transfer and transformation of sinking particles

T. Dittmar, **J.-H. Hehemann**, **G. Mollenhauer**, **M. Rhein** (project leaders), R. Amann, **A. Boetius**, G. Fischer, K. Huhn-Frehers, **M. Iversen**, F. Wenzhöfer, **K. Zonneveld**

Motivation – The extensive turnover of organic matter produced by photosynthesis fuels life in the ocean and at the ocean floor by rapidly exchanging energy, carbon and nutrients among Earth's smallest (bacteria, archaea, algae) and largest (e.g., whales) organisms. However, despite its efficiency, a certain fraction of the molecules remain indigestible or inaccessible, and store carbon in seawater and sediments for millennia. **Receiver Theme 1 will focus on processes that regulate the efficiency of the biological pump and are potentially important drivers of long-term carbon sequestration. We will establish budgets and rates for the turnover of carbon and other elements in and around particles.**

Approaches – Primary production starts the biological carbon pump, but the overall efficiency of the pump depends on additional mechanisms. For Theme 1, *we hypothesize that microbial-degradation and transformation reactions throughout the water column can effectively enhance the overall flux of biogenic particles.* Samples will be obtained from Cape Blanc (MARUM site), the Irish margin (site PAP of our British partners) and the Fram Strait (AWI site), and the results will be put into the context of the long-term time series of these sites. Initial cruises will focus on how composition, size, and settling velocity of particles relate to their origin and age. Additional knowledge of the physical behavior of water masses will reveal the sources and sinks of particles (Boetius et al., 2013). Daily measurements of particle-size distributions, abundances, sinking velocities and collections of individual aggregates with the Bio-Optical Platform will allow us to precisely determine seasonality in aggregate formation, transportation and degradation. Particle flux and it's relation to local ocean-floor biogeochemistry will be analyzed with the help of deep-ocean sediment traps and the installation of *in-situ* sensors at the ocean floor. The latter will be achieved using our in-house-constructed benthic landers and crawlers with *in-situ* respiration sensors. The age-sensitive measurements will provide estimates of particle-transformation rates and mean residence times of organic matter, both of which determine the efficiency of the biological pump. Field observations will be combined with process modeling to identify mechanisms driving peak fluxes to the deep ocean on seasonal scales (with Excellence Chair J. Middelburg).

In addition to DNA, proteins and lipids, we will investigate polysaccharides, which are rarely studied in chemical oceanography and therefore provide a window of opportunity for discovery (Lee et al., 2016). They are also the most abundantly produced organic molecules in the ocean. We will transfer and apply newly developed technologies from biomedicine such as immunological assays and enzymatic dissection to identify and quantify polysaccharides (Becker et al., 2017) (Fig. 6). Polysaccharides are generally regarded as labile compounds. In contrast to this view, *we hypothesize that polysaccharides have different levels of reactivity and therefore have the potential to transfer carbon to the ocean floor.* From the perspectives of microbial ecology and biogeochemistry, we will question how interactions between microbes and nutrients affect the degradation kinetics of labile and stable polysaccharides at the micro-scale and ultimately influence carbon burial. We will investigate the enzymes and polysaccharide compositions of particles as well as the associated microbes that catalyze organic-matter degradation. We will extract the microbial communities from natural particles and use metagenomics and proteomics to monitor the microbial communities and their expression of enzymes. Initially, we will focus on assessing the sequential degradation of labile to stabile polysaccharides along their paths through the water column toward the ocean floor. With Excellence Chair J. Middelburg, we will model the sequential degradation of organic molecules based on our measurements of substrate availability, enzyme activity and microbial community composition. Together with the REACTOR, we will explore the role of algal polysaccharides and other macromolecules as reactants for processes within the ocean floor.

Particles and solutes interact physically, chemically and biologically. For example, adsorption of dissolved organic molecules onto sinking particles could be the most important removal process for DOM in the bathypelagic (Hansell and Carlson 2013). Such a removal process could be highly relevant in the context of global biogeochemical cycles because it determines the nature of organic matter reaching the ocean floor, and it might control the pool size of organic carbon in the oceans. Furthermore, molecular assemblages of old DOM may be stored within the sedimentary record. Modifications of DOM at the molecular level and of its radiocarbon content due to interactions with settling particles will be investigated using natural as well as experimentally produced DOM and particles. Fractions of DOM will be operationally defined based on their particle affinity and characterized via ultra-high-resolution molecular techniques (FTICR-MS), conventional biochemical analyses, and radiocarbon isotopic (MICADAS) analyses. The degradability of these fractions, in solution and attached to particles, will be tested in microbial incubations. Method development and implementation for the radiocarbon dating of DOM fractions will be achieved in close cooperation with the Enabler TRACERS, including the new Marine Cheminformatics Node for the evaluation and examination of massive molecular datasets (see Section 3.4.5).

Methodology – Field experiments to investigate the composition of particles, their quantity, and their aggregation will rely on observation / collection systems such as the Bio-Optical Platform and classical deep-sea sediment-trap moorings, which have provided a > 20-year time series from the Mauritanian upwelling system that is available for the work outlined here. These observations will be complemented by data from benthic landers and crawlers related to carbon demand and respiration at the ocean floor. Our observational capabilities will be continuously advanced in close cooperation with the Enabler TECHNOLOGY (see Section 3.4.4).

In addition, we will perform proteome analyses to reveal the enzymes used by microbes for organic-matter transformation, and will trace the alteration of the molecules in particles of known origin (microscopy, sequencing, micro-FTIR) along their paths from the upper water column to their accumulation at the ocean floor. We will focus on the polysaccharide, protein and lipid compositions of particles using HPLC, metabolic profiling, lipidomics, and NMR, as well as newly developed polysaccharide microarrays with antibody-based detection (Fig. 6) to monitor the presence of complex algal polysaccharides over time, both at the surface and at various depths. Here, a special focus will be on the molecular mechanisms involved in stabilization and destabilization of organic carbon, and their eventual consequences for particulate organic matter delivered to the ocean floor. DOM and particle-active fractions will be molecularly characterized via ultra-high-resolution mass spectrometry (FTICR-MS), NMR and quantitative HPLC methods. DOM fractions will be radiocarbon dated.

Receiver Theme 2: The role of continental shelves in nutrient cycling and organic-matter transformation

A. Gärdes, M. Holtappels, **M. Iversen**, **M. Kuypers** (project leaders), S. Bühring, **T. Dittmar**, M. Könneke

Motivation – Although large amounts of organic matter and nutrients are filtered through continental-shelf sediments, very little accumulates there. Previous research into the fate of organic matter and nutrients on continental shelves has focused almost exclusively on muddy, cohesive sediments, even though around 70 % of continental shelf sediments are comprised of permeable sands. Thus, it is essential for global models of marine biogeochemistry to consider and quantify the impact of sandy continental shelves on the cycling of nutrients and organic matter. Significant advances in technology and theoretical understanding now enable the quantification of fluxes between shelf sediments and the water column in both directions. With an interdisciplinary approach, combining water-column and seabed measurements with transport-reaction modeling and process parameterization, Receiver Theme 2 will contribute to the Cluster's overall goal to provide essential information on the budgets of carbon and other elements across the ocean-floor interface under various boundary conditions.

Approaches – To assess carbon and nitrogen cycling in continental shelf regions, it is imperative to understand **the settling rates of aggregates to the predominantly sandy seabed, as well as the contribution of nutrients released from benthic remineralization** to sustained primary production and water-column processes. The extent of such benthic-pelagic coupling is an important factor in determining the timescales over which organic matter and nutrients are retained within shelf systems, as well as in the capacity of shelves to buffer the open ocean from changes in terrestrial inputs. *We hypothesize that benthic nutrient release, pelagic primary production, and pelagic formation of fast-settling aggregates form a loop that retains nutrients within sandy continental-shelf systems.* With Receiver Theme 1, we will combine experimental and observational field studies to determine whether there are links between pelagic primary production, the amount of organic carbon that reaches the shelf seabed, and benthic nutrient-release rates. We (with the Excellence Chair J. Middelburg) will focus on quantifying nutrients released by benthic remineralization, subsequently examining their contribution to sustained primary production. Our long-term goal of understanding how tightly pelagic primary production and benthic processes are coupled on continental shelves will be achieved by employing measured rates of primary production, aggregate settling, and benthic nutrient release in regional models, in order to quantify the impacts of benthic-pelagic coupling.

The **fate of organic matter that reaches the sandy continental-shelf seabed** is dependent on the cycling of particulate and dissolved organic matter between the benthic boundary layer and the sediment. Organic matter that reaches the sandy seabed is entrained in the sediments by advection and filtered out. However, when sediments are redistributed by strong currents, particulate or dissolved organic matter can be resuspended into the benthic boundary layer. The transfer of organic matter between the sediment and the benthic boundary layer, and its associated degradation, therefore depend on the rates of organic-matter filtration and resuspension. The timescales on which degradation, transformation and subsequent lateral transport of organic matter to the open ocean occur (10 – 100s of years) may be very different from the water residence times on the shelves (years). *We hypothesize that the settling rates of aggregated organic material, hydrodynamic forcing, and sediment permeability determine organic-matter cycling and degradation in continental-shelf sands, and consequently also the amount and age of organic matter that is laterally transported to sediment depocenters or the open ocean.* We will initially monitor the dynamics of organic matter in the benthic boundary layer and quantify the rates at which sands filter particulate organic matter. Furthermore, the impacts of degradation and transformation on the age and recalcitrance of organic matter prior to lateral transport will be determined under various hydrodynamic regimes. Such process understanding will allow us to quantify the timescales on which organic matter is aged on the shelves, which is imperative to understanding the type and form of organic matter that is transported to the open ocean.

Sunlight often penetrates to the sediment surface on the shallow continental shelves. The resulting **benthic primary production (BPP) provides organic matter that fuels benthic microbial activity and nitrogen loss**. Benthic primary producers are a major food source for economically important marine animals and a carbon source for benthic microorganisms. However, they also contribute to other ecosystem services. Preliminary work has suggested that they might also stabilize the sediment, which would inhibit the resuspension of organic matter into the benthic boundary layer. This could increase the capacity for organic-matter degradation and nitrogen loss within the sediment. Considering the spatial extent of shallow continental shelves, we expect BPP to have a crucial, but so far poorly understood role in the marine carbon and nitrogen cycles. *We hypothesize that the presence of benthic primary producers has a substantial impact on sediment stability, which will initially lead to the retention of nutrients and organic matter within the sediment due to reduced resuspension. However, if sediments become too stable, we hypothesize that organic-matter filtration rates and nutrient fluxes into the sediment would decrease, therefore lowering the intensity of biogeochemical cycling in continental-shelf sands.* We will begin by deploying novel *in-situ* benthic landers to monitor the interaction of currents with sediment topography and movement, as well as the distribution and concentration of benthic primary producers. Complementary laboratory experiments will quantify the impact of benthic primary producers on the rates of benthic remineralization and nitrogen loss under different transport regimes. We will integrate the results of small-scale process models developed in Receiver. In a collaborative effort with the Enabler Modeling, we will parameterize and quantify the role of BPP on benthic remineralization and nitrogen loss on regional and global scales.

Methodology – Sea-going expeditions will employ a suite of *in-situ* measuring devices, many of which have been developed at MARUM. These include bottom-water samplers, marine-snow catchers and drifting sediment traps to determine primary production and settling of organic carbon to the shelf seabed. Benthic lander systems such as LanceAlot and SedOBS as well as eddy-covariance techniques will be deployed to study the settling and resuspension dynamics within the benthic boundary layer, and the fluxes of nutrients and organic matter between the sediment and the benthic boundary layer. Furthermore, integrated hyperspectral imaging systems will allow visualization and quantification of BPP *in situ*. Improvements to these essential *in-situ* monitoring systems will be made in collaboration with the Enabler TECHNOLOGY. Sea-going expeditions will be complemented by experimental work, using flow-through reactors in combination with mass spectrometry to determine rates of primary production, organic carbon remineralization and nitrogen-cycling processes. Organic matter collected from different parts of the water column, including the benthic boundary layer, will be subject to radiocarbon age determination and compositional analysis (e.g., by FTICR-MS) to elucidate their transformation within the benthic boundary layer and during lateral transport. Our ability to decode the transformations that organic matter undergoes will be vastly improved by collaboration with RECEIVER Theme 3 and the Enabler TRACERS, including its Marine Cheminformatics Node. The RECEIVER team will combine the data generated by *in-situ* observations, experimental work and organic-matter analyses into small-scale process models and reaction-transport models. This will allow data to be parameterized and then integrated into regional and global models in collaboration with the Enabler MODELING, allowing us to achieve our long-term aim of quantifying the unknown, but likely large, impact of continental-shelf systems on global ocean biogeochemistry.

RECEIVER Theme 3: The transfer of matter and signals into the ocean floor

S. Kasemann, K. Pahnke, C. Wienberg, **K. Zonneveld** (project leaders), **D. Hebbeln**, **J.-H. Hehemann**, **K.-U. Hinrichs**, **M. Kučera**, **G. Mollenhauer**, S. Mulitza

Motivation – Despite many successes in recent decades in the development of proxies that provide information on the past ocean, there remains an urgent need for identifying signals that provide quantitative information about the oceanic carbon pump. **RECEIVER Theme 3 will explore new proxies based on organic compounds, microfossils, and isotopic compositions to extract vital information related to the receiving nature of the ocean floor, such as past algal productivity, export and burial flux, diagenetic alteration, and ocean-floor redox conditions.** In addition, by exploiting innovative technologies and novel paleoarchives, we will strive to generate reconstructions of past ocean conditions on sub-decadal to sub-annual resolutions.

Approaches – *We hypothesize that polysaccharides from diatoms and other microalgae indicate nitrogen, phosphate and carbon dioxide levels because their structure is sensitive to nutrient concentration, and that the corresponding signals are transferred into the sedimentary record.* We will validate the extent to which the concentrations of different types of algal polysaccharides in sediments and their structures relate to primary productivity and nutrient concentrations. We will use newly developed immunological assays with antibodies that identify polysaccharides in organic matter with nanomolar sensitivity without destroying their macromolecular structure. We will focus on recalcitrant polysaccharides that accumulate during diatom blooms (see also Fig. 6) and aggregate into particles. Using laboratory and sea-going experiments with nutrient amendment at Cape Blanc, we will determine the impact of nutrient concentrations on monosaccharide ratios within the pool of recalcitrant polysaccharides. Initially, we will investigate the concentrations of recalcitrant as well as more labile polysaccharides. In addition to polysaccharide analysis, transcriptomics and proteomics of the microbial core communities will reveal enzymes that are new to science and that consume recalcitrant polysaccharides in marine sediments. This will allow us to use these enzymes as novel tools for polysaccharide analysis.

Complementary to the analysis of polysaccharides in particles and sediments using biochemical assays, we will explore the potential of methoxylated polysaccharides of dinocysts to quantify the oxidation state of the ocean floor and to make quantitative reconstructions of surface-water productivity. Through the application of advanced sorting techniques that allow the extraction of monospecific cyst fractions from heterogeneous sediment samples (e.g., based on flow cytometry), we will track molecular alterations during export as recorded by sediment traps and in the sediments by non-destructive methods on single specimens (micro-FTIR), as well as by destructive methods (e.g., pyrolysis-GC-MS). We will also analyze dinocyst polysaccharides using microarrays with immunological antibody detection. Methoxylation levels will be determined in samples from cores with different redox conditions and known ages using NMR to derive a calibration. *We hypothesize that the sedimentary accumulation rates of the most stable polysaccharides and their source organisms reflect their export production rates, because they are only minimally altered between production and burial*. With knowledge of the quantitative relationships between primary production and export production, the sedimentary accumulation rates can be used to quantify past upper-ocean productivity. The more reactive polysaccharides and their carriers are sensitive to aerobic alteration at the ocean floor. When analyzed in concert with their recalcitrant-polysaccharide-bearing dinocyst counterparts, their degree of degradation can be used to quantify past redox conditions.

Exploiting new analytical approaches and emerging paleoarchives represents a great potential for increasing the temporal resolution of paleoenvironmental information to sub-decadal and even to sub-annual timescales. Using laser desorption ionization coupled to ultra-high-resolution mass spectrometry (FTICR-MS, Box 3, Wörmer et al., 2014), a wide range of oceanic properties can potentially be reconstructed at annual or higher resolutions in the appropriate archives; these properties encompass but are not limited to sea-surface temperature (SST), redox conditions, signals integrating the plankton community structure, and continental runoff. As proof-of-concept, Figure 7 illustrates a ~100-year record (1900 – 2009) of SST variations recorded in a laminated sediment core from the Santa Barbara Basin, Northeast Pacific. Particularly in laminated sediments, this technique has enormous potential to resolve climatic fluctuations with sub-annual resolution. To verify its general applicability, this concept will be tested in other settings with laminated sediments, such as the Gulf of

California and the Chilean fjords. Furthermore, it will be extended to bioturbated yet highly resolved sediments from the Mauritanian upwelling region and from the Helgoland area, in order to explore the correlation potential of bioturbated sediments to long time series, which exist for both regions.

Following this example, we will explore the information stored in the µm-scale distribution of biomarkers that records algal community structure, terrestrial input, redox conditions, wildfires, etc. in the uppermost sediments of suitable archives in relation to instrumental data. These "calibration" steps will allow us to extend the ultra-high-resolution paleo-time series into the pre-instrumental era for centuries or even millennia. In addition, based on our extensive collection of cold-water coral samples, we will test the potential of this archive to record the ocean's carbonate system and ocean circulation by using isotope systems (Li, B, Ca, Mg, Sr, Nd, Pb) and various element ratios in the aragonitic coral skeletons. While some of these proxies have been identified as suitable tracers of past ocean conditions (e.g., B for seawater pH, Pb isotopes for ocean circulation), here we aim to unlock their information potential from the corals to enable the exploitation of the unique stratigraphic resolution offered by this accurately datable archive. *We hypothesize that, with the application of novel tracer techniques, we can unlock important information from suitable ocean-floor archives regarding the frequency and amplitude of interannual to interdecadal climate variations and the associated ecological and hydrological responses.*

Methodology – Recent developments improving advanced laboratory-based analytical techniques (e.g., pyrolysis-GC-MS, pyrolysis-GC-TOF-MS, micro-FTIR, TIMS, MALDI-FTICR-MS) and sensor-equipped water-column and lander systems combined with high-precision sampling (e.g., by ROVs), now enable *in-situ* tracing of proxy-signal alteration / formation in both the water column and sediments on molecular, micro-, and centimeter to kilometer scales.

Risks and opportunities in Receiver

Risks are commonly associated with field work in the ocean, especially in the sampling of individual particles, which requires the use of various sea-going technologies (e.g., optical sensors, drifting sediment traps and benthic lander). This risk potential applies especially to the high-energy environments found in shelf settings. Such technical risks will be mitigated through close collaboration with the Enabler Technology, building on their proven expertise in designing and deploying equipment in such high-energy regions (e.g., by combining sediment traps with *in-situ* camera systems to estimate trapping efficiencies). To obtain an understanding of the temporal variability of the biological pump, the studies planned here will greatly benefit from already existing long-term time series of particle flux to the deep ocean. We will have access to the long-term particle-flux data collected off Cape Blanc, Mauritania (MARUM site), in the Fram Strait (AWI site), in the Porcupine Abyssal Plain (PAP site) near the Irish margin (through cooperation with British colleagues), and at the long-term monitoring site at Helgoland Roads; all of these will contribute to maximizing our data availability without additional operational risks.

Through successful sample and data collection in the field, critical processes such as lateral transport, POM-DOM interactions, polysaccharide degradation and *in-situ* formation of particles and signals may not be distinguishable by molecular analysis and radiocarbon dating alone. We will therefore complement geochemical and omics methods with classical biochemistry to reveal how enzymes are involved in marine organic-matter degradation. Risks can be minimized here through close cooperation with the Enabler TRACERS.

Joint expeditions

The planned research requires intensive ship-based field work, for which the RECEIVER Research Unit will conduct joint expeditions to two key study sites that involve members of all three Themes. The main working area will be the Mauritanian upwelling region (Expeditions 1 and 3; Table 3.4.16), where the long-term Cape Blanc mooring site operated by MARUM is also located. Multiple expeditions, using both mid-size research vessels and the RV METEOR (in coop. with the RECORDER) will be carried out between 2019 and 2025 in this area. As one key task, the sediment-trap moorings will be serviced to continue this unique record into the future. In addition, dedicated water-column and sediment studies with *in-situ* observation systems as well as matter cycling on the shelf and its exchange with the open ocean will be investigated.

The second key study area for the RECEIVER will be the Irish margin (Expedition 2). There, a similar approach to that off Mauritania, involving all three RECEIVER themes, will be followed in order to analyze and compare the biological pump at two very different ocean settings: the more temperate Irish margin, and the subtropical upwelling regime off Northwest Africa. Two expeditions to the Irish margin are planned with mid-size research vessels in 2022 and 2024.

Internal and external collaborations

The RECEIVER team has strong connections to existing long-term ocean-monitoring programs in the upwelling region off Cape Blanc, Mauritania (MARUM), the Porcupine Abyssal Plain Observatory (National Oceanographic Centre, Southampton, UK), and the FRAM Ocean Observing System (AWI). All three sites have long time series of organic-matter transport from deep-ocean sediment traps, but each has a different ecosystem structure. This diversity of ecosystems allows detailed studies of organic-matter transformation as a function of transport processes, e.g., fast versus slow sinking, lateral versus vertical transport, and microbial versus high-trophic-level turnover. On the program level, the RECEIVER team contributes to IMBeR, the Global Carbon Project, to PAGES, and to GEOTRACES.

The RECEIVER team collaborates in a project funded through the Helmholtz Association in the Excellence Network, “The Polar System and its Effects on the Ocean Floor”. This bridging project, coordinated by the junior research group leaders M. Iversen and J.-H. Hehemann and involving additional biologists at AWI, studies how regime shifts alter the biological carbon pump, and capitalizes on the unique existing long-term sediment-trap time-series data from the low-latitude monitoring site of

MARUM at Cape Blanc and the high-latitude observatory of AWI in Fram Strait (HAUSGARTEN), both of which experienced shifts in their biological communities between 2005 and 2008.

Strong internal collaboration already exists between the RECEIVER and the REACTOR teams on how environmental signals can be transformed by diagenesis. The RECEIVER and RECORDER teams will collaborate on signal formation and transformation in the water column and the sediment to improve the overall understanding of geological records.

Link to U Bremen Excellence Chair

Close cooperation with the Excellence Chair J. Middelburg (U. Utrecht), a distinguished expert in marine biogeochemistry, is envisaged by the RECEIVER team. This collaboration will especially focus on the fields of organic-matter decomposition at and within the seabed, and on regional and global models of benthic contribution to carbon and nutrient cycling.

Use of existing (or planned) research and information infrastructures

The tasks outlined for the RECEIVER rely heavily on cutting-edge moored and shipboard ocean technology, ranging from *in-situ* optical and chemical observatories to innovative sampling tools, all of which will be further developed in close cooperation with the Enabler TECHNOLOGY. Furthermore, giant leaps in our ability to analyze chemical and isotopic properties in ever smaller samples will help us, together with the Enabler TRACERS, to examine key aspects of the biological pump related to the biogeochemical cycling of particulate and dissolved organic matter and of (bio)minerals at unprecedented levels of detail. Model parameterizations, ranging from addressing particle interactions in the water column to local sediment movements at the ocean floor, will be provided to the Enabler MODELING to enable joint ocean-wide upscaling, allowing us to hindcast and assess matter transport in space and time.

Our research will greatly benefit from utilization of the PANGAEA data publisher (see Section 4.3) and the Marine Cheminformatics Node to be established by the Enabler TRACERS, through the collation and interpretation of multiple data sets in disciplinary as well as cross-disciplinary approaches.

Table 3.4.2: Proposed Staff in Research Unit RECEIVER

	2019	2020	2021	2022	2023	2024	2025
Staff category	**Number of persons**						
Professors	-/-	-/-	-/-	-/-	-/-	-/-	-/-
Independent junior research group leaders	-/-	-/-	-/-	-/-	-/-	-/-	-/-
Postdoctoral researchers	6	9	8	8	7	7	7
Doctoral researchers	3	4	4	4	6	6	6
Other staff	-/-	-/-	-/-	-/-	-/-	-/-	-/-

Table 3.4.3: Funding Request for Research Unit RECEIVER

	2019	2020	2021	2022	2023	2024	2025
Funding category	**Totals per year in k€**						
Staff (Total 3.4.1)	648	881	831	905	902	893	919
Direct project costs (excl. staff)	200	290	270	235	265	205	190
Total instrumentation <€150,000	310	0	0	110	0	50	0
Instrumentation >€150,000	0	0	0	0	0	0	0

Justification: Direct costs include consumables, travel costs, and student helpers as well as project-specific expenses for the expeditions listed in Section 3.4.7. The following investments are planned: flow-cytometer (100 k€, 2019) to obtain monospecific extracts of algal cyst fractions from heterogeneous samples (RECEIVER Theme 3); Fourier-transform infrared spectroscope (micro-FTIR; 100 k€, 2019) to characterize their molecular alteration during export and deposition (RECEIVER Themes 1, 3); three sediment traps (50 k€ each in 2019, 2022, 2024), and two Bio-Optical Platforms (60 k€ each in 2019 and 2022).

3.4.2 Research Unit – Ocean Floor as REACTOR

Principal investigators: W. Bach, N. Dubilier, A. Koschinsky (coordinators), A. Boetius, G. Bohrmann, T. Dittmar, M. Friedrich, K.-U. Hinrichs, M. Pérez-Gussinyé

Other key researchers: S. Bühring, M. Elvert, V. Heuer, K. Huhn-Frehers, M. Ikari, S. Kasemann, S. Kasten, A. Kopf, J. Lipp, A. Lüttge, A. Meyerdierks, T. Pape, M. Römer, H. Sahling, V. Schlindwein, F. Schubotz, T. von Dobeneck, M. Walter, G. Wegener, M. Zabel

Excellence Chairs: J. Middelburg, V. Orphan

Importance: The reactions that transform carbon and other elements at and within the ocean floor likely have a critical impact on Earth-system processes, but they are incompletely understood. The REACTOR team will generate a new level of understanding of geosphere-biosphere interactions in ocean-floor reactions and their global impact, and make essential contributions to the Cluster's overarching objective of determining the budgets of carbon and other elements across the ocean-floor interface. We will elucidate and dissect key processes and their interplay with biological communities in a wide range of ocean-floor settings and habitats. Our **main objectives**/**expected achievements** are:

- To examine the relationships between plate tectonics and the chemical composition of the ocean → we will quantify and budget chemical fluxes in a variety of marine geological settings.
- To determine habitability within the ocean floor and quantify the role of the deep biosphere in element cycles → we will reveal the chemical and physical factors that define the lower boundary of the biosphere below the ocean floor and identify its impact on element cycles.
- To disclose the impact of gas seeps and hot vents on life at the ocean floor and in the deep ocean → we will determine the relationships between geological processes, the chemical compositions of emitted fluids, and the resulting biological activity and diversity.

Contribution to the overall objectives of the Cluster of Excellence

The dynamic ocean floor is a biogeochemical reactor that influences the global-scale distribution of elements that are vital for life, modulates global climate on geological timescales, and fuels rich biological communities at and below the seabed (Fig. 8). The impacts of this reactor on the global carbon cycle, on global climate, on long-term evolution of ocean chemistry, and on the diversity of life are poorly constrained, let alone properly quantified. The Research Unit REACTOR will examine reactions in the oceanic crust and at the ocean floor, quantify their regional- to global-scale impacts, explore and quantify biotic and abiotic processes and their mechanisms, and examine the associated geosphere-biosphere interactions and key components of the related ecosystems. Many factors control the direction and magnitude of exchange between the reactive ocean floor and the ocean, including the composition of subsurface rocks, sediments and hydrocarbon reservoirs in different geotectonic settings. The three interdisciplinary Themes in the REACTOR Research Unit are (Fig. 9): (1) *Seawater-crust interactions*, (2) *Deep biosphere and element cycling in sediments,* and (3) *Processes and dynamics of vents and seeps.*

REACTOR Theme 1 – *Seawater-crust interactions,* will examine and quantify reactions between seawater, sediment and rocks, and study the consequences of tectonic faulting for the physical and chemical properties of the lithosphere and the composition of the oceans. We will examine tectonic-sedimentary-hydrological dynamics and couplings in a range of settings, including oceanic rifts (rifted continental margins, slow and ultra-slow spreading ridges), ridge flanks, and subduction zones. Our studies will address how deep reactions between seawater and rocks provide energy-rich substrates that support ocean-floor ecosystems. Rates and pathways of such reactions as well as the implications for carbonate formation will be assessed using field and laboratory experiments.

REACTOR Theme 2 – *Deep biosphere and element cycling in sediments,* will study the geological, physical, chemical and biological factors that define the habitable zone within the ocean floor, as well as the interactions of subsurface microbial life with global element cycles. We will explore the downward extent of the deep biosphere within the ocean floor. We will examine how climate-controlled fluxes of iron-bearing minerals influence carbon cycling and microbial activity

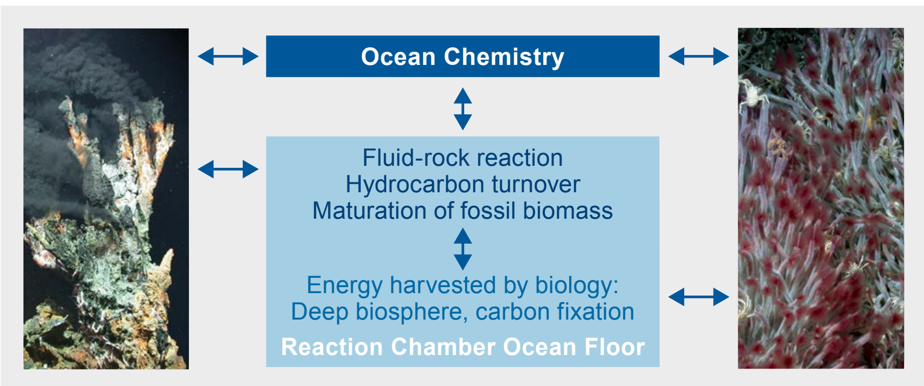


Figure 8 | The reactive ocean floor influences ocean chemistry and is vital for supporting marine life, modulating global climate on geological timescales, and supplying biological communities at and within the ocean floor with energy and nutrients.

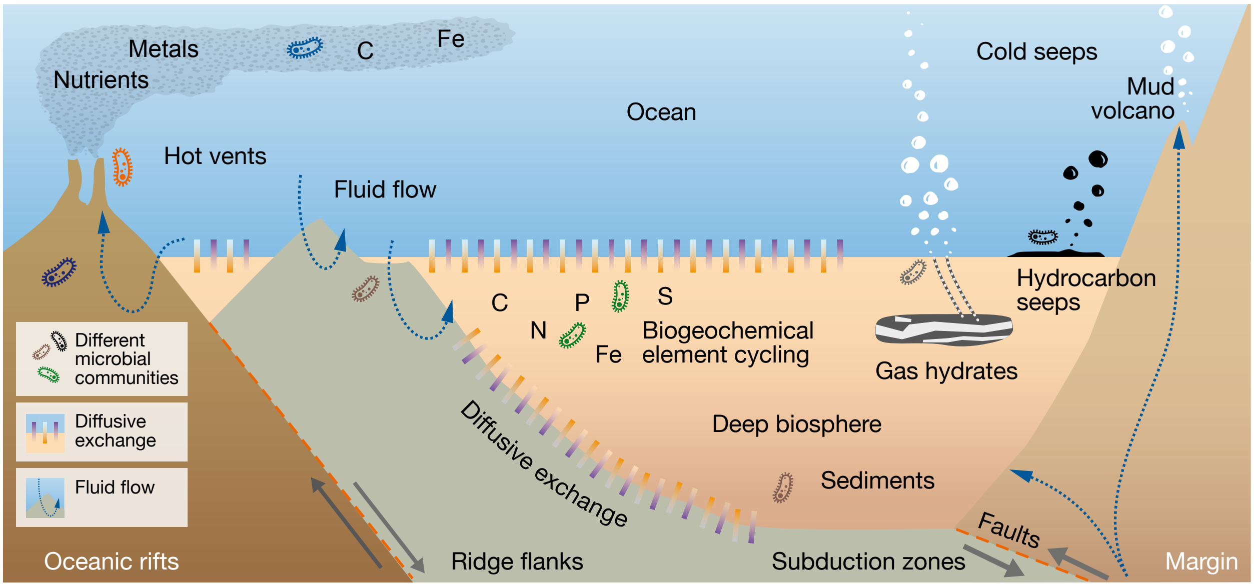


Figure 9 | Schematic overview of the research topics within the Research Unit REACTOR. Research activities will take place in oceanic rifts, ridge flanks, and subduction zones as well as in reactive sediment systems in the deep ocean and shelf seas. We will focus on examining the interrelationships between geological processes, geochemical reactions, and biology in these settings. Constraining diffusive and venting / seepage-related fluxes of matter between the ocean floor and the ocean and determining the influences of these fluxes on marine life is another major goal. An organizational overview of the program is provided in Table 3.4.4.

within the ocean floor. We will determine how vast subsurface methane reservoirs are formed by microbial degradation of sedimentary organic matter on geological timescales to reveal the deep biosphere's role in the global carbon cycle.

REACTOR Theme 3 – *Processes and dynamics of vents and seeps,* will investigate how the emissions of fluids and gases shape ocean-floor ecosystems, impact biogeochemical processes and influence element cycling in the deep ocean. We will also examine the effects of increasing ocean temperature on the vigor and style of gas emission as input to warm-world scenarios. Our goal is to understand the interplay between the geochemical attributes of vents and seeps and the biological and functional diversity in the associated chemosynthesis-based ecosystems. Symbioses between animals and microbes, and syntrophic interactions among different microbes using the abundant and diverse energy and nutrient sources will serve as model systems. We will examine the far-reaching effects of fluid emission on deep-water ocean biogeochemistry and water-column chemoautotrophy to reveal its impact on the ocean's element cycling.

The REACTOR research program (Table 3.4.4) will make full use of the unique analytical, technological, and modeling opportunities provided by the cross-cutting Enablers (Sections 3.4.4 – 3.4.6). Expeditions to key areas of the reactive ocean floor will facilitate observatory installations (see Enabler TECHNOLOGY) and provide crucial geophysical and geochemical data for the other Research Units. Close collaborations across the Cluster will target modifications of biogenic particles during their transit to and after burial in the ocean floor (RECEIVER), and the role of crust-seawater interactions in driving Earth's biogeochemical cycles and climate evolution on geologic timescales (RECORDER, Enabler MODELING).

Table 3.4.4 | Overview of the Research Unit REACTOR, its linkages within the Cluster and to its overarching objectives (see Section 2), study sites, and major disciplines involved.

REACTOR	Theme 1	Theme 2	Theme 3
Research focus, spatial	Below ocean floor, primarily non-sedimented	Below ocean floor, primarily sedimented	At and above ocean floor, primarily sedimented
Contributions to overarching objectives (Obj.) of the Cluster	Element fluxes and budgets (Obj. 2); ecosystems and biogeochemical cycles (Obj. 3)		Element fluxes and budgets (Obj. 2); ecosystems and biogeochemical cycles (Obj. 3); warm-world scenarios (Obj. 4)
Most important links within the Cluster (T = Theme)	Climate-ecosystem-biogeochemistry feedbacks (RECORDER T2); impact on ocean chemistry and climate (Enabler MODELING)	Transformation of biogenic particles (RECEIVER T1); detection of life and its activity (molecular isotopic approaches; Enabler TRACERS)	Recording the reactor (RECORDER T1 and Enabler TECHNOLOGY)
Key study sites	Eastern Equatorial Pacific ridge flanks, North Atlantic rifted margins and spreading ridges	Nankai Trough, Guaymas Basin, Helgoland mudflat, Argentine Basin	Submarine volcanic arcs, Cascadia margin, Guaymas Basin, mid-Atlantic ridge
Joint study sites	— North Atlantic, Mediterranean Sea —		
Disciplines	Geophysics, geodynamics, geochemistry, biogeochemistry, geobiology	Biogeochemistry, microbial ecology, organic geochemistry, geobiology	Biogeochemistry, microbial ecology and physiology, marine geology, chemical oceanography

Pathways for impact

A responsible use of the ocean floor – as a source of energy and materials or as a deposition site for CO_2 or other waste products – critically depends on our ability to foresee the physical, chemical, and biological consequences of this activity. Any model prediction of forced dynamic changes in natural systems relies heavily on a comprehensive understanding of the processes that govern the exchange of energy and matter in the steady-state system. Our research will provide greatly improved assessments of chemical fluxes across the ocean-floor interface. Knowledge of these fluxes is essential for predicting the role of the ocean floor as sink for CO_2 and understanding how this sink flux has varied through Earth's history. Our research will set the stage for future IODP expeditions and help to shape other ocean-floor programs in the future. Deep life, with its uncharted diversity and unique enzymatic adaptations to harsh environmental conditions, constitutes a tremendous potential asset for future biotechnology developments. We will enhance society's apprehension of the composition and functioning of these communities. This work will influence guidelines for an ecologically acceptable use of the ocean floor that will help protect this unique environment from damage.

Current state of research (own publications underlined)

A multitude of geochemical and biogeochemical reactions take place at and within the ocean floor. These reactions are driven to a large extent by the reducing power derived either from sinking biogenic particles (geochemical forcing) or from dynamic processes within the lithosphere (geodynamic forcing; Fig. 1). The associated transformations of matter influence the spatial distributions, reservoirs, and fluxes of elements and compounds that are vital for life and impact global climate. Our efforts will focus on key settings of the ocean floor (basement, sediments, fluid-emission sites) that harbor unique ecosystems and have particular relevance in controlling global fluxes of carbon and other elements.

Seawater circulation within the oceanic lithosphere controls the exchange of heat and matter between the crust (basement and sediments) and oceans in different geotectonic settings (oceanic rifts, flanks, and subduction zones) and involves different rock types (sediment, basalt, peridotite). Mantle peridotite makes up ~25 % of the ocean floor along slow and ultra-slow spreading ridges, which comprise more than half of the global spreading ridges by length (Escartin et al., 2017). This rock transforms to serpentinite when it interacts with circulating seawater, and releases copious amounts of hydrogen – the most potent energy source for chemolithoautotrophy (McCollom and Bach, 2009). Recent modeling studies have shown that, during the birth of an ocean, localization of break-up at rifted continental margins may be due to radical changes in density and mechanical strength of the lithosphere during serpentinization (Bayrakci et al., 2016; Fig. 10). Open-ocean ultra-slow rifts likewise exhibit close relations between seismicity and serpentinization of the lithospheric mantle (Schlindwein and Schmid, 2016). In ridge flanks, the permeable ocean crust is a vast, largely unexplored reactive interface and microbial habitat, in which microorganisms harness chemical energy from water-rock interactions (Edwards et al., 2012) that are in part fueled by reactions between sediment and basement (Orcutt et al., 2013; Mewes et al., 2016).

In subduction zones, fluids facilitate mass transfer along and across the plate boundaries, which may govern temporal locking of faults and the release of accumulated strain in various types of earthquakes (Wallace and Beavan, 2010). Moreover, fluids may either cause an upward ascent of mud or trigger earthquakes as a result of transients in frictional properties and pore pressure (Ikari et al., 2015).

The subsurface of the ocean floor harbors a large microbial biosphere that is adapted to extremely low energy fluxes. The size of the biomass pool within the sedimented ocean floor rivals that of all marine life in the ocean (Kallmeyer et al., 2012; Hinrichs and Inagaki, 2012). We recently demonstrated that microbial life extends at least 2.5 km into the ocean floor (Inagaki et al., 2015). Nevertheless, the lower boundaries of this vast ecosystem are still poorly constrained, as are the factors that limit microbial life at great burial depth. Similarly, it is unknown how microbes in the deepest regions of the subseafloor biosphere are impacted by the release of potential substrates through abiotic processes. Manifestations of biological activity within the ocean floor include large accumulations of methane, often in the form of hydrate, with a global carbon storage capacity rivaling that of “traditional” fossil fuels (Wallmann et al., 2012), and abundant dissolved inorganic carbon and nutrients that slowly diffuse back to the ocean. Microbial activity greatly contributes to the remineralization of sedimentary organic matter; e.g., almost a third of the organic-carbon flux to the ocean floor may be consumed by microbial sulfate reduction (Bowles et al., 2014). Interestingly, organic matter appears to be protected against microbial attack through poorly understood sorptive interactions with certain iron minerals (Lalonde et al., 2012) whose fluxes to the ocean are controlled by climate. On the other hand, these Fe minerals fuel microbial respiration of organic matter, including methane, in the ocean floor (Riedinger et al., 2014). Earth-system-scale feedbacks between the delivery of Fe minerals to the ocean floor and microbial carbon cycling in its subsurface may exist and deserve attention.

Hydrothermal vents and hydrocarbon seeps are important point sources of matter and energy, and they occupy diverse geological settings where they strongly affect the abundance and nature of marine pelagic and benthic life. Fluid venting at the ocean floor releases large quantities of energy-rich substances and metals that contribute to the oceanic budgets of key nutrients for marine life (German and Seyfried, 2014). For instance, recent work has shown that the release of Fe from hydrothermal sources at the ocean floor to the open ocean is four times higher than previously thought (Resing et al., 2015). The released metals are prone to interact with dissolved organic matter; these interactions likely play a vital role for metal availability in the oceans (Sander and Koschinsky, 2011). However, the regional to global relevance of these processes is largely unexplored.

At the ocean floor and in the shallow subsurface, reduced sulfur species, hydrogen, and organic compounds such as methane and other hydrocarbons fuel unique biological communities (e.g., Dubilier et al, 2008). Interactions between different functional groups of microorganisms are crucial for effective carbon mineralization under anoxic conditions (Stams and Plugge, 2009). For instance, syntrophy in the anaerobic oxidation of methane is based on directed electron exchange through nanowires between archaea and partner bacteria (Wegener et al., 2015). The vast potential for identifying novel metabolisms has been recently underpinned by the discoveries of syntrophic communities of anaerobic hydrocarbon degraders at butane-laden seep systems (Laso-Pérez et al., 2016; Fig. 11), and new symbioses between short-chain hydrocarbon-oxidizing bacteria and invertebrates at oil seeps (Rubin-Blum et al., 2017).

Preliminary work

The Reactor team has an outstanding track record of cornerstone and joint publications in ocean-floor science (see "Current state of research" above). Its members have also made key contributions to the development of critical analytical protocols, sampling technologies, and dedicated laboratory approaches. Some examples of central importance to our research strategy are provided in the following.

Methodology – Our ability to detect and characterize microbial life at and within the ocean floor depends on the quality of the samples and contextual data, as well as on access to state-of-the-art protocols that inform us about the quantities, identities, activities, and metabolisms of ocean-floor ecosystems. We have established a leading pool of expertise in the design of lipid-based protocols targeted to the study of microbial processes and communities at and within the ocean floor (Lipp et al., 2008; Rossel et al., 2011). We have implemented facilities for the cultivation of extremely slow-growing ocean-floor microbial communities and their investigation by modern biogeochemical techniques (e.g., Kellermann et al., 2012; Yoshinaga et al., 2014), which has allowed new insights into microbial life in energy-starved marine environments. These experiments include *in-situ* cultivation experiments in boreholes (flow-through osmo colonization system (FLOCS); e.g., Kopf et al., 2011), which will be adapted to MeBo borehole observing systems (see Enabler Technology, Section 3.4.4). We have expanded computational methods for assessing energy supply by water-rock reactions and energy demand by chemosynthetic microorganisms (Amend et al., 2011). We have developed laboratory and modeling-based methods that yield a fundamentally new concept for the kinetic treatment of mineral dissolution in fluid-rock systems (Fischer and Lüttge, 2017), and have implemented novel modeling approaches that enable us to estimate global fluxes of chemicals to the ocean floor (Bowles et al., 2014).

Customized Laboratories – Building on our expertise in lipid-specific stable isotope probing, we have established a dedicated laboratory for lipid-specific radioisotope probing assays (Box 3). These techniques will enable us to constrain the activity and metabolism of ocean-floor microbial communities with unprecedented sensitivity and specificity. A recently installed mass spectrometry imaging facility (Dubilier Lab at MPI-MM) enables the tracking of metabolic processes in symbiotic and syntrophic interactions at near-cellular resolution. Moreover, we have adapted the technology of mass-spectrometry imaging to sedimentary matrices (Wörmer et al., 2014; Fig. 7) and can now study ocean-floor microbial communities along mm-scale environmental gradients. Novel flow-through fluid-rock reaction chambers that we constructed allow the concomitant tracing of rock permeability and fluid composition (Kahl et al., 2016).

Expeditions and seagoing technology – We designed and co-led the recent IODP Exp. 370 to the Nankai Trough to constrain the influence of temperature on the downward extent of subseafloor life and to probe the impact of thermogenic generation of potential substrates on deep life. Regular expeditions to the Guaymas Basin, Gulf of Mexico and the mid-Atlantic ridge with remotely operated vehicles and submarines are the basis for vent and seep research. We have also developed small-sized *in-situ* instruments to estimate element fluxes from seeps and vents (Boetius and Wenzhöfer, 2013) and fluxes into the water column (Römer et al., 2014).

Work program

REACTOR Theme 1: Seawater-crust interactions

W. Bach, A. Kopf, **M. Pérez-Gussinyé**, V. Schlindwein (project leaders), K. Huhn-Frehers, M. Ikari, S. Kasemann, S. Kasten, A. Lüttge, F. Schubotz, T. von Dobeneck

In REACTOR Theme 1, **we propose a multidisciplinary approach for unraveling tectonic-sedimentary-hydrological interactions in oceanic rifts and subduction zones as well as hydrological-geochemical-microbiological interactions within ridge flanks.** The insights gained will be used to obtain local assessments of quantitative exchange fluxes in key areas (identified below), from which highly improved estimates of the role of crust-seawater interactions in global biogeochemical budgets will result.

Abundant exhumation of mantle rocks and associated serpentinization takes place along more than half of the global mid-ocean ridge system. Similar processes govern magma-starved rifting during the initial stages of ocean evolution. In these tectonically controlled marine settings, fascinating linkages

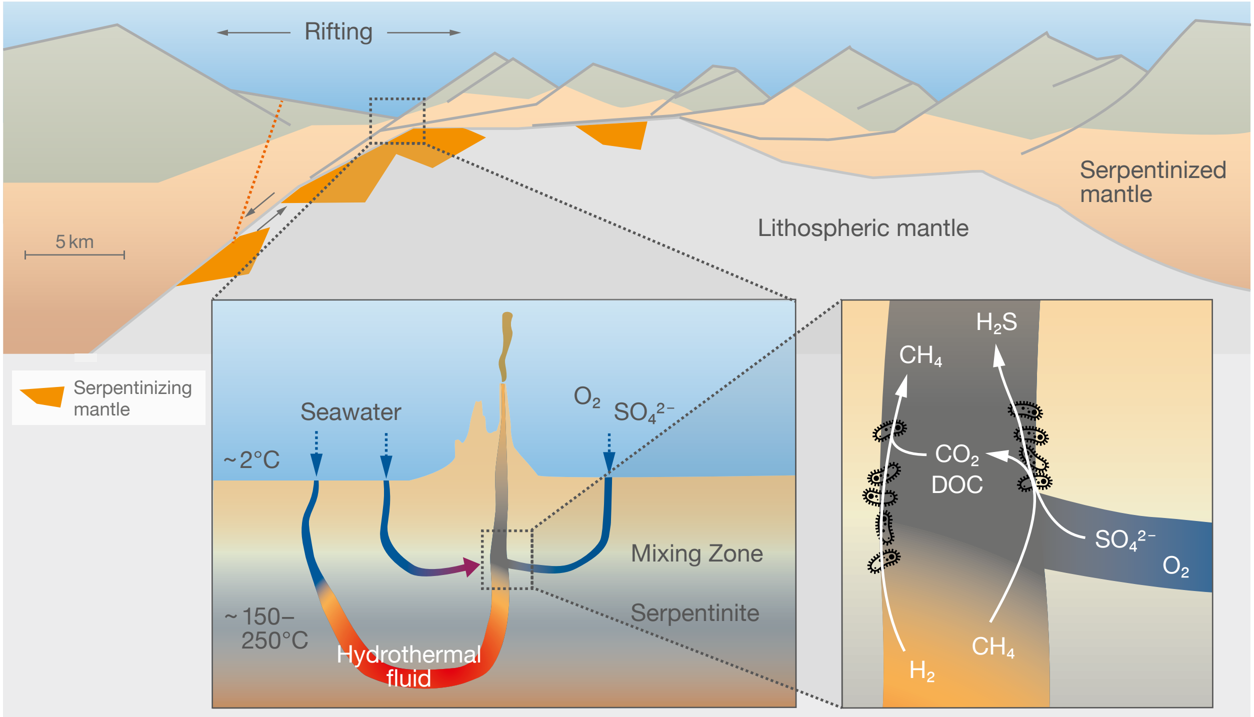


Figure 10 | Schematic representation of the connections between lithosphere deformation, serpentinization, and biogeochemical processes in rifted continental margins (modified from Ranero and Pérez-Gussinyé, 2010, Bayrakci et al., 2016, and Klein et al., 2015). Serpentinization of the upper mantle is facilitated by faulting and produces H_2 and CH_4, which support biomass production. Understanding these relationships in oceanic rifts and quantifying the implications for fluxes across the ocean-floor interface is a primary objective of the Reactor.

between rock deformation, hydrothermal reactions, geochemical exchange and microbial life exist. How these interlinked processes affect global element cycles is presently not known (Fig. 10). *We hypothesize that the exhumation of mantle peridotite along ultra-slow spreading ridges and in magma-poor margins is governed by similar tectonic modes, which are controlled by the mechanical weakening of rocks via seawater-lithosphere interactions. We postulate that these processes produce hydrogen and methane, which fuel deep life and affect the global carbon cycle on geological timescales.*

Subduction zones play an important role in element cycling, as much of the water and carbon added to the lithosphere in rifts and flanks is released from the subducting slab and transferred to the overriding plate. The associated fluid flow appears to be fault-bound, and is manifested in hydrocarbon seeps and deeply rooted mud volcanoes, both of which are key interfaces between crust and seawater and windows into deep chemical and biological reactors. *We hypothesize that the flow of fluids and their interaction with rocks in subduction zones affects the mechanical properties of faults, which in turn determine the seismogenic behavior of the plate boundary. We anticipate that studies in key areas will lead to a quantitative assessment of how deep faulting and fluid flow influences element cycling and subseafloor habitat development.*

Hydrologically active flanks of mid-ocean ridges are another key interface for ocean crust exchange processes and they constitute a vast, unexplored potential microbial habitat. Recent studies have indicated that sediment diagenesis and basement alteration are commonly linked, but details about the geochemical-microbiological interactions required to quantify these interactions, which are vital for exchange across the seabed, remain uncertain. *We hypothesize that diagenetic reactions in ridge-flank crust and the overlying sediment are heavily affected by seawater circulation within the crust. We anticipate a role for these processes in manganese-nodule formation and sedimentary Fe cycling. These processes are also expected to affect carbonate dissolution / precipitation in ridge-flank systems, which play a poorly determined role in the global carbon cycle.*

Approaches – By combining experimental and observational techniques, we will gain a better understanding of the couplings between tectonic, magmatic, and fluid-rock interaction processes that operate in oceanic rifts and subduction zones. We will establish the spatial patterns of hydrated mantle versus magmatic ocean floor and examine how these patterns relate to tectonic faulting, fluid flow, hydrogen and methane fluxes, and deep life. We will determine rates and pathways of diagenetic processes and biogeochemical reactions in ridge-flank sediments and the underlying basement, using geochemical and geophysical techniques. At this reactive interface, redox cycling of Fe may be of critical importance, and particular focus will hence be on tracing Fe host phases by determining changes in rock-magnetic properties. We will pair these investigations with laboratory studies of the kinetics of volcanic-glass dissolution and carbonate dissolution / precipitation to assess how dissolution-precipitation reactions develop in ageing oceanic crust. Shore-based work will be targeted on establishing novel laboratory experiments for measuring the rates of fluid-rock reactions in strained and unstrained systems. Synthesis of laboratory, ocean-floor observatory, and other data as well as upscaling of these results to basin and global scales, will be achieved in collaboration with the Enabler TECHNOLOGY and Excellence Chair J. Middelburg. Excellence Chair V. Orphan will be involved in evaluating the abundance and activity of intracrustal life and its consequence for rates of exchange across the ocean floor.

Samples and methods (selection) – Seismic expeditions and passive seismological experiments will be conducted in oceanic rifts to examine the spatial extent of mantle hydration and fault-related seismicity, and the thermal structure of the lithosphere. By petrological and geochemical examination of hydrothermally altered rocks, we deduce conditions and intensity of water-rock reactions. Novel laboratory-based experiments are used to determine relations between hydrothermal alteration state and mechanical strength of rocks from oceanic rifts, and fluid-controlled physical properties of underthrust material in subduction zones. Rock clasts from mud-volcano conduits (Marianas Trench and Islands) and landward mud domes (Mediterranean Ridge), with their associated fault gouge will yield unprecedented insights into processes in the decollement down-dip, water-rock reactions and related changes in physical properties. Ridge-flank processes are addressed in areas of very low conductive heat flow indicative of vigorous seawater circulation.

MeBo drilling and observatory installations serve to (i) identify and quantify fluid-driven subduction-zone processes and (ii) core the sediment-basement interface in hydrologically active ridge flanks. New logging and observatory tools developed in the Enabler TECHNOLOGY are used to monitor fluid-mediated ocean-floor processes. Geochemical and isotopic analyses of pore fluids in all settings will inform us on the physicochemical and microbial processes associated with fluid migration. Flow-through reactors equipped with real-time monitoring are used to spatially resolve dissolution kinetics and permeability development. These data will be used for the parameterization of reaction-transport models of element and isotopic exchange during fluid flow.

Reactor Theme 2: Deep biosphere and element cycling in sediments

M. Friedrich, **K.-U. Hinrichs**, S. Kasten, M. Zabel (project leaders), **A. Boetius**, C. Hallmann, V. Heuer, J. Lipp, A. Lüttge, G. Wegener

Reactor Theme 2 centers on geomicrobial and biogeochemical processes in the sedimented ocean floor. **We propose to build a mechanistic understanding of the interactions between microbes in the sediments and the fluxes of organic matter, iron, and methane, and constrain the boundary conditions under which life within the ocean floor can exist.**

The lower boundaries of the sedimentary deep biosphere are currently poorly defined. However, a groundbreaking study, under the co-leadership of K. Hinrichs and F. Inagaki in the deepest borehole ever probed for subseafloor life, has revealed a collapse of microbial life at relatively moderate temperatures (Inagaki et al., 2015). As the most plausible limiting factor, we suggested an insufficient availability of metabolic energy required for the repair of cumulative biomolecular damage during exceedingly long cellular cycles. *We postulate that the commonly assumed limiting factor alone, that is, the increase of temperature with burial depth, fails to define the lower extent of the deep biosphere. Other poorly examined factors such as accumulation of metabolic products, low energy fluxes due to slow kinetics of organic matter degradation, low porosity and water availability, among others, limit microbial life and ultimately result in sterilization.*

In terms of energy, the sedimentary deep biosphere is fueled by the degradation of fossil organic remnants from photosynthetic primary production. Subseafloor microbial activity and thus degradation efficiency depend upon factors such as fluxes and quality of organic matter and sedimentation rates, among others. One apparently important but insufficiently explored factor modulating microbial activity and carbon cycling within the ocean floor is related to the fluxes of Fe-bearing minerals into marine sediments. *We hypothesize that Fe/organic-matter interactions protect reactive organic matter from rapid degradation in shallow sediments, but that these weaken on geologic timescales, releasing both reactive organic matter and oxidation power at depth, and thus stimulating carbon cycling and microbial respiration in the deep biosphere. Paleoenvironmental processes modulate the coupling between these subsurface processes, which influence the redox balance at Earth's surface in as yet unknown ways.*

One major end product of organic matter degradation in deeply buried sediments is the powerful greenhouse gas methane. Its roughly billion-fold concentration range within the ocean floor testifies to a vast spectrum of organic-matter propensities for methane generation. Immense quantities of this highly dynamic and large carbon pool accumulate in marine sediments, and during the Earth's history may have repeatedly escaped into the ocean and possibly the atmosphere. Much progress on the mechanistic understanding of sedimentary methane oxidation has been made, but curiously only little is known about the kinetics and factors controlling the formation of methane. *We predict that the type, quality and mineral association of organic matter critically impact the rates of biological methanogenesis, the yields of methane, and the abundance and composition of methanogenic communities.*

Approaches – We will conduct experimental field- and lab-based studies combined with modeling approaches to shed new light on the limits of life within the ocean floor, and to determine the interactions between microbes, Fe minerals, organic matter and methane on molecular to Earth-system scales. Whenever feasible, we will extrapolate field and laboratory observations to larger spatial or temporal scales using the resources of the Enabler MODELING, e.g., to simulate relationships between climate and Fe-mineral-enabled burial of organic matter in the ocean floor. Future expeditions and laboratory experiments with subsurface samples will specifically address biological, chemical and physical factors, such as metabolic energy limitation, accumulation of metabolic products, and temperature, respectively, all of which may play a part in defining the lower boundaries of Earth biosphere. We will examine potential survival strategies under conditions near life's limits, such as the recycling of membrane lipids from fossil remnants and their substitution by chemically more resistant analogues. We will examine the quantitative relationships and compositional selectivity of the sorption of various representative Fe-mineral / organic-matter systems, determine the availability of Fe-bound organic matter and the coated mineral surfaces for microbial respiration and its kinetics, and elucidate the role of extracellular electron transport in subsurface Fe reduction. We will examine sediments representing contrasting depositional settings (shelf to deep sea, algal vs. continental organic-matter input) and ages for their potential to generate biological methane. In laboratory microcosm experiments with natural subseafloor sediments, we will determine rates of methanogenesis, observe and quantify compositional changes in DOM during methanogenesis in order to establish reactant-product relationships, and quantify and characterize active methanogenic members of the microbial community.

In the first three years we will focus on establishing a coordinated set of microcosm and pure-culture experiments, advancing methodologies for life detection, and the study of various field sites. Our efforts to place our findings on methanogenesis kinetics and relationships of Fe delivery and organic-matter burial into a broader Earth-system context will intensify with time, in collaboration with the Enabler MODELING and Excellence Chair J. Middelburg. Our program will benefit from the involvement of Excellence Chair V. Orphan, who has made crucial contributions to our understanding of Fe-based methane oxidation.

Samples and methods (selection) – Samples from IODP expeditions that probe severely limited deep microbial life (e.g., past IODP expeditions 337 and 370, co-led by REACTOR members; future expeditions scheduled and/or to be initiated by team members and collaborators such as IODP Exp. 385, Guaymas Basin, 2019), as well as samples from joint expeditions with other REACTOR themes and Research Units (e.g., Argentine Basin, Helgoland) and cruises of opportunity will be used. State-of-the-art analytical techniques will be applied for detecting faint microbial life occupying the transition to the abiotic world (see Enabler TRACERS), for quantifying and characterizing subseafloor microbial communities and their activities related to the cycles of carbon and Fe, and for studying Fe-reducing model cultures to explore interactions with various mineral/organic-matter systems. Microcosm experiments will be carried out with deep subseafloor sediments using stable and radioisotope tracers to study potential substrates and process rates as well as biomass formation of subseafloor communities. DOM will be analyzed to track its transformation during methanogenesis and Fe cycling, and sub-nanometer-scale examinations will be made of mineral surfaces employing atomic force microscopy and vertical scanning interferometry. Modeling procedures will include reaction-transport and geochemical box models.

REACTOR Theme 3: Processes and dynamics of vents and seeps

G. Bohrmann, **N. Dubilier**, M. Elvert, **A. Koschinsky** (project leaders), **W. Bach**, **A. Boetius**, S. Bühring, **T. Dittmar**, **K.-U. Hinrichs**, A. Meyerdierks, T. Pape, M. Römer, H. Sahling, M. Walter, G. Wegener

REACTOR Theme 3 will focus on biogeochemical processes and (micro)organisms associated with emissions of particles and fluids rich in gases and trace elements at vents and seeps. **We propose to constrain the nature and origins of the geochemical diversity of vents and seeps, to determine biological strategies of energy extraction from emitted matter, and quantify emissions and far-field oceanographic effects, such as the fate of hydrocarbons and micronutrients, and their impact on oceanic ecosystems**.

Vent and seep research has revealed a high diversity of geological settings on the ocean floor where energy- and gas-rich fluids are emitted. This diversity is exemplified by emissions of methane from various sources, e.g., biogenic methane from dissociating gas hydrate at cold seeps at continental margins, biogenic and thermogenic methane from mud volcanoes, abiotic production of methane by serpentinization in off-axis hydrothermal systems, and thermogenic methane in hot fluids at mid-ocean ridges and in submarine arc volcanoes. How these extremely diverse environments affect metabolic processes and rates is still not understood. *We expect that the compositions and emission rates of fluids at both vents and seeps impact the composition of microbial communities, the prevailing metabolic pathways, and the transfer of energy into deep-sea food webs in predictable ways.*

Microbial oxidation of hydrocarbons is a key biogeochemical process at vents and seeps that requires concerted action among different types of microorganisms. Anaerobic archaea have developed highly specific strategies for activating and fully oxidizing hydrocarbons (Laso-Pérez et al., 2016) that rely on tight syntrophic interactions (Wegener et al., 2015; Fig. 11). Diverse invertebrates live in symbiosis with partner bacteria, yet their metabolic traits and interactions are largely unknown. The reactions degrading seep and vent effluents and the associated ecosystems are influenced by variations in emission rates and fluid composition. *We hypothesize that syntrophy of anaerobic archaea and bacteria, and symbioses between aerobic bacteria and invertebrates, are based on unique biochemical strategies for substrate utilization, which result from adaptations to highly dynamic conditions at hydrocarbon-emitting vents and seeps.*

Intense emissions, specifically at vents, result in extreme pH values and high concentrations of sulfur, gases, DOM and metals. Recent studies show that shielding complexation leads to an unexpectedly far-reaching dispersal of metals such as Fe into the ocean, suggesting substantial effects of venting on regional-to-global element cycles (Sander and Koschinsky, 2011). *We hypothesize that the release of chemical energy and nutrients at vents and seeps significantly affects biological productivity and element cycling on various scales from the deep to the upper ocean.*

Approaches – We will investigate how geological, physical and biogeochemical conditions shape the biological and functional diversity of chemosynthesis-based ecosystems at vents and seeps. We will identify the relationships between energy availability and its use by various microbial groups. Comprehensive characterizations of natural vent and seep environments with contrasting emission intensities, substrate compositions, and temperature regimes will provide new insights into the underlying geosphere-biosphere interactions.

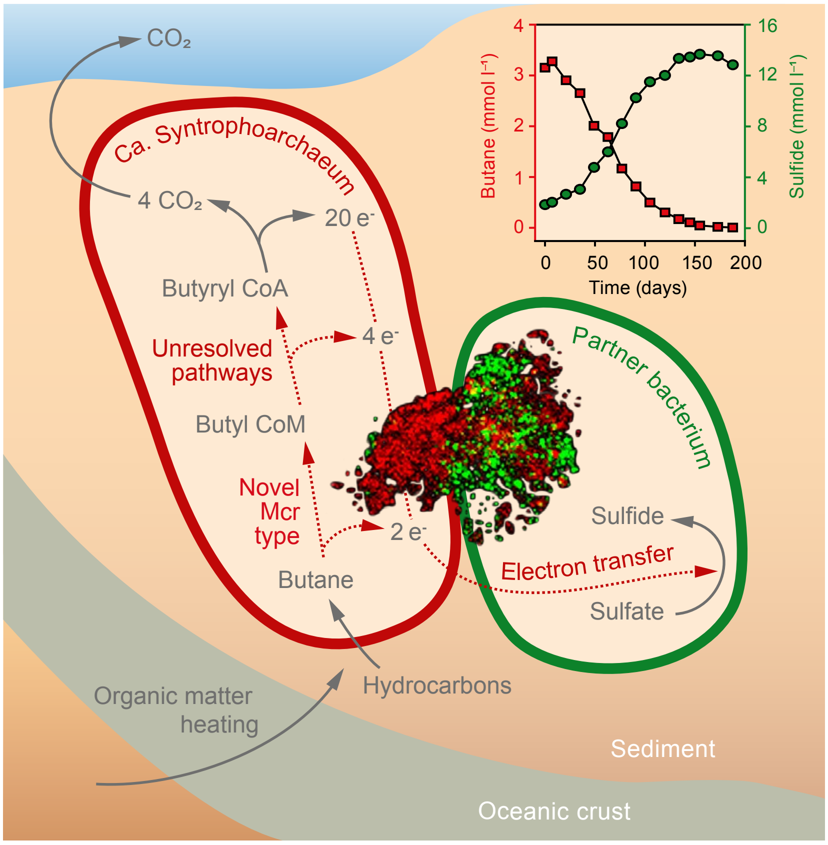


Figure 11 | Recently discovered anaerobic oxidation pathway of hydrocarbons produced by hydrothermal heating of organic-matter-rich ocean-floor sediments. Microbial enrichment from hydrothermal sediments in the Guaymas Basin couples the oxidation of butane to sulfate reduction (see insert of reaction development over time). The culture is dominated by large consortia (~30 µm in diameter) of archaea (red) and bacteria (green). The novel archaeon *Candidatus Syntrophoarchaeum* oxidizes butane via the formation of butyl coenzyme M, and additional yet to be resolved steps (Laso-Pérez et al., 2016), to CO_2 (red dotted arrows mark current and future research foci). Electrons released in this process are shuttled to partner bacteria similar to that seen in methane-oxidizing consortia (Wegener et al., 2015).

We will examine how hydrocarbons are biochemically activated and subsequently degraded, how energy and reducing equivalents are transferred between the participating organisms, and which compounds are exchanged in the carbon-flow network. We will start by establishing hydrocarbon-oxidizing cultures and symbiont-invertebrate systems from different sampling sites. Established cultures and symbioses are characterized by meta-omics approaches, and organisms are visualized with nano-scale tools in collaboration with Excellence Chair V. Orphan, a pioneer in studies of seep-hosted microbes.

We will investigate the far-field effects of the emitted matter and energy on ocean biogeochemistry. These studies will benefit from the implementation of a ROV-based *in-situ* mass spectrometer, through collaborative efforts with the Enablers TECHNOLOGY and TRACERS. Our research on hydrothermal vents will focus on submarine volcanic arcs where the plumes of some vents reach into the photic zone. We will quantify the emissions of Fe, manganese, copper and other trace metals, and determine their physical transformation (dissolved, colloidal, particulate), chemical speciation (free ions vs. organic complexes), and interaction with DOM. Methane seeps will be studied in several areas in the high-latitude oceans, where the warming of seawater influences the dynamics of methane seepage. Studies at hydrate-driven seep sites will involve collaboration with the RECEIVER and RECORDER units in order to constrain how seep emissions affect biogeochemical processes in the water column, and to reconstruct the temporal dynamics from the sedimentary record.

Samples and methods (selection) – Sampling of seawater and sediment, partly with autoclave technology, and *in-situ* measurements will aid in the quantification of emissions of gases, metals, and other compounds. Echosounders will be installed in the cabled network of the US Ocean Observatories Initiative (OOI) at the Cascadia margin to monitor gas emissions in real time over many years. State-of-the-art hydroacoustic seabed exploration will be used to quantify the areal extent of seepage from the ocean floor. We will employ geochemical analyses of fluids and gases, stable isotopic analyses, including isotopologues of methane and carbon dioxide, and metabolite analysis of other carbon substrates. Syntrophy and symbiosis of hydrocarbon oxidation will be explored with enrichments obtained by long-term cultivation approaches, and through experiments with fresh sediment samples and biota to be recovered during upcoming expeditions. We will investigate substrate spectra, lipid inventories, metagenomes and metabolic pathways in combination with physiological experiments and molecular imaging techniques in order to understand the functioning of key organisms and pathways of hydrocarbon degradation. Electrochemical experiments will provide insights into multispecies interactions. Environmental analyses, stable isotope probing and radiotracer incubations, as well as gene-based techniques, will be combined to determine the environmental factors shaping the ecosystem composition and expression of biogeochemical pathways in the various seep and vent systems.

Risks and opportunities in REACTOR

Our proposed research is based on a balance between novel, risk-bearing approaches and well-established techniques. There are substantial risks associated with exploring life at its limits due to the necessary low detection limits and inherent possibility of contamination. There is a risk of a loss of time-series acquisition in ocean-floor observatory research. Risks are also associated with the availability and function of underwater technologies (i.e., ROV, AUV, *in-situ* devices etc.). The imminence of these risks will be mitigated by innovations in the Enablers TRACERS and TECHNOLOGY. Ocean-floor observatories yield unparalleled quantitative insights into processes, and novel constraints for the rates of exchange between lithosphere and the oceans. Our expected advances in detecting biosignatures of deep life will be of relevance beyond the marine sciences, for example, in astrobiology in its search for extraterrestrial life. Furthermore, the outcomes will be relevant to the understanding of subseafloor microbial life at its limits, its interactions with petroleum reservoirs, and its coupling with the surface world.

Joint expeditions

To facilitate its research program, the REACTOR will occupy diverse study sites, some as joint expeditions involving members of all three themes (Table 3.4.16). A primary target site for joint research involving all three themes is the northernmost Atlantic, from the bend between the Mohns and Knipovich Ridges all the way to the westernmost Gakkel Ridge, and including the Molloy Ridge (off Svalbard) and Lena Trough (Fram Strait). Preliminary results indicate that this area features some of the most extreme examples of ultra-slow spreading ridges and systems that are transitional between rifted continental margins and oceanic spreading centers. These systems host abundant vents and seeps, and they are affected by a highly dynamic history of sedimentation that is linked to glaciation-deglaciation events. Multiple expeditions, using both RV MARIA S. MERIAN and RV POLARSTERN, will be carried out between 2019 and 2025 in this area (Expeditions 5, 8, and 9). We plan to conduct a joint cruise with the RECORDER to explore and sample the mid-Atlantic ridge around the Azores in order to constrain the temporal variability of element fluxes related to hydrothermal and volcanic activity (Expedition 4). We also intend to drill a series of basement holes in the flank of the Reykjanes Ridge and establish a ridge-flank observatory for flux measurements where water depths $<2{,}700\,m$ allow the deployment of MeBo200 (Expeditions 6 and 7).

With the new RV POLARSTERN and its improved capabilities for carrying out ocean-floor research in ice-covered seas, we will explore lithospheric accretion as well as vents and seeps along the Gakkel Ridge in the Arctic. Another high-latitude area of interest is the South Sandwich System, with abundant methane seepage in the forearc area and hydrothermal venting in the back-arc basin. Yet another potential area for multiple joint expeditions is the Mediterranean Sea, with abundant shallow-water hydrothermal vents, methane seepage in accretionary prisms and serpentinite mud volcanoes (Expeditions 10 and 11). The margin off Northwest Africa will be a site of joint research between the Reactor and Recorder Research Units in order to constrain temporal variability of past methane seepage from the sedimentary record (Expeditions 1 and 3).

In addition to these targets, the Mariana island arc in the Western Pacific represents a focus for vent emission and impact studies (Fe and other micronutrients), as well as for research on serpentinite mud volcano dynamics and seismogenic zone behavior. Researchers of both the Reactor and Receiver units will examine how hydrothermal supply of nutrients affects the biogeochemical cycling and carbon export in the water column.

Internal and external collaborations

The Reactor team will make use of its strong ties to outstanding researchers in the international marine science community. Chris German at WHOI is a close collaborator in the exploration of oceanic rifts in high-latitude seas. He was involved in three recent cruises with A. Boetius, V. Schlindwein, and W. Bach. This collaboration will be continued in future endeavors in the northernmost Atlantic (Expeditions 5, 8, and 9). Likewise, researchers at the K.G. Jebsen Centre of the University of Bergen and at the University of Tromsø will be partners in expeditions to the northernmost Atlantic. A joint proposal for IODP drilling off the Southern Knipovich Ridge is planned, as are joint seismological experiments in the northernmost Atlantic. Fumio Inagaki at JAMSTEC will be a central collaborator in research efforts related to the deep biosphere. With his lab he is an international leader in quantifying microbial cells in sedimentary matrices. Andreas Teske at Univ. of North Carolina at Chapel Hill is a long-term collaborator of several Reactor PIs; he regularly leads expeditions on US vessels to the Guaymas Basin with participation by our team members. He is also a lead proponent of IODP expedition 385 in the Guaymas Basin that will take place in fall 2019. Shuhei Ono at MIT (USA) will be our partner for clumped methane isotopologue analysis.

Beyond what is fostered by joint expeditions, diverse additional opportunities for internal collaborations with other Research Units exist. Two examples are provided here: (i) Reactor shares a common goal with the Recorder in terms of understanding how variations in plate-tectonic constellations have affected ocean-water compositions. For instance, the modern ocean has exceptionally high Mg / Ca ratios, which may be due to the post-Cretaceous slowdown of global plate divergence and associated magma production rates, or to accelerated weathering and continental runoff. Both Research Units will work closely with the Enabler Modeling to develop computational tools for examining the role of different forcing factors on ocean composition. (ii) Receiver and Reactor are linked, for example, by joint interests in transformations of organic matter, with the Receiver covering transfer from the photic zone to the ocean floor and the Reactor unit post-deposition in sediments.

Scientists of the Reactor and further experts at AWI and the University of Bremen are part of the Excellence Network "The Polar System and its Effects on the Ocean Floor", funded by the Helmholtz Association. This group (including the junior research group leaders M. Ikari and

V. Schlindwein) takes an interdisciplinary approach in advancing the systematic understanding of fluid circulation at ultra-slow spreading ridges, linking multidisciplinary observations at very different scales to understand the geological framework of polar deep-sea hydrothermal systems, thus exploiting the wealth of available seabed imagery.

Work in the REACTOR will be strongly connected to IODP. Our proposed research includes many aspects that will contribute to future IODP drilling proposals by helping to refine testable hypotheses and providing essential site-survey data. Our work will benefit from the Deep Carbon Observatory (DCO; co-led by REACTOR PI Hinrichs) and its international network.

Links to new professorship and U Bremen Excellence Chairs

The new professorship in Marine Geology will have a strong focus on ocean-floor processes and dynamics. Particular focus will be on the complex interplays between the hydrosphere and geosphere in settings ranging from rifts and ridges to collision zones. As a world-leading expert in geomicrobiology, Excellence Chair V. Orphan (California Institute of Technology) is a pioneer in tracking the metabolic activity of ultra-slow-growing microorganisms. Excellence Chair J. Middelburg (University of Utrecht) is a world leader in marine biogeochemistry, and will contribute his pioneering expertise in dissecting aquatic food webs via isotope approaches and in models examining the degradation of organic matter.

Use of existing (or planned) research and information infrastructures

Quantitative data for exchange fluxes will be obtained through our studies in representative settings. Close linkages to the Enabler MODELING will be advanced (i) to develop strategies for field measurements that allow upscaling to regional scales, and (ii) to feed observational data into a new Earth-system model that addresses the role of the reactive ocean floor in global biogeochemical cycles.

Collecting long-term data and time-series fluid samples using new observatory technology is a prerequisite for the work within REACTOR. These services are based on science-driven developments, and will be provided by the Enabler TECHNOLOGY. The working spectrum includes ROV and AUV missions and their innovative 3D data processing and visualization capabilities (see TECHNOLOGY Task 3), MeBo drilling and observatories (see TECHNOLOGY Task 2), and *in-situ* mass spectrometry (see TECHNOLOGY Task 4).

Across all three themes, molecular and isotopic lines of investigation will play a major role in studying microbes, their activity, and characterizing the sources of fluids. The backbone for research-data management in REACTOR will be the PANGAEA data publisher (see Section 4.3). Close collaboration with the Enabler TRACERS is crucial for achieving our ambitious goals; over time, its Marine Cheminformatics Node will increasingly serve as an interface for members across the Cluster by enabling the 3D queries of the ever-growing datasets of quantitative and isotopic distributions of chemicals within, at and above the ocean floor.

Table 3.4.5: Proposed Staff in Research Unit REACTOR

	2019	2020	2021	2022	2023	2024	2025
Staff category	**Number of persons**						
Professors	-/-	-/-	-/-	-/-	-/-	-/-	-/-
Independent junior research group leaders	-/-	-/-	-/-	-/-	-/-	-/-	-/-
Postdoctoral researchers	6	8	8	8	8	8	8
Doctoral researchers	4	7	7	7	7	7	7
Other staff (half-time lab technician)	-/-	-/-	1	1	1	1	1

Table 3.4.6: Funding Request for Research Unit REACTOR

	2019	2020	2021	2022	2023	2024	2025
Funding category	**Totals per year in k€**						
Staff (Total 3.4.2)	1,006	933	1,022	658	1,035	1,066	1,407
Direct project costs (excl. staff)	230	230	230	230	230	225	225
Total instrumentation <€150,000	0	0	0	0	0	0	0
Instrumentation >€150,000	0	0	0	0	0	0	0

Justification: Direct costs include consumables, travel costs, and student helpers as well as project-specific expenses for the expeditions listed in Section 3.4.7

3.4.3 Research Unit – Ocean Floor as RECORDER

Principal investigators: M. Kučera, H. Pälike, U. Röhl (coordinators), A. Freiwald, D. Hebbeln, H. Hillebrand, G. Lohmann, J. Müller, M. Schulz, H. Westphal, K. Zonneveld

Other key researchers: T. Bickert, L. Dupont, T. Felis, F. Lamy, M. Mohtadi, S. Mulitza, A. Paul, M. Prange, A. Rovere, E. Schefuß, R. Tiedemann, T. von Dobeneck, T. Westerhold, M. Zabel

Excellence Chair: E. Willerslev

Importance: Ocean-floor sediments will be investigated as an archive of past climate, element cycles and ecosystem responses, on timescales beyond instrumental observations and during climate states significantly warmer than the present, providing scenarios for assessing the consequences of warmer-than-present worlds. Our **main objectives**/**expected achievements** are:

- To assess the sensitivity of the Earth System to perturbations → we will decipher the physical and biogeochemical responses to large carbon releases, changes in the hydrological cycle (incl. monsoon systems), and sea-level variations.
- To determine feedbacks between climatic perturbations, water-column processes, and the ocean floor → we will evaluate the controls on temporal variability of the biological pump, the consequences for carbon cycling in the ocean and carbon deposition at the ocean floor.
- To decipher the reactions of marine ecosystems to perturbations → we will determine oceanic ecosystem diversity and function under changing climatic and geodynamic conditions

Contribution to the overall objectives of the Cluster of Excellence

Ocean-floor sediments provide a continuous record of environmental and climatic conditions from the Earth's past. Our objective is to provide the time dimension for processes in the Earth system beyond the limits of the instrumental record, complementing investigations in the REACTOR and RECEIVER Research Units, and to produce records of processes that are not observable on laboratory timescales. We will investigate selected cases of Earth-system behavior under different climatic and geodynamic boundary conditions (e.g., warmer climates, different sea-level stands and plate-tectonic spreading rates). Using sedimentary sequences covering key intervals of Earth-system variability at high temporal resolution, research within RECORDER will focus on three themes (Fig. 12, Table 3.4.7). **RECORDER Theme 1 – *Perturbations*** will identify mechanisms of natural perturbations of the climate system, and their consequences for biogeochemical cycles and the global hydrological cycle. We will quantify changes and thresholds in water-column carbon cycling and carbon deposition at the ocean floor. Biogeochemical changes in the deep sea related to variable "geofluxes" (i.e., fluxes from the Earth's interior, e.g., CO_2 emitted by hydrothermal vents) and external controls such as sea-level change will be explored. **RECORDER Theme 2 – *Feedbacks*** will identify and constrain interactions between climate change, sea-level and sea-ice variability, and biogeochemical cycling, all of which ultimately determine the sensitivity of the Earth system to changing greenhouse-gas concentrations. We aim for a better understanding of how long-term feedbacks involving oceanic carbon cycling and marine ecosystems operate under climate conditions different from those of today. **RECORDER Theme 3 – *Paleoecosystems and paleobiodiversity*** will develop new integrated approaches to biodiversity assessment, combining molecular biomarkers with ancient DNA and microfossils. The expertise of Excellence Chair E. Willerslev will enable us to systematically utilize the pool of ancient DNA in ocean-floor archives for the reconstruction of past ecosystems. We will deliver innovative estimates of past biodiversity, marine ecosystem turnover, and rates and patterns of adaptation. We will develop a novel conceptual framework for marine ecosystem change and stability and its role in the evolution of marine biogeochemical cycles.

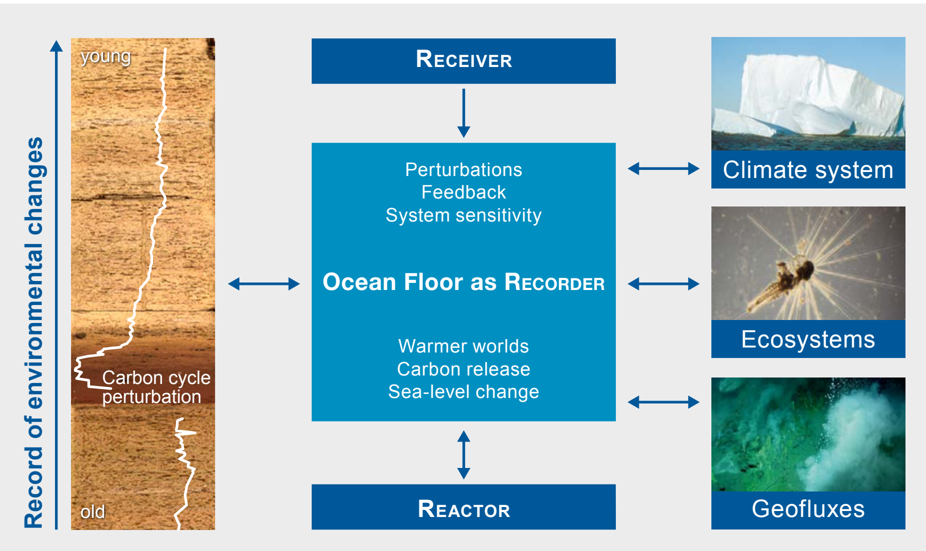


Figure 12 | The ocean floor records signals of environmental change, providing unique information on the responses and sensitivities to perturbations in the Earth system. An organizational overview of the program is provided in Table 3.4.7.

Table 3.4.7 | Overview of the Research Unit RECORDER, its linkages within the Cluster and to its overarching objectives (see Section 2), study sites, and major disciplines involved.

RECORDER	Theme 1	Theme 2	Theme 3
Research focus, spatial	Below ocean floor, sedimented	Below ocean floor, sedimented	Below and at ocean floor, primarily sedimented
Contributions to overarching objectives (Obj.) of the Cluster	Element fluxes and budgets (Obj. 2); warm-world scenarios (Obj. 4)	Biogenic particle transfer and transformation (Obj. 1); element fluxes and budgets (Obj. 2); warm-world scenarios (Obj. 4)	Biogenic particle transfer and transformation (Obj. 1); ocean-floor ecosystems (Obj. 3)
Most important links within the Cluster (T = Theme)	Emissions at seeps (REACTOR T3), transfer and transformation of sinking particles (REACTOR T1); impact on ocean chemistry and climate (Enablers TECHNOLOGY, MODELING)	Crust-seawater interactions (REACTOR T3), Earth-system sensitivity, dynamic sea-level in biogeochemical models (Enabler TECHNOLOGY, MODELING)	Ecological signal modification and transformation in marine sediments (RECEIVER T3); decoding molecular information (Enabler TRACERS)
Key study sites	Equatorial Atlantic, Equatorial Pacific, Eastern Equatorial Pacific, NW African margin	Equatorial Atlantic, Pacific, Arctic and Antarctic sea-ice, Greenland margin	NW African margin, Mediterranean
Joint study sites	— North Atlantic, NW African margin, Mediterranean —		
Disciplines	Paleoceanography, biogeochemistry	Paleoclimate, paleoceanography, biogeochemistry, organic geochemistry	Marine ecology and paleoecology, paleogenetics, organic geochemistry, marine geology

To meet our objectives, we will make use of the unique capabilities of the MARUM technology, in particular the MeBo drilling systems. We will recover high-resolution sedimentary sequences and exploit the new downhole logging tools that will be developed in the Enabler TECHNOLOGY. To foster synergies within RECORDER, joint expeditions will focus on key systems: (i) high-accumulation ocean-margin systems (e.g., off Northwest Africa, facilitating close cooperation with RECEIVER) covering diverse and highly productive ecosystems (incl. cold-water corals); (ii) a joint expedition with REACTOR to the mid-ocean ridge in the North Atlantic to study climate, hydrothermal activity, and transformation processes through time, and (iii) MeBo drilling (Expedition 12) to retrieve records of Greenland ice-sheet collapse. With the ENABLERS, novel methods will be developed and applied for reconstructing changes in the marine physical environment, in marine paleoecology and paleobiodiversity, and for complex Earth-system modeling.

Pathways for impact

RECORDER will provide crucial input to a global assessment of ocean-floor fluxes of carbon, and help to understand the impact of climate perturbations on the ocean system during high-CO_2 conditions (with significant relevance to IPCC scenarios). The RECORDER team will provide programmatic contributions to IODP. By assessing past sea-level variability and regional sea-level change, RECORDER will contribute to current discussions on the impacts of climatic change. Understanding Earth-system sensitivity in the context of "warmer-than-present worlds" will result in a better assessment of likely future warming sensitivities as well as the timescales of negative feedback regulators. RECORDER will provide new insights into the impacts of perturbations on ecosystem function and assessments of the natural variability of ecosystem composition, as well as a global assessment of biodiversity and ecosystem services.

Current state of research (own publications underlined)

Ocean-floor sediments provide records of past conditions that are required for understanding long-term Earth-system processes (Fig. 13). Significant progress has been made in reconstructing physical and biogeochemical conditions (temperature, atmospheric partial pressure of CO_2 (pCO_2), ocean alkalinity, productivity, hydrological cycle, and ocean structure) for past large-scale perturbations and feedback responses (Zachos et al., 2005, Pälike et al., 2012, Anagnostou et al., 2016, Schefuß et al., 2016). In particular, it is possible to use proxy- based reconstructions to test the predictions of comprehensive climate models for different climatic states (Fig. 14). Although efforts have been made to assess the impacts of such perturbations on ecological systems (Hönisch et al., 2012, Yasuhara et al., 2017), the interactions between physical climate-relevant processes and ecological systems have not been studied in detail on geological time-scales, nor have they been captured by experimental methods. This lack of knowledge remains a

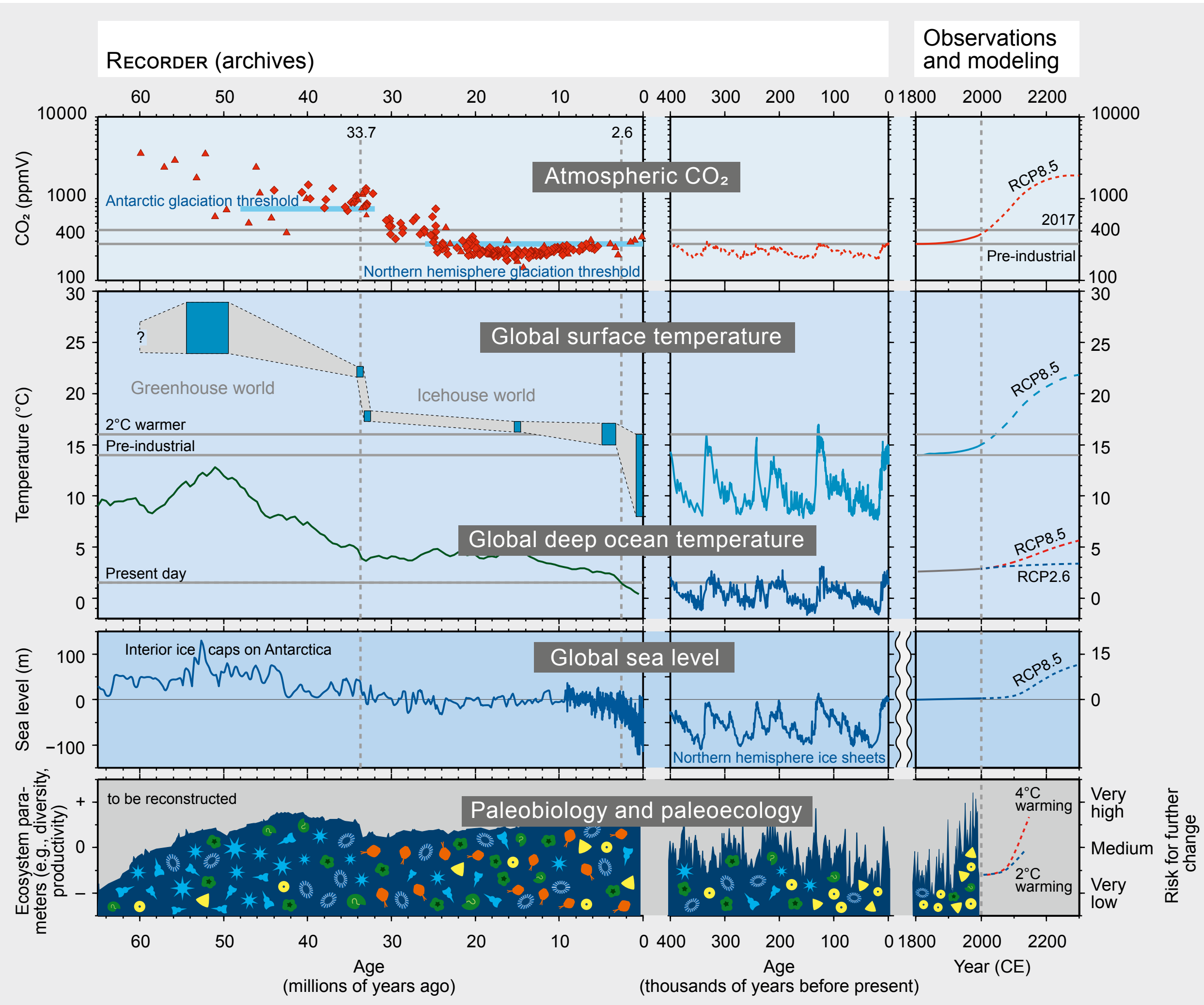


Figure 13 | Timelines of parameters to be included for investigation of possible warmer worlds. Shown are summaries of current paleorecords of atmospheric CO_2, global (sea) surface temperature (using IPCC business as usual scenario), deep-ocean temperature, and global sea level (with future prediction from DeConto and Pollard, 2016). Very little is known about the evolution of paleobiology- and paleoecology-related parameters, here exemplified by records of planktonic foraminifera turnover (modified from Yasuhara et al., 2017), and by the risk of future change in ocean productivity as assessed by IPCC (2014). Future "deep-ocean" temperatures are estimated from CCSM-derived model ensembles for the upper 3 km ocean. Data modified and extended from references in Hansen et al. (2013).

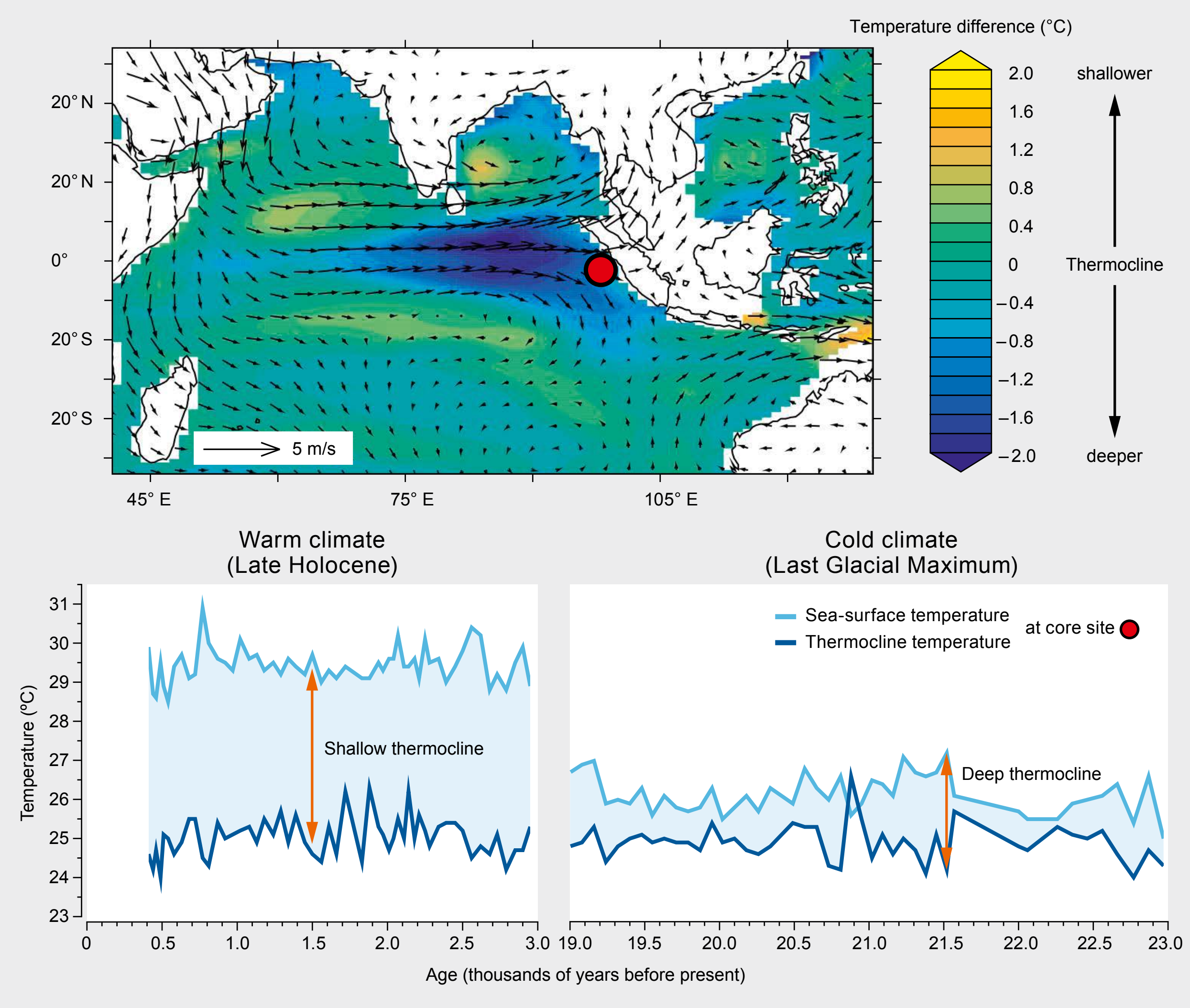


Figure 14 | Annual mean surface-wind and thermocline-depth anomalies at the Last Glacial Maximum (LGM) relative to today in the Indian Ocean as simulated by the fully-coupled climate model CCSM. As a measure for thermocline depth the ocean temperature difference between surface and 70 m is taken. During the LGM, westerly wind anomalies over the equatorial Indian Ocean associated with a strengthened Walker circulation induce a deepening of the tropical thermocline west of Sumatra. Modeled thermocline depths are confirmed by proxy-derived temperature gradients between surface- and thermocline-dwelling foraminifera (modified from Mohtadi et al., 2017).

major hurdle in obtaining a detailed understanding of how thresholds, feedbacks and processes of the climate system operate over different timescales and as a result of various forcing factors. This information is critical as Earth's climate is evolving toward boundary conditions last seen some millions of years ago.

An understanding of how Earth-system processes react to strong ***perturbations*** and which ***feedbacks*** are involved in restoring the system to a new post-perturbation state is critical for projections of future climatic conditions (Rothman, 2017). ***The impact of physical changes on ecological systems*** and the feedbacks these systems apply to climate parameters are largely unknown. It is particularly important to resolve the IPCC-relevant question of how a world with an average global temperature of at least 2 °C warmer than pre-industrial will operate, and how the global carbon cycle and ecosystem will respond. ***Perturbations*** of the Earth's climate system affect several key aspects of the Earth system (pCO$_2$ and methane release, surface and ocean temperature, hydrology, ice volume, sea-level history) and these can be investigated by exploiting marine sedimentary archives (Zachos et al., 2005). A crucial component in assessing the impact of physical perturbations on ecological systems is the determination of their intensity, duration and recovery (Ruppel and Kessler, 2017, Gutjahr et al., 2017). For example, although the processes at modern seep sites have been previously studied (e.g., Rossel et al., 2011), the history of methane input from cold seeps in relation to environmental controls is still poorly understood, and we will apply the unique expertise of the RECORDER team to resolve this important question (Davies et al., 2017).

The ocean floor, and in particular ocean sediments, have the potential to provide insights to ***feedbacks*** that exist between the physical components of the Earth system (e.g., atmosphere, ocean and ice) and the biota and their ecology (John et al., 2013). Ocean sediments also provide a powerful tool for evaluating long-term modifications of the interaction chain between feedbacks and external forcing factors (varying orbits, ocean alkalinity, biogeochemical fluxes, ocean circulation, sea level, ice-albedo feedback, and others), providing crucial information for long-term Earth-system sensitivity studies (Fig. 15). For example, the latest methods for reconstructing past ice-volume and sea-ice changes will be applied to material from Expedition 12 (see Table 3.4.16) to assess the interplay between ice-sheet melting and ice growth during warmer climate periods (de Vernal and Hillaire-Marcel, 2008). The coupled climate and ecological responses to temperature and carbon-cycle changes are mediated by feedbacks, including metabolic rates and weathering processes (John et al., 2013).

Global change and anthropogenic activities induce stress in ***marine ecosystems*** (Hönisch et al., 2012). In response, species and ecosystems move in space, or they adapt, or they perish (Hillebrand and Matthiessen, 2009, Yasahura et al., 2017). Changes in recent biotic composition and ecosystem functioning have previously been interpreted without the historical context of the dynamics of biodiversity fluctuations and changing environments. The dynamics of biological systems may exist on timescales beyond instrumental observations, but the lack of long-term observational records hampers the assessment of system sensitivity. Marine sedimentary archives provide a unique opportunity to obtain such long records, including information on the magnitude of ecosystem variability, trends, changes of biogeographic ranges, and the extinction and emergence of species. Compared to direct biological observations, the fossil record contains only a fraction of the information on the state of past ecosystems and their constituent species. The range of taxa covered by the fossil record can be extended by analyzing information-bearing biomarker molecules in the sediment (Willerslev et al., 2003, Orsi et al., 2017). Taxa that leave skeletal fossils facilitate the assessment of trait evolution and ecological function. Based on both established and newly developed approaches for extracting information on past biodiversity and ecosystem functioning, we will combine observational data with ecological and evolutionary theory in order to establish a historical baseline and conceptual framework for interpreting current ecosystem changes.

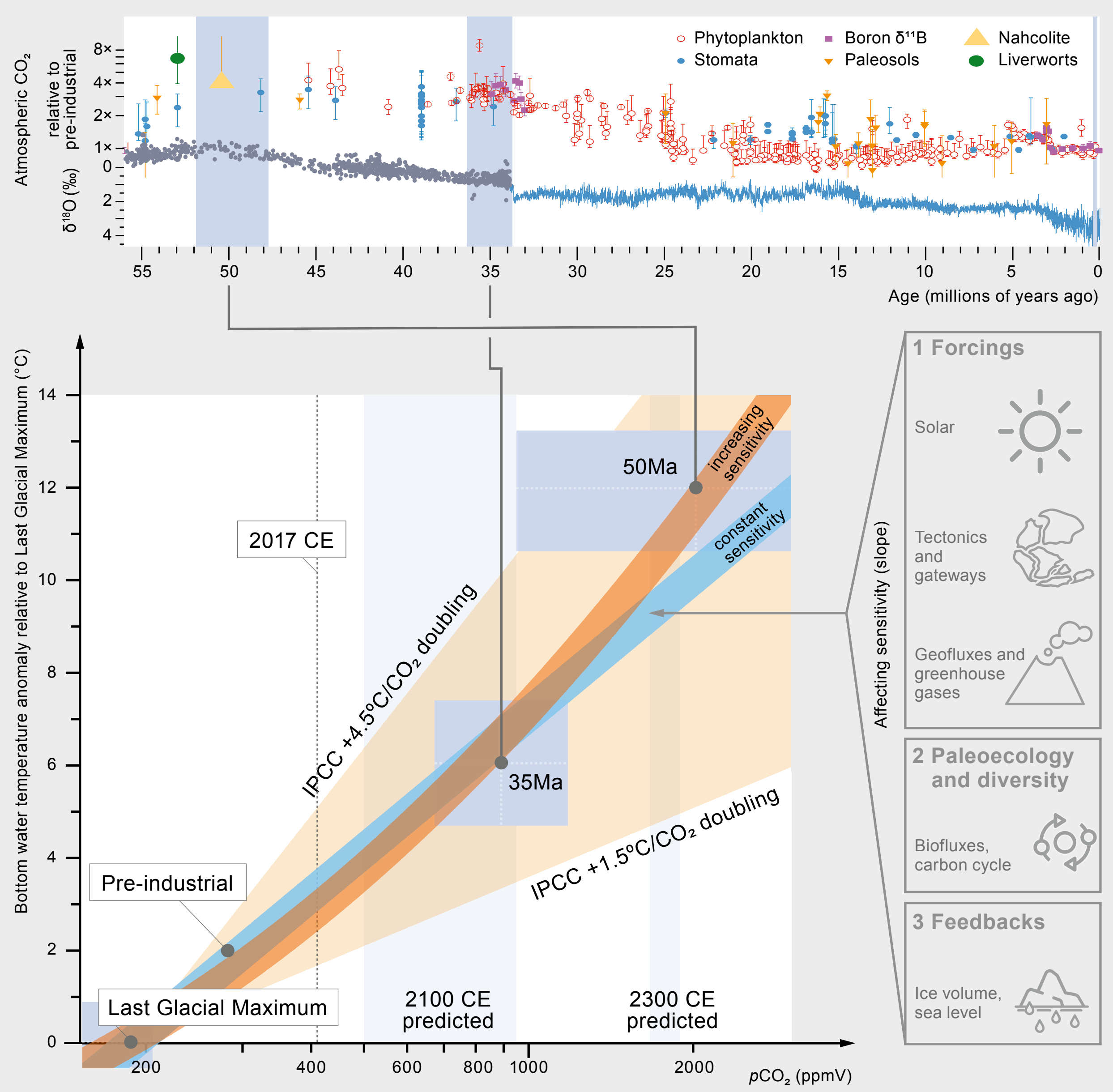


Figure 15 | Earth-system sensitivity describes the sensitivity of temperature response to changes in radiative forcing, amplified by long-term feedbacks depending on the timescale considered, and dependent on the initial climatic state (Hansen et al., 2013). Top panel shows example parameters involved in determination of Earth-system sensitivity (atmospheric CO_2 and stable oxygen isotope values representing deep-water temperature and ice volume. The slope of ΔT vs. ΔpCO_2 (lower panel) is an approximation of climate sensitivity, and a function of various forcings, biogeochemical processes and feedbacks (illustrated on right). The functional nature of the slope is currently poorly constrained. It could be constant (blue thick line labelled "constant sensitivity") or progressively increasing with higher CO_2 levels (thick orange line "increasing sensitivity"). Paleoproxies can be used to reconstruct past climate variables, and then allow a determination of time-dependent Earth-system sensitivity. Oxygen-isotope data from De Vleeschouwer et al., 2017; Zachos et al., 2008. CO_2 compilation modified from Beerling and Royer (2011).

Preliminary work

The RECORDER team has a strong expertise in deciphering records of changes in oceanic properties in order to understand the functioning of the Earth system and to detect perturbations and feedback processes. For example, data on the radiocarbon content of marine lipids acquired before (cf. Schefuß et al., 2016) indicate that the uptake of pre-aged carbon into marine algal classes is documented in ocean-floor archives. MARUM has long-term experience in the exploration of modern cold-seep systems, as well as in the investigation of stable carbon isotopes of benthic foraminifera (Lynch-Stieglitz et al., 2014) and specific lipids from chemosynthetic microbes (e.g., Rossel et al., 2011).

The MARGO Project Members (2009) provided a benchmark in global reconstructions of sea-surface conditions for the Last Glacial Maximum, for the evaluation of Earth-system models that are used for future climate projections. The notable prerequisites for new paleoceanographic insights and the proposed novel research approaches for the Paleogene (Littler et al., 2014) are astronomically-tuned age models. The RECORDER team has played a major role in providing such models over the course of more than two decades. The timing and extent of carbon-cycle responses after a massive carbon injection into the climate system have been unraveled by Zachos et al. (2005), with the first direct evidence for an over-deepening of the carbonate compensation depth in the North Atlantic deciphered by Penman et al. (2016). A modeling-based approach was developed by Gutjahr et al. (2017) to establish carbon-cycle perturbation amplitudes. A compilation of equatorial Pacific carbonate burial over long timescales has been collated by Pälike et al. (2012). A major contribution toward collecting crucial deep-sea sediment records from the Paleogene will be made as part of IODP Expedition 378, “South Pacific Paleogene Climate”, with RECORDER PI U. Röhl as Co-Chief Scientist in 2018. IODP Expedition 320 provided important material and data for addressing Earth-system sensitivity (PI H. Pälike, Co-Chief Scientist). A critical appraisal of the occurrence of widespread and diverse deep-water coral ecosystems opened new perspectives in the responses of benthic ecosystems to climatic perturbations (Roberts et al., 2006). In this respect, the human modifications of ecosystems worldwide were determined to be a cause of the global decline in biodiversity (Hillebrand and Matthiessen, 2009), which laid the foundations for future work on biodiversity effects on ecosystem function and the detection of human impacts on ecosystems.

Work program

The RECORDER mission is to investigate the unique informational archive provided by the ocean floor to develop an Earth-system perspective on climate, ocean and biological processes. Research within this unit will use the potential of sediment archives to provide important insights into the amplitude, nature and timing of high signal-to-noise events for boundary conditions not found in instrumental data, and will therefore exploit unique opportunities to study transient perturbations to Earth-system processes, internal and external feedbacks, as well as paleoecological and paleodiversity responses and their roles in mediating and/or coupling to non-biological processes. The key features of the work plan include a new focus on the interactions of the biosphere in Earth-system-relevant processes, and providing reconstructions and process understanding to underpin the RECEIVER and REACTOR Research Units. It will provide data for, and use modeling results from the Enabler MODELING and use new proxy developments from the Enabler TRACERS to understand Earth-system behavior, particularly for boundary conditions approaching an at least 2 °C warmer world.

Recorder Theme 1: Perturbations in the Earth system

M. Mohtadi, S. Mulitza, **U. Röhl**, E. Schefuß (project leaders), **D. Hebbeln**, **H. Pälike**, F. Lamy, T. Westerhold

Motivation – The marine carbon cycle is a key element in understanding the responses of the Earth system to external forcing and system-relevant perturbations, particularly during warmer (> 2 °C) climate conditions. Changes in the hydrological cycle or in ocean circulation affect various aspects of the Earth system that ultimately also influence the input, storage and distribution of carbon in the ocean on timescales that are beyond instrumental observations, but are relevant for future predictions. Particularly, the investigation of past large-scale changes in the climate system will provide clues to key mechanisms that cannot be understood from instrumental data alone. Marine archives provide records of natural Earth-system experiments that can be used to understand the mechanisms and the scale of dynamic responses of the marine system to external perturbations (Fig. 14). Identifying the key links between climate variability and the marine carbon cycle in a focused regional approach has great potential for advancing the understanding of the role of the ocean and its interfaces in acting on and responding to perturbations in the Earth system.

Approaches – We propose to exploit detailed large-amplitude events recorded in the sediment archive, such as the Paleocene-Eocene Thermal Maximum (PETM) perturbation of the carbon cycle, which greatly impacted ocean alkalinity and atmospheric CO_2, and their pronounced effects on the biosphere, in order **to study perturbations to the Earth system with a high signal-to-noise ratio, and to elucidate instrumentally uncharted boundary conditions only approximated by events in the geological record**. We will improve our understanding of the transition from greenhouse to icehouse worlds and of climate behavior during Earth's warmest Cenozoic periods by including these scenarios in Earth-system models of intermediate complexity within the Enabler Modeling. One of the unresolved aspects of these events is the extent to which their timing and rates of change can be assessed as relevant and informative to verify or assess predicted future changes, particularly as the modern ocean-floor CH_4 emission regime is potentially comparable to that during the PETM (Ruppel and Kessler, 2017). Specific research tasks include the question of the mechanistic differences in climate shifts between periods of ice-free, unipolar, and bipolar glaciated conditions. We will decipher the records and timing of large-amplitude events for Cenozoic climate variability: Do Cenozoic hyperthermal events have a common mechanistic cause, and what would be a predictive scaling of such events, particularly with respect to the interactions between physical and biological components of the Earth system? Can we establish a scaling ratio between physical perturbation and biological / ecological response? Initially, *we will test the hypothesis that mechanistic differences in climate-shift forcing for geological periods of ice-free, unipolar and bipolar glaciated boundary conditions are caused by underlying reconfigurations of the global carbon cycle.* This work will be in close collaboration with Recorder Theme 2 (Earth-system sensitivity, ice-ocean interactions during climate shifts), Theme 3 (ecosystem change), and will interlink with work in the Enabler Modeling.

Past changes in methane seepage at the ocean floor are recorded in the carbon isotopic compositions and the radiocarbon content of benthic foraminifera, and in the lipids produced by bacteria and archaea. We intend to use sediment cores from the upper continental slope off Mauritania (Davies et al., 2017) to reconstruct past changes in methane release and the associated changes in the marine environment. The comparison to cores from seepage areas will show when methane was released and will shed light on the mechanisms involved (i.e., state of Atlantic meridional overturning circulation, ocean temperature, sea level). Initially, *we will test the hypothesis that changes in methane seepage are primarily driven by changes in hydrostatic pressure associated with sea-level variations.* This work will provide a long-term geological view of methane seepage processes and thus complement REACTOR Theme 3. It will benefit from the Enabler TECHNOLOGY and, through provision of customized protocols for biomarker- and isotope-based detection of methane-related signatures, from the Enabler TRACERS.

An overall goal of the Cluster is to study different components of the global carbon cycle and their roles in Earth-system processes. A unique contribution of MARUM is the study of marine records of terrigenous organic-carbon sources. Large amounts of previously stored carbon can be released as a result of continental hydrological changes. While it has been inferred that the released carbon acts as a positive feedback for increasing atmospheric greenhouse-gas concentrations, carbon burial offshore of river mouths is regarded as a highly efficient and long-term carbon sink. Here, we will study the entrainment of pre-aged carbon into marine carbon cycling and its export into marine sedimentary archives. Following a combined approach using specific algal, bacterial and terrigenous lipids, as well as carbonate microfossils extracted from sedimentary archives, we will investigate the carbon uptake, remineralization and export in the water column during hydrological perturbations. Initially, *we will test the prediction that hydrological perturbations lead to increased burial of pre-aged terrigenous carbon combined with enhanced entrainment of old carbon into marine carbon cycling.* This work will link with RECEIVER Theme 1 and provide a longer-term perspective on these processes. Propitious methodological links exist with the Enabler TRACERS for jointly expanding the spectrum of informative terrigenous biomarkers. In the long run, the Marine Cheminformatics Node implemented by the Enabler TRACERS will improve our capability to examine and quantify regional patterns of terrigenous components in a 4D context.

Samples and methods (selection) – Work addressing climate in a high-CO_2 world will be conducted on samples related to RECORDER Theme 2 and share records with that theme. In addition, key records for the study of large-amplitude events are found in the Atlantic and high-latitude oceans, two regions that allow for interlinking studies among the various projects within RECORDER (MeBo, Expedition 13), as well as with topics in RECEIVER and REACTOR. To address past changes in methane seepage across the ocean-floor interface, we will use a combination of oxygen-isotope and scanning-XRF data to establish a timescale in seep-influenced sediment cores, as the use of radiocarbon as a dating tool is potentially limited in seepage areas due to the release of radiocarbondepleted carbon. New sampling will be conducted during Expedition 3 from the upper continental slope off Mauritania (Davies et al., 2017). We will reconstruct past changes in methane release and the associated changes in the marine environment (Hinrichs et al., 2003), and use nearby cores from similar water depths (but unaffected by methane seepage) to reconstruct the evolution of background climate. To study marine records of terrigenous organic-carbon sources, hydrogen- and oxygen-isotope analyses will be employed to characterize hydrological changes. Radiocarbon analyses will resolve the uptake and export of pre-aged carbon into marine sediments, while stable-carbon isotope analyses will allow the assessment of changes in carbon remineralization. We aim to quantify changes in pre-aged carbon fluxes related to hydrological perturbations.

RECORDER Theme 2: Feedbacks in the Earth system

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Motivation – The ocean floor, and ocean sediments in particular, are powerful recorders of the response and sensitivity of the Earth system to changes and perturbations, and they hold the potential to unravel feedbacks between various physical components of the Earth system (e.g., atmosphere, ocean and ice) and the biota and ecology as direct feedback components. (Fig. 15).

Ocean sediments allow proxy-based reconstructions of large-scale climatic processes, tying events to geological, geochemical and paleoecological responses. Ocean sediments also provide a powerful tool for evaluating modifications of the action chain between feedbacks and external forcing (varying orbits, ocean alkalinity, biogeochemical fluxes, ocean circulation, hydrology, sea level, ice-albedo feedback, and others). The coupled climate and ecological responses to change are mediated by these feedbacks, including metabolic rates and weathering processes. The feedbacks involved act on different timescales and can be best studied through a combination of Earth-system modeling and observations from periods of past change.

Approaches – We will conduct a systematic analysis of "***Earth-system sensitivity as a function of time and climatic state***" and address the question: "How do long-term feedbacks (primarily silicate and carbonate weathering), the carbon cycle and ecosystem changes affect the total interplay between greenhouse-gas release and removal and global temperatures?" This sensitivity acts beyond the traditionally studied equilibrium and steady-state but shorter-term Charney climate sensitivity. By using proxy-based reconstructions of the key parameters of the global carbon cycle (ocean alkalinity, ocean and atmospheric CO_2 and other greenhouse gases, global carbonate burial and diagenesis, temperature) we will gain a unique view of the transient nature of Earth-system sensitivity characterizing Cenozoic background states and boundary conditions.

All of these efforts will involve biogeochemical cycles and the endogenic carbon exchange, as well as new developments for including biological mediation of these cycles. This work will incorporate and combine new proxy developments, such as linked temperature reconstructions with existing temperature proxies (e.g., Mg/Ca and clumped isotopes), thereby reducing uncertainty. Initially, *we will test the hypothesis that Earth-system sensitivity varied during the Cenozoic and is greater during warmer climatic states*. Factors controlling Earth-system sensitivity may include atmospheric pCO_2, ice cover, sea level, and global mean temperature. This work will closely interact with the RECORDER Theme 1. and will benefit from novel Earth-system modeling capabilities to be applied in the Enabler MODELING, and will provide context for the research topic ice-ocean interactions:

Transitions from glacial to interglacial climate states are intrinsically tied to changes in sea-ice coverage, ice-sheet configurations and, consequentially, also sea level. We will use ***the ocean floor as a recorder of ice-ocean interactions during past climate shifts,*** and identify and link past ice-mediated Earth-system feedbacks recorded in ocean sediments. A key unresolved issue for the future of the Earth under sustained warming is the fate of the Greenland ice sheet in a warmer-than present world. Reconstructions of past ice-sheet behavior using time series from proximal records and regional sea-level fingerprints will help us to understand not only how much ice was melting, but also from where the ice originated. We will investigate periods of rapid sea-level rise within past interglacials, and extreme atmospheric events resulting from complex ocean-atmosphere feedbacks during periods of warmer climate. While changes in sea-ice coverage do not directly affect sea level, they are important for the (in)stability of the marine-terminating outlet glaciers of ice sheets. Sea ice in front of glacier termini may reduce the oceanic heat transfer and hence the calving and drift of icebergs. Further important ice-ocean feedbacks concern the impact of sea ice on the rate of deep-water formation driving thermohaline circulation processes and the exchange of heat and gas (CO_2). Identifying and linking past changes in sea ice with ice-sheet dynamics will provide valuable insights into high-low latitude climate coupling. Initially, *we will test the hypothesis that sea-ice variability is linked to ice-sheet (in)stability and sea-level changes, including feedbacks between sea ice and atmospheric/oceanic circulation.* This work will benefit from studies of past extreme events in RECORDER Theme 1.

Expanding this research on the physical manifestations of climate feedbacks, a unique contribution to the understanding of ***climate-ecosystem-biogeochemistry feedbacks*** between and within climatic processes, ecosystems, and biogeochemical processes can be achieved by combining traditional proxy-based reconstructions with new proxies to be developed in the RECEIVER for productivity and metabolic rates and the study of paleoecological signals. These would include, for example, high-resolution analyses of species composition and distribution, as well as other changes, in major marine organism groups (e.g., coccolithophores, foraminifers, diatoms, radiolarians) on long geological timescales (complementing research in RECEIVER, which focuses on instrumental timescales). We will constrain the geobiological feedbacks that affect the physical feedbacks, which ultimately control and regulate climate-relevant components such as greenhouse-gas concentrations, carbon burial, and diagenesis. We will develop new methods to pinpoint these biological interactions in long-term proxy records, and will make use of fossil molecular recorders of these components to obtain at least a semi-quantitative view as to how important these interactions were in the past.

Specific research tasks include: (i) improving our understanding of the interactions between ocean-crust processes and seawater chemistry with respect to the observed changes in seawater Mg / Ca concentrations over long timescales (these activities will establish a close link with Reactor Theme 1 and the Enabler Modeling); (ii) linking with Recorder Theme 3 in resolving whether higher global temperatures in the past led to quantifiable changes in metabolic rates and coupled remineralization of organic carbon (John et al., 2013); (iii) investigating what changes in biodiversity and major carbonate producers can be expected with global environmental change; (iv) unraveling which ecological and evolutionary changes lead to biodiversity patterns in time and space. Initially, *we will test the hypothesis that higher global temperatures in the past led to quantifiable changes in metabolic rates and the coupled remineralization of organic carbon.*

Samples and methods (selection) – Earth-system sensitivity will be studied by combining existing proxy measurements with refined temperature estimates (using new "clumped isotope" methodology). This work involves the use of key existing records (e.g., ODP / IODP Expeditions 138, 154, 162, 177B, 198, 199, 207, 208, 320, 321, 342), primarily obtained through ocean drilling, but will also include strategic development of new drilling operations (e.g., IODP Expedition 378 in 2018, Expedition 13 using the MeBo; see Table 3.4.16) and transects in critical regions and time slices, to finally allow a Cenozoic synthesis of key parameters from different major ocean basins and depths. These will be analyzed coherently and for the first time through the use of forward and inverse Earth-system models of various complexity, closely linking with the Enabler Modeling. The fate of the Greenland ice sheet under warmer global conditions will be addressed by Expedition 12 to the Baffin Bay.

Recorder Theme 3: Ocean floor as recorder of paleobiodiversity and paleoecosystem functions

A. Freiwald, **H. Hillebrand**, **M. Kučera**, **H. Westphal** (project leaders), L. Dupont, T. Felis, **D. Hebbeln**, L. Wörmer, **K. Zonneveld**

Motivation – Global change and anthropogenic activities induce stress in marine ecosystems. In response, species and ecosystems move in space, they adapt, or they perish, and the food chains in which they participate may be modified, thus altering carbon and element cycles. Analyses of these consequences have been dominated by short-term artificial experiments on timescales insufficient to cover evolutionary or spatial responses, so that observed changes in marine ecosystem composition and functioning are often interpreted without considering their historical context (Hillebrand and Matthiessen, 2009). Yet, natural dynamics and resilience of the network of constituent species superimpose a distinct but poorly understood imprint of historical legacy on observable ecosystem trends. The rates of response critically depend on adaptability – an evolutionary process acting at timescales that are not practicable for experimentation. Without a long-term perspective, responses of ecosystems to perturbations, and the functional consequences of the resulting turnover for marine food webs and element cycles cannot be properly assessed. The appropriate timescale for providing such long-term context is given by the geological record. Marine sedimentary archives provide long time series of environmental and ecological change, including information on the magnitude of ecosystem variability, trends, changes of biogeographic ranges, and the extinction and emergence of species. Despite its potential, this archive remains largely unexplored (Yasuhara et al., 2017). Compared to biological observations in modern ecosystems, the fossil record contains only a fraction of the information on the state of past ecosystems and their constituent species. The range of taxa covered by the fossil record can be expanded by analyzing information-bearing biomarker molecules in the sediment, while taxa that leave skeletal fossils allow the assessment of trait evolution and ecological function. Based on established and newly developed approaches for extracting information on past biodiversity and ecosystem functioning, **Theme 3 will combine data from the fossil record with ecological and evolutionary theory in order to establish a historical baseline and conceptual framework for interpreting current ecosystem changes and their functional consequences.** In doing so, it will contribute to the overarching goal of the Cluster to understand the responses of marine ecosystems and their Earth-system relevant functions to climate change.

Approaches – *We hypothesize that paleobiodiversity time series extracted from marine sediments will provide information on the structure of past communities and food webs, rates of productivity and decomposition, their natural variability, and their transformation during environmental perturbations.* These parameters are not accessible through the study of fossils alone. Traditional, fossil-based methods are limited in the efficiency by which their remains are transferred into the ocean-floor archive. By contrast, all organisms produce organic biomolecules that are embedded in marine sediments, preserving information on the identities and abundances of their producers. We propose to access the full paleobiodiversity archive in ocean-floor sediments by using molecular fossils, including organic biomarkers such as lipids or polysaccharides and ancient DNA (aDNA), to allow more complete estimates of diversity in entire ecosystems and to deliver information on diversity changes at evolutionarily relevant taxonomic resolution. Analogous with observations from lake sediments (Willerslev et al., 2003) and organic-rich marine layers (Orsi et al., 2017), we expect that a broad range of marine sediments covering the last glacial cycle contains a record of pelagic and benthic aDNA that can be decoded and linked with lipid and polysaccharide biomarkers, as well as with conventional fossils located in the same archive.

The ability of marine organisms to persist and retain their functions under increasing intensity of global change depends on their capacity to adapt. Therefore, understanding the rates and patterns of adaptation in individual species is essential to predicting the fate of marine ecosystems under global change. Although limited in the scope of available recorded information, *we* *hypothesize that changes in the traits of fossils recovered from marine sediments record information on the rates of adaptation at times of environmental change or stability, and that the study of local extinctions reveals limits of adaptability.* Observations of the patterns, rates and thresholds obtained from the fossil record will be contemplated with respect to the theoretical framework of trait evolution and incorporated into predictive models. The evolution of adaptations and the thresholds of change causing regional extinctions will be studied in the fossil record of marine plankton and benthos obtained from archives with co-registered information on abiotic and biotic change. These efforts will cover pelagic settings, continental slope cold-water coral ecosystems, and shelf carbonate factories. These archives allow simultaneous quantification of species success as measured by abundance and by changes in the functional traits of individual taxa, such as body size and biomineralization intensity. By comparing records of reactions to environmental transitions in different regional settings, we can detect the variability of sensitivities within species resulting from regional adaptations.

The sum of individual adaptations and adaptability of species determines the resilience of communities and ecosystems. Integrating observations of trait and abundance patterns in individual species with data on community turnover in response to perturbation will allow us to address the determinants of marine ecosystem change and stability. The concept of ecological stability is central to understanding ecosystem changes as responses to natural and anthropogenic perturbations (Donohue et al., 2016). Because of insufficient historical data, reconstructions of ecosystem variability are often oversimplified, and closely related aspects such as resistance, resilience, and recovery are studied separately from each other and separately from the composition of biotic communities and the functions these communities perform. *We predict that applying conceptual advances in understanding multidimensional stability on long time series obtained from marine sediment records will allow us to establish a new historical framework for stability and ecosystem change.* We will do so by determining the temporal dynamics of intrinsic compositional turnover, and analyze it in a modeling framework that includes adaptation, immigration and (regional) extinction. In the initial phase, we will develop the theoretical modeling framework, and later apply it to records of ecosystem change. We will compare rates of biodiversity turnover under stable and changing environmental conditions, explicitly questioning whether immigration and extinction events occur on different timescales and whether they are preceded by dominance shifts and changes in trait variance. Co-registered time series of proxies for ecosystem functions performed by different groups will be used to compare functional to compositional stability. Analyses of spatial grids of fossil records will allow us to understand how these temporal dynamics resonate with biogeography and macroevolution.

Samples and methods (selection) – Community turnover, adaptation and ecosystem function will be studied at sites with high sediment-deposition rates, which enable annual or shorter temporal resolution, and where contextual data are available for calibration from historical records of ecological and environmental changes. Key regions will be the Northwest African margin with a multidecadal sediment-trap record and associated process studies by the RECEIVER unit, and the Mediterranean, where marine sediment records with multiannual resolution can be linked to historical climate data, and where new molecular proxies will be developed by the Enabler TRACERS. Both regions allow simultaneous assessment of biotic responses in pelagic and benthic ecosystems, and across strong ecological gradients that experienced large changes during Quaternary climate shifts. New material from these regions will be obtained during Expeditions 3, 10, and 11. To extract information on past ecosystem compositions, together with the Excellence Chair E. Willerslev and the Enabler TRACERS, we will combine classical micropaleontology with organic molecular biomarkers and aDNA. In the initial project phase, we will ground-truth the combined approach and then apply it to late Quaternary sediments obtained during the above expeditions. Variations in fossil traits will be determined using computer-assisted image analysis and biometry. Organic-matter and carbonate production will be quantified as key carbon-cycle relevant functions.

Risks and opportunities in RECORDER

Earth-system processes are recorded in sedimentary archives, overcoming the temporal and spatial limitations of direct observations. The specific objectives of RECORDER will require access to sediment cores from specific water depths, locations and ages. Finding the best sites will be challenging, but this will be facilitated through a vast amount of existing site-survey data and core material from key areas like the continental slope off Northwest Africa. Further risks arise from the need to reconstruct key parameters from sediment archives of different ages within acceptable error limits. These risks are mitigated by new methodological opportunities and developments of proxies in close cooperation with RECEIVER and the Enabler TRACERS. New opportunities exist for temperature reconstructions based on clumped isotopes and improved Mg/Ca, TEX_{86} and alkenone techniques, and through access to exceptionally well-preserved cores from past or scheduled expeditions focusing on key intervals from the Cenozoic (including new archives sampled by the MeBo seafloor drilling system). Collectively, these new opportunities will greatly improve the availability and quality of data for constraining perturbations and feedbacks in the Earth system. Extracting data on ecosystem turnover and trait variability from the fossil record is a new field, in which a theoretical framework is needed that considers the timescale of the involved processes and the nature of the sedimentary record. We will meet this challenge by considering knowledge on ecological signal transfer to the sediment obtained in RECEIVER. The fidelity and accessibility of the marine aDNA archive, which we consider essential to constraining biotic responses to environmental change, has not yet been fully established. We will meet this challenge by benchmarking these results through the multi-decadal record of particle flux from the Mauritanian margin, by complementing aDNA studies with analyses of organic molecular biomarkers, and by combining analytical innovations in the Enabler TRACERS with the expertise of Excellence Chair E. Willerslev.

Joint expeditions

In addition to a large archive of sediment cores available through previous campaigns and stored in international repositories, the research of Recorder requires access to new records from as yet unsampled regions, and access to fresh material to apply novel proxies. Recorder will thus conduct research expeditions, largely through concerted research efforts at common sites jointly with Receiver and Reactor. To constrain key aspects of the warmer-worlds scenario theme of Recorder, Expedition 12 to the Baffin Bay will recover archives of the Greenland ice-sheet collapse during Marine Isotope Stage 11 (de Vernal and Hillaire-Marcel, 2008). Expedition 13 will provide exceptionally well-preserved records of a Miocene warm-world climate from the Rio Grande Rise, with more complete core recovery than prior DSDP attempts and allowing a much better constrained temperature determination required to address Earth-system sensitivity. The most dynamic part of the ice sheet discharged into the Baffin Bay, but no record exists covering the history of the collapse, its link with local oceanic conditions and sea-level history, or the associated changes to the local environment. Due to elevated clastic sedimentation during deglacials, the target sequence in the Baffin Bay is not retrievable through classical coring, and its recovery during Expedition 12 is contingent on the use of the MeBo drilling system. The expedition will also serve as a basis for preparing an IODP proposal for material, recording the state of Greenland and the Baffin Bay prior to the glaciation. Expedition 3 to the Northwest African margin will obtain records that allow the quantification of ecosystem turnover, adaptation rates and ecological thresholds and their functional relevance to perturbations. The cores will provide co-registered records of abiotic change and biotic response under different regimes of external forcing (e.g., climate and nutrients), allowing the combination of classical and new molecular (aDNA, biomarkers) and isotopic (cold-water coral skeleton) proxies. This expedition will be carried out jointly with the Receiver for particle-transport work in the Cape Blanc area. The unique capabilities of the MeBo drilling systems are required to recover high-resolution sedimentary sequences at high-accumulation sites, and records encompassing the life span of a cold-water coral ecosystem. Expedition 4 to the mid-Atlantic ridge will be carried out jointly with Reactor, combining remote (geophysical) and *in-situ* methods to locate and sample potential natural "sediment traps" with records suitable for constraining temporal variability of element fluxes related to hydrothermal and volcanic activity. Expeditions 10 and 11 to the Mediterranean will serve to provide material to constrain the history of venting at seep sites, to test the recovery of lipid biomarker and aDNA signals from marine sediments, and to obtain records of ecosystem variability under terminal stress (leading to local extinctions).

Internal and external collaborations

The Recorder team is nationally and internationally closely networked by active participation in ocean drilling programs and their research initiatives. The team will continue to lead and support IODP drilling proposals and site surveys linked to its research themes. Besides benefitting from access to international seagoing platforms, our network of collaborators will facilitate access to core material from the repositories of partner institutes, such as the NIOZ, and enable the collection of new material by participation in cruises of opportunity. RECORDER will contribute to the aims of international Future Earth projects (e.g., PAGES and the Global Carbon Project) to constrain the carbon fluxes and Earth-system processes of warmer climates. Active participation of RECORDER in PAGES is mirrored by high-level involvement in international initiatives coordinating Earth-system modeling efforts and data-model comparisons (e.g., PMIP, DeepMIP).

RECORDER activities involving the cryosphere are the result of joint activities in the AWI-MARUM Alliance (AMAR) and build on intense ongoing collaboration with Canadian colleagues within the joint DFG-funded International Research Training Group ArcTrain (Processes and impacts of climate change in the North Atlantic Ocean and the Canadian Arctic). RECORDER collaborates in a project funded through the Helmholtz Association in the Excellence Network "The Polar System and its Effects on the Ocean Floor", which involves young investigator group leaders (J. Müller and A. Rovere) and additional AWI experts focused on the interaction and feedback mechanisms between Antarctic ice-sheet dynamics, changes in sea level, ocean temperature and sea ice. SGN, ZMT and the University of Bremen have a long history of joint research on cold-water coral ecosystems and warm-water carbonate factories, carried out in bilateral projects and large consortia with funding from the European Union.

The analysis of community dynamics and stability will strongly profit from interactions with the newly founded Helmholtz-Institute for Functional Marine Biodiversity at the University Oldenburg (HIFMB). Combining existing expertise from the University of Oldenburg and AWI with the recruiting of four new professorships, HIFMB aims at understanding the drivers and consequences of biodiversity change across various marine ecosystem types. HIFMB will develop data-analysis tools (e.g., for compositional turnover) and models for biodiversity scenarios, which, in the context of RECORDER, will be adapted to the analysis of long time series. Warmer-world scenarios and understanding the responses of element cycles to perturbations provide the framework connecting RECORDER with other Research Units. Collaboration with the REACTOR unit and the Enabler MODELING will provide constraints of temporal geoflux variability. This work will be coupled through a modeling framework to explore scenarios of long-term variability in global seawater composition and biogeochemical cycling. Collaboration with RECEIVER will lead to an improved ability to decipher proxy information in geological records, and will enhance our ability to reconstruct key aspects of the biological pump.

Links to new professorship and U Bremen Excellence Chairs

By focusing on ocean-floor dynamics and fluid fluxes in settings ranging from rifts and ridges to collision zones, a new professorship in ocean-floor geology will contribute to our research on long-term variability of geofluxes. Excellence Chair E. Willerslev (University of Copenhagen) has pioneered the analysis of ancient DNA from environmental archives. He heads a world-leading facility for geo-genetics and the RECORDER will benefit from his expertise in aDNA extraction and identification. Excellence Chair J. Middelburg (University of Utrecht) is a world leader in marine biogeochemistry; the RECORDER research unit will benefit from his expertise in analyzing organic matter in marine sediments as a record of production and degradation.

Use of existing (or planned) research and information infrastructures

The Enabler TECHNOLOGY is crucial to providing access to records from burial depths inaccessible to classical coring, specifically by the unique drilling range of MARUM MeBo200. New opportunities will arise from work in the Enabler TECHNOLOGY to enhance MeBo capabilities with additional downhole-logging-tool development (XRF-based density probe and ultrasonic caliper tool). Links with RECEIVER provide an understanding of signal formation of environmental and ecosystem changes, and their modification before being embedded in the sedimentary record. Cooperation with REACTOR facilitates study of the role of crust-seawater interactions in driving biogeochemical cycles, deep-sea ecosystems, and climate evolution on long timescales. The Enabler MODELING will quantify the impact of physical forcing on biogeochemical cycles and paleoecosystems at a range of spatial and temporal scales. Key methods of the Enabler TRACERS will be applied, such as novel paleo-thermometers, ultra-high-resolution molecular-level analysis, and the reconstruction of changes in marine paleoecology and -diversity based on taxon-specific information, such as ancient DNA analysis. The Marine Cheminformatics Node (Enabler TRACERS) and PANGAEA (see Section 4.3) will provide unprecedented opportunities for hypothesis-driven queries of the massive molecular datasets of compounds informing us on past climate, biota and environmental configurations. PANGAEA is an established framework for storing research data related to paleoceanographic and paleoclimatological data. Proxy data (including high-resolution XRF, computer tomography and color-scanning data) generated within RECORDER will be integrated into PANGAEA in a way that allows new cross-disciplinary analyses. This will be achieved by developing new scientific workflow systems that query partially processed and raw data, for example by tapping into PANGAEA content from the "R" scientific analysis package. This approach will contribute toward more easily reproducible scientific data analysis and extraction, and expand data portals like PANGAEA from a passive storage role to an active component of interactive data analysis, thus providing a new research tool.

Table 3.4.8: Proposed Staff in Research Unit RECORDER

	2019	2020	2021	2022	2023	2024	2025
Staff category	**Number of persons**						
Professors	-/-	-/-	-/-	-/-	-/-	-/-	-/-
Independent junior research group leaders	-/-	-/-	-/-	-/-	-/-	-/-	-/-
Postdoctoral researchers	3	6	7	7	7	6	6
Doctoral researchers	4	6	8	8	8	8	5
Other Staff	-/-	-/-	-/-	-/-	-/-	-/-	-/-

Table 3.4.9: Funding Request for Research Unit RECORDER

	2019	2020	2021	2022	2023	2024	2025
Funding category	**Totals per year in k€**						
Staff (Total 3.4.3)	393	716	917	944	973	918	787
Direct project costs (excl. staff)	100	190	220	210	195	160	135
Total instrumentation <€150,000	100	0	0	0	0	0	0
Instrumentation >€150,000	0	0	0	0	0	0	0

Justification: Direct costs include consumables, travel costs, and student helpers as well as project-specific expenses for the expeditions listed in Section 3.4.7. Instrumentation costs are for a preparative gas chromatograph for compound-specific natural abundance radiocarbon (^{14}C) analyses (RECORDER Theme 1).

3.4.4 Enabler DEEP-SEA TECHNOLOGY AND OCEAN-FLOOR OBSERVING SYSTEMS (TECHNOLOGY)

Project leaders: R. Bachmayer, **A. Boetius**, **G. Bohrmann**, T. Freudenthal, A. Kopf

Other involved researchers: W. Bach, **N. Dubilier**, M. Elvert, **M. Iversen**, F. Maurelli, G. Meinecke, N. Nowald, **H. Pälike**, T. Pape, V. Ratmeyer, C. Waldmann, M. Zabel

Excellence Chair: V. Orphan

The comprehensive and continuous exploration of the deep ocean and ocean floor requires smart, innovative solutions for observation and sampling techniques and monitoring devices under extreme environmental conditions, including robotics, new sensors and advanced digital solutions. This Enabler strives to improve MARUM's existing technology and develop new technologies and instrumentation tailored to the Cluster's ambitious scientific goals.

Contributions to the overall objectives of the Cluster of Excellence

The objectives described in Research Units RECEIVER, REACTOR and RECORDER are closely linked to innovative developments in the existing fleet of seagoing systems working in the water column, at the sediment-water interface, and within the ocean floor (Box 2 and Fig. 16). Science-driven improvements and new developments in marine robotic systems, particularly in their payloads,

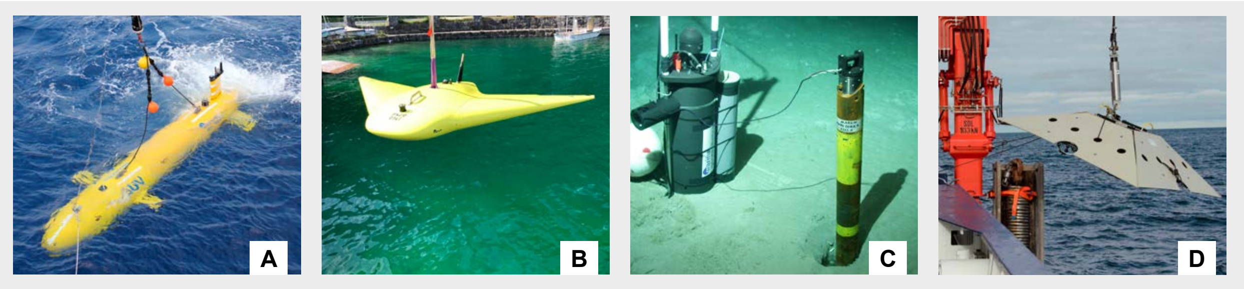

Figure 16 | Examples of underwater equipment that will be deployed within the framework of the Cluster: A) AUV SEAL 5000, B) Deep-sea glider MAPPA, C) MeBo CORK (Circulation Obviation Retrofit Kit) for long-term subseafloor hydrogeological observations, D) gas-bubble meter mooring.

focus on (i) systems to measure and sample particles throughout the water column (most important in RECEIVER), (ii) enhancement of MeBo seafloor drill-rig capabilities (main focus in RECEIVER and REACTOR), (iii) remotely operated vehicle (ROV) real-time 3D environmental mapping (main focus in RECEIVER and REACTOR), and (iv) implementation of *in-situ* mass spectrometry (REACTOR, jointly with Enabler TRACERS). These developments encompass significant key technological advancements to achieve the overarching objectives of the Cluster. The close interaction between ocean-floor research and the development and use of sophisticated technology will provide an excellent environment for training a new generation of marine scientists.

Current state of development (own publications underlined)

The control of ROVs has evolved from direct pilot-issued propulsion commands to increasingly sophisticated closed-loop control systems that allow the ROV to automatically hold an operator-defined position and attitude, and in some cases to follow a pre-described path above the seabed. Through a combination of increasingly sophisticated robotic manipulators, substantial advances in available subsea communication bandwidth, and a growing number of dedicated sensors, we will obtain unprecedented access to real-time data from the ocean floor. One such sensor is the *in-situ* mass spectrometer that enabled scientists to unravel key chemical processes such as methane turnover (Wankel et al., 2012) and to identify hydrogen as a powerful energy source for hydrothermal vent symbioses (Petersen et al., 2011). Also, developments such as advanced haptic user interfaces for manipulators and graphical user interfaces for sensor visualization have advanced ROV capabilities (Ratmeyer and Rigaud, 2009).

Parallel to the development of ROVs, the role of operational autonomous underwater vehicles (AUVs; Fig. 16), including underwater gliders (Fig. 16), has significantly increased in our research over the past decade. Our AUV was initially used for seabed mapping and imaging tasks, but with the availability of more sophisticated, compact and low-power sensors, more complex, multi-modal *in-situ* environmental measurements have emerged as an additional field of application.

Seafloor robotic drills bridge the gap between conventional seabed sampling techniques carried out from multi-purpose research vessels (like gravity coring or dredging) and dedicated drilling vessels. As a consequence of the increasing demand for cored material in the range of 10 – 200 m below the ocean floor for paleoclimate studies, geotechnical site investigation, and mineral exploration, MARUM has developed two seafloor robotic drill rigs within the past decade (Freudenthal and Wefer, 2013). These systems are complemented by logging tools and borehole observatories, opening the way for producing time series of ocean-floor dynamics.

For proprietary instruments and sensors serving in observatory networks, standards have been defined by large international networks in which we participate (e.g., OOI, ONC, EMSO), and have been recently refined at the European FP7 Project COOPEUS, coordinated at MARUM. Concepts accompanying this approach are based on Open Geospatial Consortium (OGC) Sensor Web Enablement (SWE). We can now include sensor registries, domain-specific semantics, long-term archive and alert capability (see details in O'Connor et al., 2005; Botts et al., 2008), which we are presently refining for both scientific application (e.g., in real-time observing networks) and long-term potential for industry use (e.g., ocean-floor surveys).

Preliminary work

Through recent decades, MARUM and its partners have been at the forefront in the development and operation of marine robotic systems (MeBo seafloor drill rig, ROV, AUV, lander, and crawler), helping to answer key scientific questions (see Box 2 "Underwater Technology and International Core Repository" and Fig. 16). The Cluster will take the next step to enhance our leading role in the direct application of innovative, emerging technologies by helping to answer key scientific questions raised in this proposal and beyond. Our fleet of existing instruments includes two ROVs deployable to water depths of up to 4,000 m and two AUVs (1,500 m / 5,000 m) with capabilities for seabed mapping, sampling, and installation of observation systems. Special tools have been developed, e.g., for autonomous detection and sampling of gas emissions. Furthermore, we have two portable robotic seafloor drills, which can drill and sample soft sediments and hard rocks to depths of 70 m and 200 m into the ocean floor (MeBo70/200, Freudenthal and Wefer, 2013), an unmanned crawler (C-Move), as well as an underwater glider (Mappa), and a Liquid Robotics Wave Glider "SV3". These unmanned systems enable the acquisition of time-series data such as particle-size distributions and sinking velocities via ROV camera systems (Karakas et al., 2009), and are used for mass-budget estimates (e.g., Fischer et al., 2016). With the seafloor drills, a suite of borehole observatories (Fig. 16) has been successfully deployed in Arctic gas-hydrate fields, subduction-zone mud volcanoes, and landslides (Kopf et al., 2015). Specific autoclave tools were developed for a piston corer or the MeBo drill rig to sample sediments and gases under *in-situ* pressure for sophisticated shore-based analyses.

The combination of low-power sensors, substantial increases of on-board computational power and the development of new and robust control algorithms are leading to an increased level of autonomy for AUVs (Bachmayer and Claus, 2012). These approaches can be used to direct AUVs to follow and map highly unknown underwater terrains (e.g., hydrothermal vent sites) or icebergs (Zhou et al., 2016), or to track and map ocean features with high temporal and spatial variability such as buoyant plumes.

Work program: approaches and methods

The following science-driven tasks in the Enabler Technology go well beyond the state-of-the-art instrumentation and thus call for cross-cutting activities that ties together the operations in Receiver, Reactor and Recorder (see also Fig. 17). This Enabler will design and develop deep-sea equipment that is more robust, energy-efficient and versatile, and that facilitates budgeting fluxes across the ocean-floor interface and within the ocean floor. The individual tasks will be divided into Phase I (Year 1 – 3) and Phase II (Year 4 – 7):

Task 1. Particle sampling and tracking. Daily particle abundances, sizes and settling velocities will be acquired using a camera system installed in the Bio-Optical Platform (Receiver Theme 1). In addition, this platform will simultaneously collect individual particles in a specialized, rotating sampling device with gel-filled cups to estimate particle fluxes during a mooring period of one year (Phase I). An improved vertical-profiling camera system will be developed to acquire the majority of the marine particle-size spectrum down to ≥25 µm via adaptive optics and freely selectable sample volume (Phase II). We will further develop a miniaturized particle camera and particle sampler (Receiver Theme 1) to be integrated into an underwater glider, such as the Mappa (Fig. 16). The ability of underwater gliders to act on the one hand as neutrally buoyant drifting platforms while also being capable of moving horizontally and vertically makes them attractive for conducting higher-resolution sampling campaigns of limited duration.

Task 2. Upgrade of seafloor drilling devices and borehole observatories. Key avenues in this Task aim to advance the capabilities of the MeBo systems and to design and produce modular observing systems and other long-term equipment to serve the scientific needs of the three Research Units. In Phase I we will enhance MeBo capabilities for *in-situ* measurements

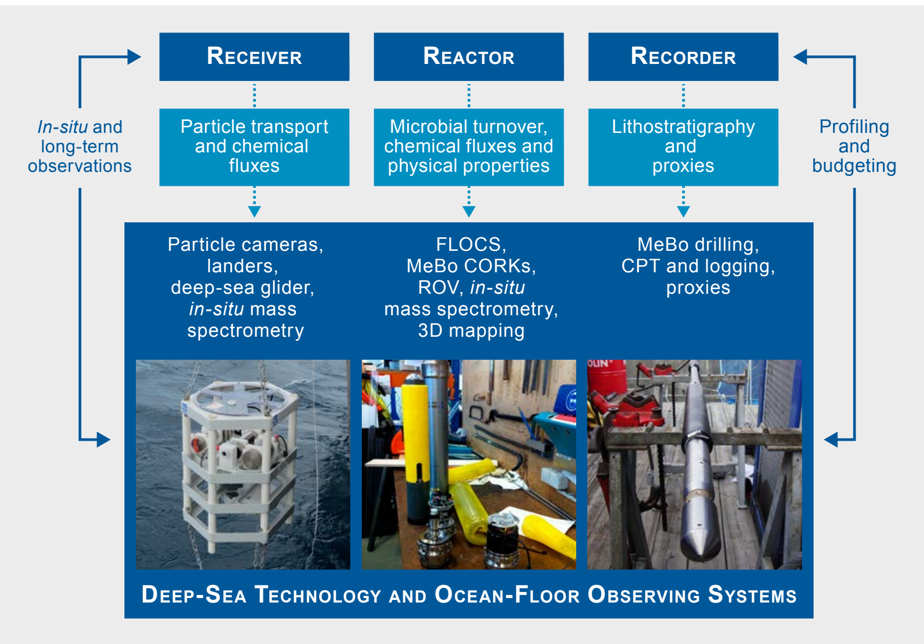

Figure 17 | Flow chart illustrating links between technological advancements and the Cluster's objectives and activities. Photos show prototypes of the equipment to be refined in the Cluster (left to right: Bio-Optical Platform, pop-up observatory, MeBo logging probe).

through adaptation of additional downhole-logging tools (X-Ray fluorescence based density probe and ultrasonic caliper tool), and a CPT (cone penetration testing) device to measure *in-situ* physical properties (see REACTOR Theme 3, RECORDER Theme 1).

In Phase II, smart sensors and low-power intelligent loggers for mission-specific high-resolution long-term observations of physical and chemical processes in the oceans and on the ocean floor will be developed to enhance the duration of *in-situ* observations. A special focus is on standardized protocols, web-enabled control and compatibility with various platforms and existing international networks (e.g., OOI, ONC, EMSO). Miniaturized *in-situ* FLOCS cultivation experiments in MeBo boreholes will be used to quantify microbial turnover in different geological settings (see REACTOR Theme 1).

Task 3. Improvement of AUV / ROV-based navigation and mapping. In Phase I, we will develop and implement ROV-based 3D environmental seabed mapping with stereoscopic high-resolution video cameras and state-of-the-art-image processing algorithms. The goal is to provide an innovative tool to enhance existing photographic 2D area mapping with structural 3D information and the ability to generate high-resolution, textured seabed micro-bathymetry models in near real-time (see REACTOR Themes 1 and 3, RECORDER Theme 3). The innovative near-real-time functionality also applies to the operational telepresence. We co-lead a national agenda for improved telepresence at sea, to aid in the direct communication of expedition activities to scientific partners and to the public.

In Phase II, we will implement reactive mission handling and path planning for the AUV, whereby the vehicle will self-direct its path according to current measurements of chemical, biological or physical environmental parameters according to measurement metrics, i.e., gradient-following, that are pre-specified and driven by specific scientific objectives (REACTOR Themes 1 and 3, RECORDER Theme 3).

Task 4. Integration of an ROV grade in-situ mass spectrometer. For Phase I, we plan the acquisition and implementation of a versatile *in-situ* mass-spectrometer (MS) platform suitable for ROV deployments. An *in-situ* MS will provide real-time information, providing immediate guidance for water / sediment sampling during field campaigns. This will enable the identification of small-scale biogeochemical gradients, fluid flow, and may provide information about microbial activity of seep and vent communities. The *in-situ* MS will enable high-resolution spatial and temporal concentration analysis for specific gases (e.g., H_2, CH_4, CO_2, O_2, He) in the water column and at seeps and vents. Determination of dissolved gases has a strong relevance to climate change in terms of identifying hotspots influenced by far-field effects near seeps and vents and sites of gas escape to the upper water column and eventually the atmosphere (see REACTOR Themes 1 and 3). In Phase II, long-term operation at defined sites and implementation of the carbon isotope measurement of critical CH_4 and CO_2 is planned with the help of industrial partners (e.g., Thermo Scientific Bremen) and scientific colleagues actively working on this development (S. Wankel, WHOI; R. Grilli, University of Grenoble).

Project development

Initially, we will (i) build a new multi-collector sampler and optical systems for particle-flux studies; (ii) develop new downhole-logging equipment for the MeBo systems, the main challenge being the reduction in diameter and length of existing equipment to fit the MeBo geometry; (iii) improve our understanding of highly dynamic sites such as vents and seeps by visual 3D reconstruction and textural mapping of small- to medium-scale ocean-floor structures, whereby camera and telemetry technology will be developed at MARUM while visual reconstruction algorithms and stitching / mapping software will be developed in close cooperation with Fraunhofer FOKUS, Berlin; and (iv) acquire and test *in-situ* laser-based isotope measurements in the water column and at seep / vent environments in cooperation with the Enabler TRACERS and other scientists, the challenge being the adaption of the instrument for long-term operation in the deep ocean. For 2020 and 2023 the Enabler TECHNOLOGY team plans short cruises in the northern Atlantic (Expedition 14, Table 3.4.16) for the purpose of providing dedicated field-testing time for crucial technology developments, such as underwater docking and communications, sampling, and data logging, etc. In parallel, specific technologies will be tested during cruises of opportunity with our research partners (e.g., Ifremer La Seyne in the Mediterranean Sea). The Enabler TECHNOLOGY is further involved in most of the expeditions in the Cluster. We exemplarily emphasize Expeditions 5 and 10, during which refinements of path-planning and mission-control features will be tested with the AUV SEAL, in order to study topographically challenging terrains such as mid-ocean ridges and mud volcanoes. In collaboration with the REACTOR, Expedition 6 will use the MeBo system to emplace borehole observatories and FLOCS units, and Expedition 7 will use the ROV SQUID to subsequently recover them and to deploy the new *in-situ* mass spectrometer.

Developments in this cross-cutting enabler will significantly benefit from two new working groups "Marine Environmental Technology / Deep-Sea Engineering" (University of Bremen, R. Bachmayer) and "Marine Systems / Marine Robotics" (Jacobs University, F. Maurelli), both established in 2017, as well as from collaboration with the polar-ocean technology hosted by AWI (e.g. FRAM observatory with under ice, deep-water AUV, lander and crawler technologies).

Risks and opportunities in TECHNOLOGY

The development of new instruments for application in the deep sea is always a venture into uncharted technological terrain and hence bears high risks, including uncertain project costs and the dedication of external project partners. The operation of an *in-situ* mass spectrometer at depth entails risks related to the technological challenges of its deployment, which demand experience in calibration and stability in membrane function, the latter enabling the unbiased transfer of gas species from the water into the gas phase at high pressure. Similar risks exists regarding the *in-situ* downhole-logging tools and the proposed sensors (density probe and ultrasonic caliper tool), which have a different status of maturity and complexity. A pilot study, with careful evaluation of the sensor-specific technical adaption and development challenges, will lower the risk for subsequent applications in research. Moorings always include the risk of long-term deployment stability, battery lifetime, and corrosion stability. However, with our long experience we are well prepared to tackle these issues. Real-time processing of the large datasets within the Cluster demands special data-processing skills and suitable mechanisms for data management, which are provided by the experts at PANGAEA (see Section 4.3) to make those available. For real-time image processing and structural reconstruction of ROV data, we have established a close collaboration with the world-leading research group at Fraunhofer FOKUS.

Internal and external collaborations

In the field of robotics and enhanced autonomy in the deep sea, we collaborate with J. Opderbecke (Ifremer), I. Haulsen (Fraunhofer FOKUS), R. Garcia (University of Girona), J. Brito (PLOCAN), G. Dudek (NSERC Field Robotics Network / McGill), A. Bowen (WHOI), and D. Kelley (OOI Regional Scale Nodes, University of Washington). For *in-situ* mass-spectrometer development, we team up with P. Girguis (Harvard), S. Wankel (WHOI), R. Kipfer (ETH Zurich), and R. Grilli (University of Grenoble). In observatory science, we collaborate with I. Simonis (iGSI, Emden), B. Orcutt (Bigelow Laboratories), M. Motz (develogic Hamburg), R. Lampitt (NOC), and D. Wallace (Ocean Frontier Inst. / Dalhousie). For MeBo downhole logging, we have strong ties to F. Bauer (ANTARES), U. Harms (GFZ), and V. Berhorst (Geomil).

The majority of these collaborators, augmented by colleagues from their companies and institutions, will participate in bi-annual knowledge-transfer workshops planned within the Cluster (see Section 5.3). When appropriate, we also envision residencies of our PhD students at companies and institutions as part of the graduate training program.

Links to international programs

ECORD, IODP: MARUM provides MeBo and other facilities to ECORD and has key researchers contributing as proponents, chief scientists, panel members and scientists. EMSO, ONC / OOI, GOOS, EuroGOOS, AtlantOS: MARUM actively participates into observatory science worldwide and particularly on the European level.

Table 3.4.10: Proposed Staff in Enabler TECHNOLOGY

	2019	2020	2021	2022	2023	2024	2025
Staff category	**Number of persons**						
Professors	-/-	-/-	-/-	-/-	-/-	-/-	-/-
Independent junior research group leaders	-/-	-/-	-/-	-/-	-/-	-/-	-/-
Postdoctoral researchers	-/-	-/-	-/-	-/-	-/-	-/-	-/-
Doctoral researchers	-/-	-/-	-/-	-/-	-/-	-/-	-/-
Other staff	5	5	3	3	3	3	3

Table 3.4.11: Funding Request for Research Enabler TECHNOLOGY

	2019	2020	2021	2022	2023	2024	2025
Funding category	**Totals per year in k€**						
Staff (Total 3.4.4)	315	324	229	236	243	250	258
Direct project costs (excl. staff)	90	90	90	90	90	90	90
Total instrumentation <€150,000	400	150	0	100	0	100	0
Instrumentation >€150,000	0	0	0	0	0	0	0

Justification: Planned staff consists of engineers only. Two additional positions are included during the first two years to boost technological developments of logging tools and multi-sampler for particle-flux studies, and to get refined observing systems underway for use in the Cluster. Direct project costs include consumables to develop and build observatories or their components in MARUM's in-house workshops and laboratories and travel costs to project partners as well as project-specific expenses for the expeditions listed in Section 3.4.7. Key instrumentation to be purchased includes 4 MeBo borehole observatories (40 k€ each in 2019), two MeBo logging tools (density probe and ultrasonic caliper tools, 90 k€ each in 2019), multi-sampler (60 k€ in 2019), *in-situ* mass spectrometer including integration into ROV (100 k€ in 2020), and modular ocean-floor lander (50 k€ in 2020). Further investments include equipment for 3D mapping (100 k€ in 2022) and for reacting to technological developments (e.g., smart sensing) in logging tools and observatories (100 k€ in 2024).

3.4.5 Enabler MOLECULAR AND ISOTOPIC TRACERS (TRACERS)

Project leaders: V. Heuer, **K.-U. Hinrichs**, J. Lipp, **G. Mollenhauer**

Other involved researchers: T. Dittmar, M. Elvert, **M. Friedrich**, C. Hallmann, **J.-H. Hehemann**, S. Kasemann, **M. Kučera**, **M. Kuypers**, M. Liebeke, J. Müller, E. Schefuß, F. Schubotz, G. Wegener, L. Wörmer

Excellence Chairs: J. Middelburg, V. Orphan, E. Willerslev

Molecules and isotopes encode enormous amounts of untapped information. The Enabler MOLECULAR AND ISOTOPIC TRACERS (in short, Enabler TRACERS) will advance the Cluster's capabilities for decoding information on important biological, geochemical and paleoenvironmental processes by ultra-sensitive chemical analyses of diverse marine samples, and implement a Marine Cheminformatics Node enabling 3D-visualization and exploration of data.

Contribution to the overall objectives of the Cluster of Excellence

The Cluster's future research on marine ecosystems, climate change, paleoenvironments, and global budgets of carbon and other elements relies on molecular and isotopic tracers in seawater and the ocean floor as central sources of information. Organic molecules and the isotopic compositions of organic and inorganic matter carry information about biological, chemical, physical and geological processes in the ocean. Despite the decades-long history of molecular and isotopic approaches in geosciences, there remains a vast reservoir of information waiting to be decoded. The Enabler TRACERS aims to advance the Cluster's capabilities for deciphering this information. To this end, it will interlink a unique array of state-of-the-art analytical technologies already in operation at MARUM and its partner institutes, implement a Marine Cheminformatics Node enabling 3D visualization and exploration of large datasets, and further advance *in-situ* measurements using instrumentation on remotely operated vehicles (ROVs). Molecular and isotopic approaches will be crucial for achieving the first four of the Cluster's six overarching objectives (Section 2).

Current state of research (own publications underlined)

The Enabler TRACERS seeks to advance principal methodological strategies aimed at solving major problems related to the global carbon cycle, the forces shaping past environments and ecosystems, and microbial life in extreme marine environments. The initiative will build on the international leadership that MARUM and its partners have established in the analysis of a wide range of informative organic molecules and isotopic compositions of organic and inorganic matter in sediments, rocks, marine particles, calcareous fossils, seawater, gases, microbial cells and the tissues of marine animals (see Box 3: "Analytical Facilities"). Molecular and isotopic techniques, partly developed in the laboratories of the PIs of the Enabler TRACERS and the Cluster in general, have been instrumental in discoveries that contribute to the foundation for this Cluster proposal (e.g., Dittmar and Paeng, 2009; Hehemann et al., 2010; Inagaki et al., 2015; Lipp et al., 2008; Müller et al., 2011; Pape et al., 2010; Petersen et al., 2011; Sander and Koschinsky, 2011; Wegener et al., 2008). This initiative will take advantage of our most recent analytical developments, and will enable major progress in (i) building a mechanistic understanding of the cycling of marine and sedimentary organic matter, (ii) quantifying the activity and carbon metabolism of microbial communities inhabiting extreme marine settings such as vents, seeps and the deep biosphere, (iii) extracting information on past marine ecosystems and environments at unprecedented temporal and taxonomic resolution, (iv) ground truthing and implementing ROV-based chemical sensors for detecting trace constituents in ocean floor settings, and (v) building interfaces enabling the resident scientific community to computationally query large molecular-chemical datasets generated during the Cluster's research.

Preliminary work

MARUM and its partner institutions are home to several research groups that extract critical information on biogeochemical and paleoenvironmental processes from organic molecules and the isotopic compositions of organic and inorganic matter (Box 3). These groups jointly host a combination of state-of-the-art analytical equipment that is extremely rare in the marine biogeosciences. Our current "flagship" technologies include a recently installed small accelerator mass spectrometer for the micro-scale analysis of natural abundance levels of radiocarbon (AWI, PI G. Mollenhauer), enabling the high-throughput dating of organic compounds isolated from water-column and sediment samples and with the potential to revolutionize our understanding of their cycling in marine environments. Among the most powerful of its kind at academic institutions worldwide, an ultra-high-resolution mass spectrometer (University of Oldenburg, PI T. Dittmar) is available for the in-depth compositional examination of dissolved organic matter in ocean water, sedimentary pore-waters and ocean-crust aquifers. These studies will enable us to shed new light onto the cycling of these least understood carbon pools on Earth. A recently established laboratory for the quantitative analysis of radiotracer uptake by individual biomarker molecules in marine cultures and enrichments (MARUM, PI K.-U. Hinrichs) allows us to devise highly sensitive experiments constraining the carbon metabolism, biosynthesis and metabolic rates of natural microbial communities. Experiments of similar scope can even be conducted at the single-cell level at the NanoSIMS facility (MPI-MM, PI M. Kuypers), where stable-isotope tracer incorporations can be mapped on marine cells of known taxonomic affiliation. MARUM hosts the first laser-desorption-ionization system coupled to ultra-high-resolution mass spectrometry worldwide dedicated to the sub-millimeter-scale analysis of distributions of diagnostic biomarkers in sedimentary and rock matrices for reconstructions of paleoenvironments and paleoecosystems at up-to intra-annual-scale resolution (MARUM – *Geobiomolecular Imaging Lab,* PI K.-U. Hinrichs; Wörmer et al., 2014). This technology opens a molecular window for tracking changes in the mode, pacing, and amplitude of environmental changes on timescales of human generations. Moreover, through involvement of Excellence Chair E. Willerslev in the Cluster, we gain access to his internationally esteemed expertise in analyzing ancient DNA (aDNA) and plan to transfer this capability to the reconstruction of past marine ecosystems. There remains a vast potential for tailoring science-driven analytical protocols to the specific sample types examined and research questions addressed by the Cluster's research.

Work program: approaches and methods

The TRACERS Enabler will serve as a science-driven, Cluster-wide platform for the advancement of existing and development of new molecular and isotopic techniques. We will seek to implement analytical solutions tailored to the scientific needs of the three Research Units, provide new methodologies that extend the scope of the envisioned research, and advance the major analytical facilities with technical support and strategically selected extensions of the infrastructure throughout the next decade (Fig. 18). We will establish a novel Marine Cheminformatics Node that will serve as a central interface between researchers producing molecular and isotopic data within the three Research Units and the PANGAEA data-information system. The TRACERS Enabler will benefit from the internationally leading expertise of the resident PIs and the three proposed Excellence Chairs

J. Middelburg, V. Orphan and E. Willerslev, who will be integrated in research projects aimed at advancing the frontiers of marine molecular and isotopic lines of investigation.

The Tracers Enabler will foster continuous innovation through a combination of five dedicated PhD projects and smaller, science-driven internal research grants (typically < 25 k€, 290 k€ in total) for the establishment of new and / or advancement of existing analytical protocols. With the aim of rapid response to new scientific developments, these grants will be awarded to Cluster-based applicants through a framework of annual competitions. Additionally, resources will be made available for technical support of major molecular and isotopic facilities and for strategic investments in the instrumental infrastructure.

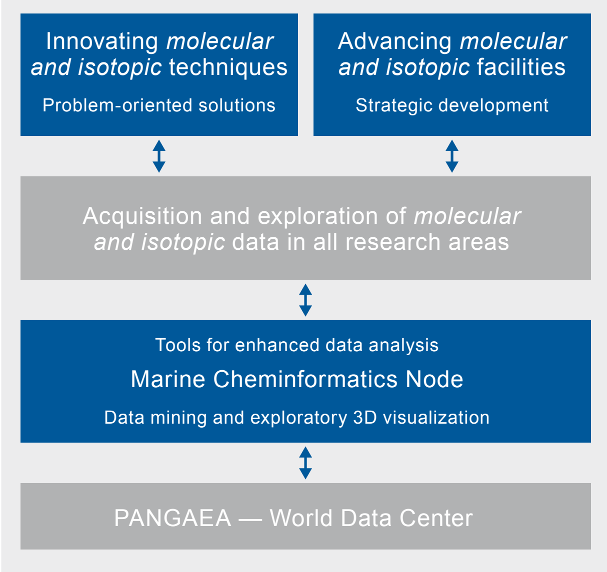

Figure 18 | Major tasks of the Enabler Tracers (blue) in relation to other research activities in the Cluster.

The dedicated PhD projects will address pressing methodological challenges in the areas of (i) radiocarbon dating of compositional sub-fractions of marine and sedimentary dissolved organic matter (DOM) to illuminate its sources and role in the carbon cycle (relevant to Receiver and Recorder), (ii) extracellular (fossil) DNA in sedimentary matrices to explore the mechanisms facilitating preservation of signals from both decayed sedimentary microbes and oceanic algal communities (particularly relevant to aDNA studies in Recorder Theme 3 and to studies of sub-seafloor life in Reactor Theme 2) in order to strengthen our foundation for confidently utilizing the pool of aDNA for marine paleoecological studies, (iii) molecular-level radiotracer analysis to quantify the activity of microbes mediating central biogeochemical processes in seawater and sediments (Receiver, Reactor), (iv) micrometer-scale analysis of microbial biomarkers by mass spectrometry imaging across sharp chemical and physical gradients in ocean-floor settings to locate, identify and quantify microbes inhabiting extreme environments (Reactor), and (v) ROV-based *in-situ* mass spectrometry for the quantitative and isotopic analysis of CO_2 and CH_4 around vents and seep sites (Enabler Technology, Reactor, Receiver). Each of the proposed Excellence Chairs will contribute to at least one of these projects with their world-leading expertise in aDNA (E. Willerslev), isotope tracer techniques (J. Middelburg, V. Orphan) and microscale analysis of microbial communities (V. Orphan) and co-supervise graduate students with one or more resident PIs.

An additional major goal will be the implementation of informational techniques that facilitate the interpretation and curation of raw chemical data and enable their exploratory analysis (cf. Fig. 18). Such an initiative, focusing on marine organic molecules, has not been pursued at the proposed scale, and we expect to generate substantial added value by enabling an integrated view on large datasets. This Marine Cheminformatics Node will serve as a central interface between researchers producing molecular-chemical data and the PANGAEA data-information system (see Section 4.3), in which published molecular data will be ultimately stored. We envision implementation of a module for the exploratory 3D visualization and mining of any sort of molecular-chemical data (concentrations, molecular ratios, compound-specific isotope data, molecular formulas etc.) in the water column and the ocean floor. This module will be connected to an intermittent data-archive module, which holds unpublished data available to the resident scientific community for exploration prior to its ultimate publication in PANGAEA; this data archive will be closely connected to PANGAEA, allowing simultaneous access to published and unpublished molecular data. The interpretation of mass spectrometric raw data is typically time-demanding; modules will be designed that automate this process, e.g., by screening raw data files for known analytes, recognizing compounds based on mass spectrometric fragmentation patterns, and computing of concentrations. All informatics modules will be open-source and made publicly available.

Risks and opportunities in Tracers

The Enabler Tracers is an investment in advancing excellence in the analytical marine environmental sciences with the aim of producing the best possible data. As such, it lowers the risks of the Cluster's projects that rely on analytical data. Additionally, the proposed Marine Cheminformatics Node will provide added value by creating a framework allowing a broader community of researchers within the Cluster to query the datasets. Given the novelty of the above-described technologies, there remains an inherent risk of not fully accomplishing some of the technical goals, e.g., by not achieving the desired analytical specificity or sensitivity, but at the same time the Tracers Enabler is specifically designed to tackle such problems and develop solutions.

Project development

The establishment of the Marine Cheminformatics Node will commence in Year 1. After hiring a suitable informaticist with a background in chemistry and / or environmental sciences, the initial objective will be to create dedicated semi-automated routines for streamlined evaluations of marine-compound data generated by data-intensive modern mass-spectrometric approaches. Subsequently, the implementation of the module for examination and visualization of marine molecular data will begin. Two PhD projects on radiocarbon dating of DOM and aDNA in marine sediments will start in year 1; a project on compound-specific radioisotope probing will start in year 2; a project on microscale molecular imaging of microbes in marine sediments will start in year 3; and a project on ROV-based *in-situ* mass spectrometry will start in year 4. Support for the MARUM *Geobiomolecular Imaging Lab* will increase in year 3 when the method is expected to become routinely available. We will award innovation grants from year 2 until year 7.

Internal and external collaborations

D. de Beer (MPI-MM) – microsensors; T. Eglinton (ETH Zurich) – compound-specific radiocarbon dating; F. Inagaki (JAMSTEC) – nanoSIMS, cell sorting for taxon-specific lipid analysis; B. Koch (AWI) – ultra-high-resolution mass spectrometry; M. Lever (ETH Zurich) – extracellular DNA in sediments; S. Ono (MIT) – clumped isotopologues of methane; S. Wankel (WHOI) and P. Girguis (Univ. of Harvard) – *in-situ* mass spectrometry.

Table 3.4.12: Proposed Staff in Enabler TRACERS

	2019	2020	2021	2022	2023	2024	2025
Staff category	**Number of persons**						
Professors	-/-	-/-	-/-	-/-	-/-	-/-	-/-
Independent junior research group leaders	-/-	-/-	-/-	-/-	-/-	-/-	-/-
Postdoctoral researchers	1	1	2	2	2	2	2
Doctoral researchers	1	3	4	4	2	1	-/-
Other staff	-/-	-/-	-/-	-/-	-/-	-/-	-/-

Table 3.4.13: Funding Request for Enabler TRACERS

	2019	2020	2021	2022	2023	2024	2025
Funding category	**Totals per year in k€**						
Staff (Total 3.4.5)	115	208	341	351	262	218	171
Direct project costs (excl. staff)	38	108	103	103	79	67	37
Total instrumentation <€150,000	0	30	20	20	20	20	20
Instrumentation >€150,000	200	0	0	0	0	0	0

Justification: Direct project costs include funds for consumables, travel and student assistants (12 k€/yr per PhD project), and consumables for the radiotracer and molecular-imaging facilities (together ~26 k€/yr). Small instrumentation (total of 130 k€) is foreseen for the innovation grants in years 2020 to 2025. A critical investment in 2019 will be the acquisition of an ultra performance liquid chromatography mass spectrometer (UPLC-MS) system (200 k€) for the radiotracer facility.

3.4.6 Enabler OCEAN FLOOR MODELING FRAMEWORK (MODELING)

Project leaders: K. Huhn-Frehers, **G. Lohmann**, A. Paul, **M. Pérez-Gussinyé**

Other involved researchers: S. Ahmerkamp, **W. Bach**, M. Holtappels, S. Kasten, **H. Pälike**, **M. Schulz**

Excellence Chair: J. Middelburg

The geodynamic diversity of the ocean floor is not considered in ocean biogeochemical models. The Enabler OCEAN-FLOOR MODELING FRAMEWORK will develop a modeling system that includes a dynamic ocean-floor component and integrates the diverse observational data generated by the three Research Units.

Contribution to the overall objectives of the Cluster of Excellence

The goal of the Enabler Ocean-Floor Modeling Framework is to estimate element fluxes and budgets, including their uncertainties, and to facilitate the understanding of the feedbacks between marine ecosystems and the reactive ocean floor, ocean circulation, and marine biogeochemical cycles. The following two tasks will be central to our activities (Fig. 19): (i) exploration of the impacts of ocean-floor dynamics on the variability of seawater composition and global biogeochemical cycling, and (ii) exploration of the interactions between the shelf-sea and open-ocean circulations and marine biogeochemical cycles and ecosystems.

Current state of research and preliminary work (own publications underlined)

A key challenge in Earth-system science today is to understand and quantify the fluxes of elements that are exchanged between the crust, ocean and atmosphere. The critical micronutrient iron, for example, is variably affected by sediment transport, by iceberg and glacier melting, and by hydrothermal venting in different parts of the oceans (Tagliabue et al., 2017). The role that the flanks of mid-ocean ridges play in global budgets is poorly understood, although the flow of seawater here is as great as the total riverine water flux into the oceans (Fisher, 2005). Likewise, the ocean floor in coastal areas is affected by current-driven advection, which leads to a strong bentho-pelagic coupling and to enhanced biogeochemical cycling in coastal seas, the significance of which has only recently been appreciated (Ahmerkamp et al., 2015).

Interactions between mantle rocks and seawater in oceanic rifts greatly affect the tectonic style of the oceanic lithosphere, and they result in the release of reducing gases (H_2, CH_4), which fuel life in the subseafloor (Bach, 2016). Detailed 3D seismic imaging at rifted margins suggests that the main conduits for water into the mantle are active faults (Bayracki et al., 2016). At ultra-slow spreading ridges, seismic data indicate that mantle serpentinization may reach far deeper than previously thought (up to 15 km to 20 km deep), with implications for fluid circulation, lithosphere-ocean exchange fluxes, and ocean-floor deformation (Schlindwein and Schmid, 2016). Furthermore, lithosphere-ocean exchange fluxes are influenced by climate-driven sea-level changes (Hasenclever et al., 2017; Lund et al., 2016; Middleton et al., 2016).

The thermodynamics and kinetics of water-rock reactions are key to estimating element fluxes during fluid flow in the oceanic lithosphere (Klein et al., 2014), but they have not been typically taken into account in this context. Scientists at MARUM have co-led the development of thermodynamic models for these reactions and performed bioenergetic calculations of the resulting catabolic energy available for microbial life (Klein et al., 2014; Bach, 2016). Additionally, they have developed models of tectonic deformation including serpentinization, mantle melting and sedimentation (MILAMIN-RIFTS, Ros et al., 2017). Tectonic deformation, hydrothermal flow and its thermodynamics still need to be coupled in order to quantify element fluxes across the ocean-floor interface.

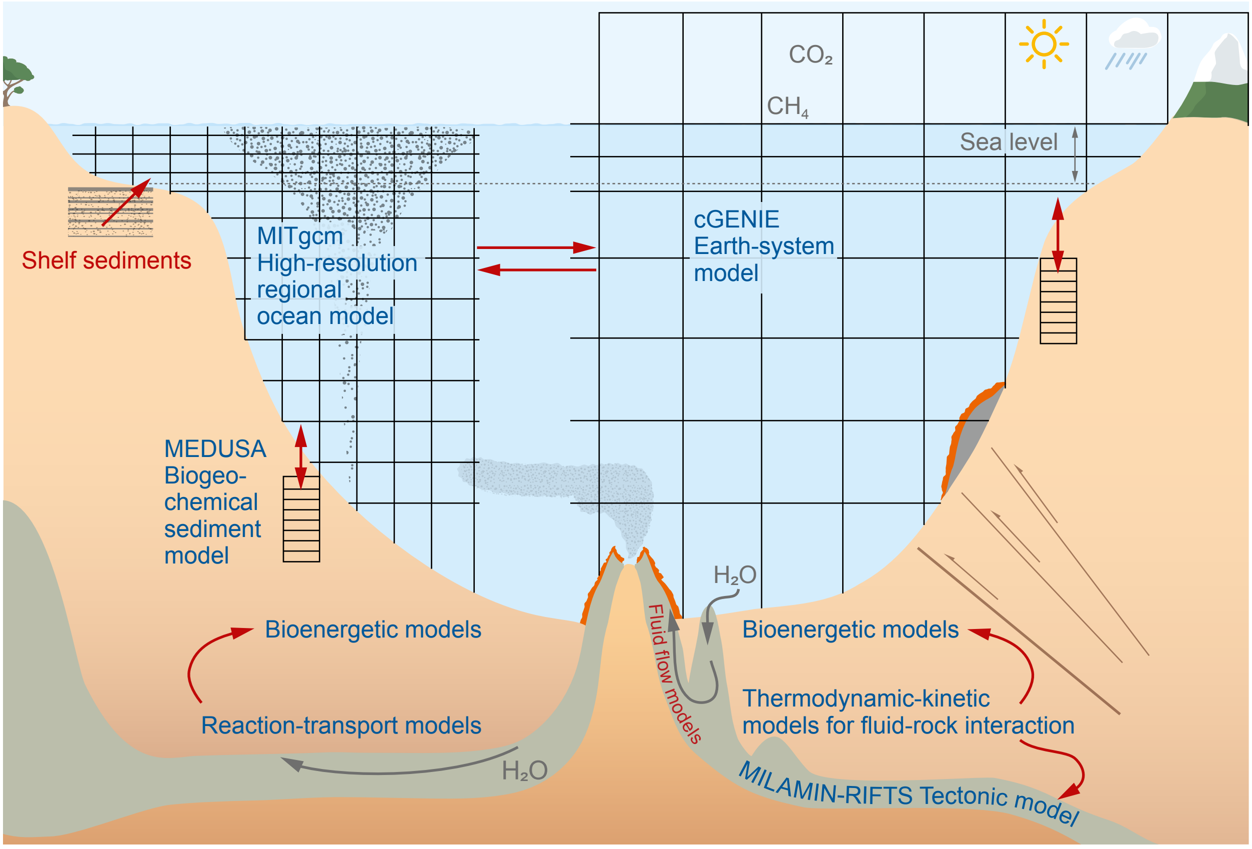

Figure 19 | Existing models are shown in blue (with representative model grids), while the processes and interactions to be added in the ENABLER OCEAN-FLOOR MODELING FRAMEWORK are depicted in dark red.

Progress has been made in applying Earth-system models to problems related to the global carbon cycle, including the long-term feedbacks responsible for modifying the short-term (Charney) sensitivity towards Earth-system sensitivity (Hülse et al., 2017, von der Heydt et al., 2016). For example, our work has shown that changes in the primary productivity of the North-west African upwelling system during the Last Glacial Maximum are not necessarily reflected by local increases in the organic-carbon flux to the sediments (Giraud and Paul, 2010). However, key challenges remain in the study of transient feedbacks over timescales longer than 50,000 years.

In a previous project at MARUM the importance of coastal sands as a bioreactor was demonstrated. The advection of porewater causes a fast and dynamic inflow of oxidants and organic matter that controls microbial remineralization and denitrification at rates higher than previously assumed. The complex transport-reaction dynamics in sands were investigated with a model that included the increased mobility of the surface sand layer (Ahmerkamp et al., 2015). The benthic fluxes can be parameterized in terms of the flow velocity, sediment topography and grain size (Ahmerkamp et al., 2017).

The implied return of nutrients from pelagic and coastal sediments to the shelf waters and open ocean can be taken into account in the next generation of models of the marine biogeochemical and isotopic cycles, which have been developed at MARUM at global and regional scales and applied to present and past climate conditions (Karakas et al., 2009; Giraud and Paul, 2010; Pälike et al., 2012; Kurahashi et al., 2014, 2017; Völpel et al., 2017).

Work program: approaches and methods

In-situ observations and modeling of specific processes will be carried out in the individual Research Units. The results will first be generalized in terms of suitable parameterizations and then integrated at the regional or global scale in this Enabler (Figs. 19 and 20). Our goal is to calculate global budgets based on input from all three Research Units for the various domains of the reactive ocean floor (ridges, flanks, arcs and shelves).

Task 1. Exploration of the impacts of ocean-floor dynamics on the variability of seawater composition and global biogeochemical cycling.

To assess the variability in seawater composition and global biogeochemical cycling, we will first estimate the influence of water circulation in the oceanic basement on ocean-floor element fluxes. For each geodynamic context, we will develop a module of subseafloor fluid-flow circulation using Darcy-type porous flow. An important innovation will be to take into account the thermodynamics and kinetics of fluid-rock reactions along the fluid-flow path, which strongly control ocean-floor element fluxes. The catabolic energy resulting from these interactions and available for fueling microbial life will be calculated, and first-order estimations of biomass amount and its implications for the carbon cycle will be made. In areas where fluid flow is influenced by tectonic activity (e.g., at rifted margins or ultra-slow spreading centers), we will couple these modules to a model of ocean-floor tectonic deformation. These numerical tectonic models are already available for extensional rift settings (MILAMIN-RIFTS, Ros et al., 2017).

In the first phase of the project we will focus on tectonic environments that have not been extensively explored, such as ultra-slow spreading ridges, ridge flanks and passive rifted margins, where our sea-going expeditions will take place. This will allow us to calibrate and constrain our model parameters and results with *in-situ* observations and the knowledge gained from laboratory experiments in the Reactor. We will be focusing on estimating the fluxes of H_2, CH_4, and Ca coming from mantle serpentinization at ridges and rifted margins, the fluxes of CO_2, Mg and Ca resulting from fluid circulation at ridge flanks, and CO_2 from mantle degassing. We will upscale the fluxes of elements obtained for particular tectonic environments to global fluxes, using the fact that hydrothermal circulation and CO_2 degassing mainly depend on spreading velocity and sea level (Lund et al., 2016; Hasenclever et al., 2017). Extrapolations of element fluxes for the geological past will be based on the corresponding plate-tectonic configurations.

The influence of our new ocean-floor element fluxes on the global biogeochemical cycles will be studied using the cGENIE Earth-system model (Ridgwell and Schmidt, 2010), which will include the two-way interaction between seawater and pelagic sediments and be forced by changes in weathering and sea level. This Earth-system model will be employed to estimate global budgets using methods that make optimal usage of the diverse observations and reconstructions, including new time series of carbonate chemistry and ocean saturation, from the Recorder (Pälike et al., 2012).

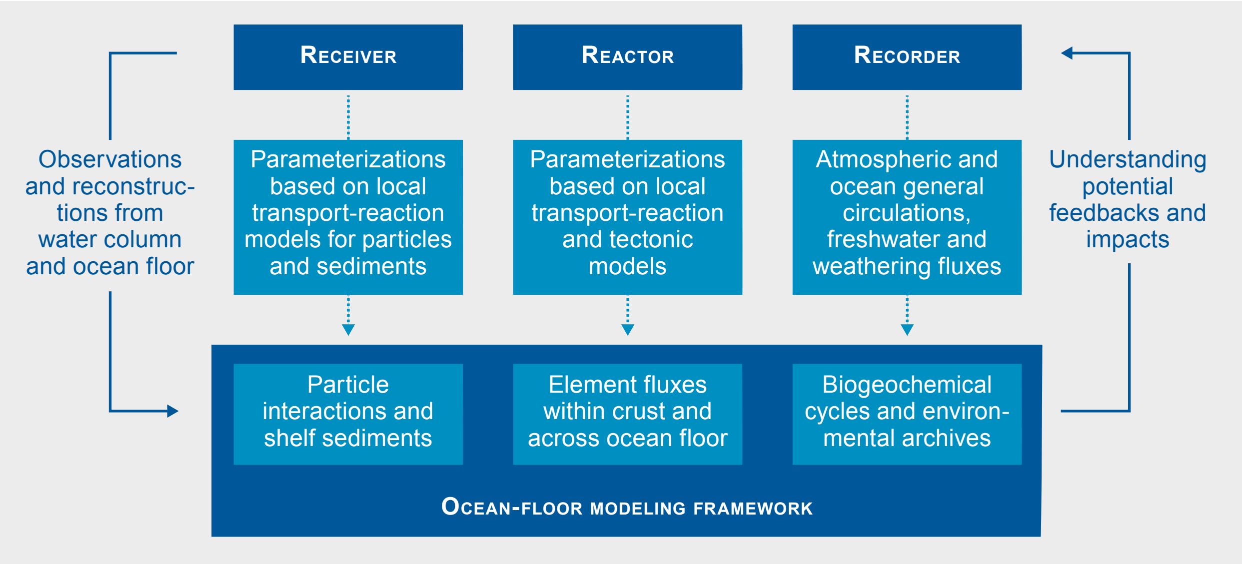

Figure 20 | Exchange of data, concepts and model results between the Enabler Ocean-Floor Modeling Framework and the three Research Units of the Cluster.

A key task will be to represent the full global carbon cycle and seawater chemistry over a wide range of timescales up to a million years, because the element fluxes and budgets have been observed to change over such long time periods. In the first phase of the project we will focus on representing ocean-floor processes in the carbon-cycle component, including carbonate dissolution and bioturbation effects on carbon burial and re-dissolution, building on previous studies (Munhoven, 2007; Zeebe and Zachos, 2007; Kirtland Turner and Ridgwell, 2013). Over longer timescales the exchange of elements between ocean water and crust will need to be considered, particularly regarding the Mg/Ca ratio of seawater (Coggon et al., 2010). Including changes of seawater chemistry in the model will be an ambitious attempt to evaluate the factors controlling long-term carbonate solubility and dissolution.

Task 2. Exploration of the interactions between shelf-sea and ocean circulation and marine ecosystems.

A high-resolution regional ocean model based on the MITgcm, including marine-ecosystem and sediment-transport components, will be used to study the impact of sinking biogenic particles ("marine snow") and the influx of nutrients from permeable sandy sediments on the marine biogeochemistry. The MITgcm is well suited for this task, because additional code packages may be conveniently added to its modular structure. Existing code packages include biogeochemical and marine ecosystem components (e.g., the Darwin model, Follows et al., 2007) or water isotopes (Völpel et al., 2017). In collaboration with Guy Munhoven in Liége, Belgium, coupling of the MITgcm to a more complex and flexible model of pelagic sediments (the MEDUSA model, Munhoven, 2007) is already ongoing at AWI. Building on a previous implementation in ROMS (Karakas et al., 2009), a more advanced parameterization of particle aggregation and disaggregation will be included in the MITgcm. Finally, a one-dimensional transport-reaction model to be developed in the Receiver will be used to derive a new parameterization of shelf/ocean-floor fluxes for the MITgcm.

The regional ocean model will be applied to exemplary areas (initially to the Northwest African upwelling system) in order to investigate the effects of large-scale lateral transport of particulate and dissolved organic matter, examine regional budgets of carbon and nutrient cycling in shelf sediments, and identify the main parameters that regulate global budgets. It will enable us to trace oceanic signals from their formation in the shallow waters to their preservation in the sediments, and to assess the element fluxes between the shelf sea and open ocean.

All Research Units will provide data from *in-situ* observations, experiments and reconstructions from the water column and the ocean floor to force and evaluate the modeling system (Fig. 20). The particle-transport and biogeochemical modeling will be developed together with scientists working in the RECEIVER. New parameterizations based on local transport-reaction models will be developed both in the RECEIVER (here especially in Theme 2) and REACTOR. Information on the atmospheric and ocean circulation changes, as well as freshwater and weathering fluxes from land, will be provided by the RECORDER. In turn, the Enabler MODELING will assist in understanding the potential feedbacks and impacts of the processes and systems studied in the individual Research Units. All model results will be made accessible to the scientific community through the PANGAEA data information system.

Risks and opportunities in MODELING

Understanding the impacts of ocean-floor dynamics on the variability of seawater composition and global biogeochemical cycling, as well as the interactions between shelf-sea and open-ocean circulation and marine ecosystems, requires the description of a great number of tectonic, biogeochemical and physical-oceanographic processes that occur within a large range of temporal and spatial scales. This poses multiple challenges relating to parameterizations that need to be included in the descriptive mathematical models, the large number of processes involved, and the associated computational demands. We deal with these challenges by close interaction among the three Research Units, which will generate an observational database and a conceptual framework for modeling the diverse processes. Furthermore, we count on a framework of existing, well-established numerical models that are best suited for each individual task. New parameterizations and components, as well as the interactions between the different models, will be added one step at a time, and at each step the model results will be checked for consistency with observations and reconstructions. Computational demands will be dealt with by acquiring a cluster of 40 nodes and using the facilities of the North-German Supercomputing Alliance. There are great opportunities that emerge from this close integration of data and models, such as in the planned MeBo drilling and the associated logging and installation of observatories to measure fluid fluxes on the flanks of the Reykjanes Ridge. The resulting data will greatly help to constrain the fluid-flow models; at the same time, the flux data collected from the drilling and observatories in the Enabler TECHNOLOGY for REACTOR Theme 1 can be used to ground truth the parameterizations to be implemented in the cGENIE Earth-system model.

Project development

Overall, we want to assess the impacts of previously neglected processes at and beneath the ocean floor on global budgets. Initially, the project will be structured in three postdoctoral researcher positions. The first two positions will tackle Task 1 and develop parallel modules to (i) calculate element fluxes out of the ocean floor by coupling hydrothermal fluid flow within the crust with the thermodynamics of fluid-rock reactions for different tectonic environments, and to (ii) simulate changes in seawater composition in the cGENIE Earth-system model, forced by element fluxes out of the ocean-floor. The third position will be dedicated to Task 2, and will set up a regional ocean-marine biogeochemistry model based on the MITgcm, including an aggregation module to simulate the interactions of particles and a parameterization of shelf / ocean-floor fluxes, in order to investigate interactions between the shelf-sea and open-ocean circulations and marine ecosystems.

Internal and external collaborations

Valuable advice on the representation of the remineralization of organic matter at and within the ocean floor will be provided by U Bremen Excellence Chair J. Middelburg. In the field of biogeochemical sediment modeling, we will closely interact with G. Munhoven (Liége, Belgium).

Table 3.4.14: Proposed Staff in Enabler MODELING

	2019	2020	2021	2022	2023	2024	2025
Staff category	**Number of persons**						
Professors	-/-	-/-	-/-	-/-	-/-	-/-	-/-
Independent junior research group leaders	-/-	-/-	-/-	-/-	-/-	-/-	-/-
Postdoctoral researchers	3	3	3	3	3	3	3
Doctoral researchers	-/-	-/-	-/-	-/-	-/-	-/-	-/-
Other staff	-/-	-/-	-/-	-/-	-/-	-/-	-/-

Table 3.4.15: Funding Request for Enabler MODELING

	2019	2020	2021	2022	2023	2024	2025
Funding category	**Totals per year in k€**						
Staff (Total 3.4.6)	216	223	229	236	243	251	258
Direct project costs (excl. staff)	45	46	48	49	51	52	54
Total instrumentation < € 150,000	120	0	0	0	0	0	0
Instrumentation > € 150,000	0	0	0	0	0	0	0

Justification: Direct projects costs include consumables, travel and student helpers. Instrumentation is included to acquire a high-performance computer cluster of 40 nodes with 2 CPUs and 64 GByte per node, which will ensure rapid testing and prototyping of numerical models. For final computations, we will use the computing facility of the North-German Supercomputing Alliance.

3.4.7 Central research support – Excellence chairs, professorship, joint expeditions

Principal investigators: M. Schulz, N. Dubilier, K.-U. Hinrichs

To systematically strengthen our research profile, three **U Bremen Excellence Chairs** will be filled by distinguished international scientists who will work part-time in Bremen. Chairs can be appointed as honorary professors at the University of Bremen and will have the right to promote PhD candidates in Bremen. Besides their own position (part-time equivalent up to 0.25 W3), each Chair will include a working group in Bremen (1 scientist, 1 PhD, 20 k€ annually for consumables and travel) and will be established for an initial period of 4 years with an option for extension. Specific plans for such arrangements have been made with three outstanding international scientists who were selected based on their highly complementary expertise: Jack Middelburg (University of Utrecht) in the fields of biogeochemical element cycling and modeling, Victoria Orphan (California Institute of Technology) in marine geomicrobiology, and Eske Willerslev (University of Copenhagen) in marine paleogenomics. Planned research activities of the Excellence Chairs are elucidated in the descriptions of the Research Units and Enablers. The following statements by the three Excellence Chairs underline their motivation and enthusiasm for the planned collaboration:

"*Participation in this Cluster would provide me with unprecedented opportunities for access to deep-sea observational and experimental facilities, and for use of novel analytical facilities. I am therefore really looking forward to interacting with Cluster members to design joint tracer experiments to elucidate ocean-floor ecosystem functioning and to develop an in-depth, integrated research program on organic carbon processing from the twilight zone to the deep biosphere. Moreover, the proposed research program will generate unique data and new understanding on ocean-floor biogeochemistry. Together with Cluster members I hope to develop new conceptual and improved numerical models of sediment biogeochemistry, benthic-pelagic coupling, organic-carbon dynamics over multiple timescales and long-term carbon cycling in the ocean.*" (Jack Middelburg)

"The involvement in the Cluster would give me the opportunity to expand my research on studying fundamental microbial interspecies interactions, metabolic activities, and collective influence on biogeochemical transformations within ocean-floor ecosystems. I am particularly excited by the potential to develop new synergistic collaborations with members of the Cluster that complement my expertise in molecular microbial ecology/geobiology and single-cell ecophysiology. Together, I expect to build new understanding regarding the flux and dynamic transformation of carbon, nitrogen, and sulfur species within microbial communities using state-of-the-art analytical facilities and unique deep-ocean instrumentation in Bremen." (Victoria Orphan)

"It is with excitement that I involve myself in this Cluster. This truly provides a unique opportunity to establish important cross-disciplinary links for paleo-environmental reconstruction of marine

environments and will undoubedly expand and further my field in ancient environmental DNA. This project will also serve as a platform for expanding, improving and developing our state-of-the-art genomic methodologies. I am convinced that through a strong symbiosis with the other team members we can obtain an unseen and deeper understanding of past and present ocean-floor ecosystem dynamics." (Eske Willerslev)

New professorship in ocean-floor geology: A full professorship incl. working group (1 W3, 1 scientist E13, 1 technician E9, 0.5 secretary E8, 20 k€ annually for travel and consumables) will be filled at the University of Bremen in the second half of 2019. With its expertise, the professorship will strengthen the research program through exploration of the relationships between geodynamic processes and the ocean-floor environment, making full use of the underwater technology during ship-based expeditions.

Joint expeditions: Ship-based expeditions are a backbone of our research program. Across the Research Units, several focus areas have been carefully selected that allow for a maximum integration of the planned interdisciplinary research activities (Fig. 21). A number of focal areas are located in the Atlantic Ocean and Mediterranean Sea, due to the availability of German research vessels in these regions. Budgets for the planned expeditions (Table 3.4.16) include costs for large-scale equipment (based on DFG standard rates for internal projects; www.portal-forschungsschiffe.de/geraete), travel, and container transport. The scientific rationales for the expeditions are outlined in the descriptions of the Research Units and the Enabler TECHNOLOGY. The Cluster will benefit further from expeditions that are planned within the frameworks of other national and international projects.

To support the expeditions and subsequent work on sample material, funding is requested for central science-support personnel. This includes 3 engineers and technicians for the operation and maintenance of the seagoing equipment, 1 scientist to manage the samples and cores in the core repository, and 1 scientist to oversee the large number of samples for stable isotope analyses, which are central to the scientific goals of the Cluster.

To be able to react to changes in the working program, e.g., initiation of new research projects and cooperation with external research groups, **incentive funds** (250 k€ per year for staff, and direct project costs for individual projects of up to 45 k€ each) will be available for projects to address the latest scientific developments. All members of the Cluster are eligible to submit short proposals (5 pages or less) at two appointed dates per year. The proposals are reviewed with regard to their scientific quality by two independent colleagues, and the funding decision is made by a committee selected by the Steering Committee of the Cluster. Decisions are based on scientific criteria, but also take into account equal opportunity issues, international collaboration, and risk-benefit ratio.

Table 3.4.16: Planned expeditions in the Cluster. Rationale for individual expeditions is outlined in the description of the three Research Units and Enabler TECHNOLOGY.

Exp. #	Research Unit	Vessel	Region	Large Equipment	Working Days	2019	2020	2021	2022	2023	2024	2025	Sum [k€]
1	RVR	MGS	Mauritania	–	7	35		35		35		35	140
2	RVR	MGS	Irish margin	–	7				35		35		70
3	RVR/RCT/REC	MSM/MET	Mauritania	MeBo70	28			307					307
4	RCT/REC	MSM/MET	North Atlantic – MOR	ROV QUEST	21	210					210		420
5	RCT/TEC	MSM/MET/MGS	northern North Atlantic – MOR (Survey)	AUV SEAL	7			37					37
6	RCT/TEC	MSM/MET	northern North Atlantic – Flanks	MeBo200	28			331					331
7	RCT/TEC	MSM/MET/MGS	northern North Atlantic – Retrieval Observatories	ROV SQUID	14					35			35
8	RCT	MSM	northern North Atlantic – MOR	ROV QUEST	21				210				210
9	RCT	MSM	northern North Atlantic – MOR	MeBo200	28					331			331
10	RCT/REC/TEC	MET	Mediterranean	AUV SEAL	21		158					158	316
11	RCT/REC	MET	Mediterranean	ROV SQUID	21							128	128
12	REC	MSM	Baffin Bay	MeBo70	28		307						307
13	REC	MSM/MET	South Atlantic Rio Grande Rise	MeBo200	28				331				331
14	TEC	MGS	North Atlantic	Technology Test	7		35			35			70
	Total [k€]					245	500	710	576	436	245	321	3,033

Costs (in k€) include large sea-going equipment (consumables, wear, maintenance), travel, and container transport. Costs for consumables and student helpers included in the budgets of the Research Units and Enablers. Vessels include METEOR (MET), MARIA S. MERIAN (MSM), and mid-sized vessels (MGS, e.g., HEINCKE or ALKOR). MOR: mid-ocean ridge.

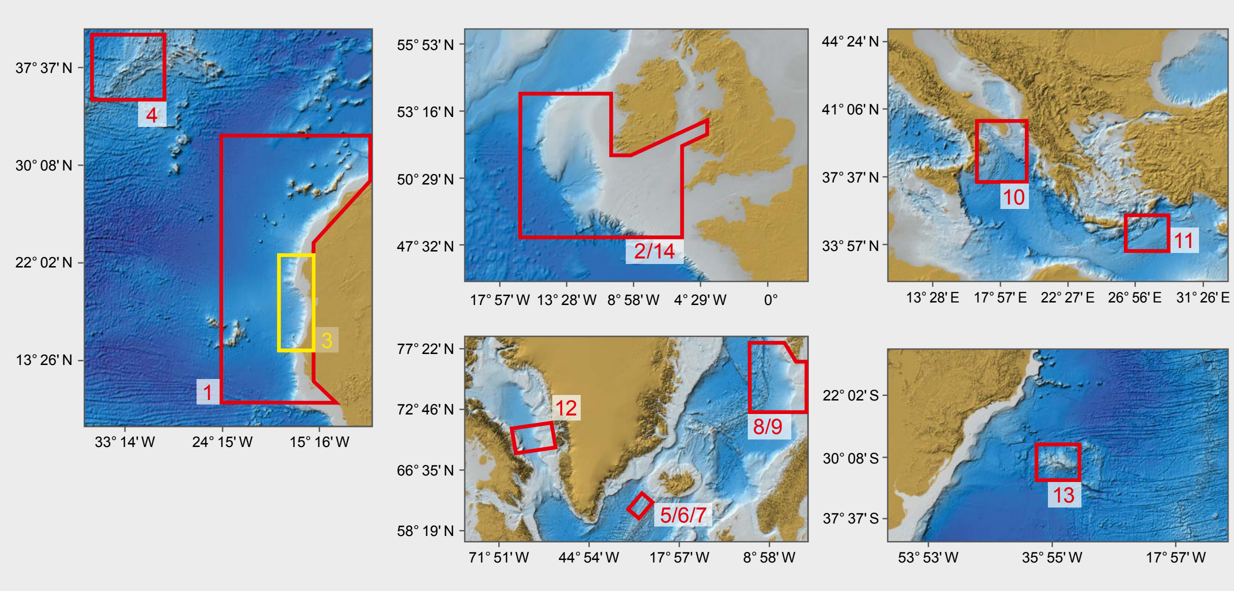

Figure 21 | Focus areas for joint expeditions of the Cluster in the Atlantic Ocean and Mediterranean. Numbers refer to expeditions in Table 3.4.16.

Table 3.4.17: Proposed Staff in Central Research Support

	2019	2020	2021	2022	2023	2024	2025
Staff category	**Number of persons**						
Professors	1	1	1	1	1	1	1
Excellence Chairs	3	3	3	3	3	3	3
Independent junior research group leaders	-/-	-/-	-/-	-/-	-/-	-/-	-/-
Postdoctoral researchers	6	6	6	6	6	6	6
Doctoral researchers	3	3	3	3	3	3	3
Other staff	4	4	4	4	4	4	4

Table 3.4.18: Funding Request for Central Research Support

	2019	2020	2021	2022	2023	2024	2025
Funding category	**Totals per year in k€**						
Staff (Total 3.4.7)	951	1,050	1,081	1,114	1,147	1,181	1,217
Direct project costs (excl. staff)	695	950	1,161	1,026	886	695	771
Total instrumentation <€150,000	0	0	0	0	0	0	0
Instrumentation >€150,000	0	0	0	0	0	0	0

Justification: Direct projects costs include incentive funds (250 k€ / yr), consumables and travel for one professorship and three Excellence Chairs (20 k€ / yr each = 80 k€ / yr), student helpers for expeditions (40 k€ / yr), small expedition equipment and its maintenance (60 k€ / yr for liners, pumps, etc.), consumables for core repository (20 k€ / yr), and expedition costs according to Table 3.4.16.

3.5 BIBLIOGRAPHY

Authors involved in the previous cluster and / or this proposal are underlined; intermediate authors involved in this proposal are given in parentheses.

Ahmerkamp, Winter, et int, Holtappels, 2017: Regulation of benthic oxygen fluxes in permeable sediments of the coastal ocean, Limn Ocean, doi:10.1002/lno.10544 (Kuypers)

Ahmerkamp, Winter, et int, Holtappels, 2015: The impact of bedform migration on benthic oxygen fluxes, J Geophys Res Biogeosci, doi:10.1002/2015JG003106 (Kuypers)

Amend, McCommon, et int, Bach, 2011: Catabolic and anabolic energy for chemolithoautotrophs in deep-sea hydrothermal systems hosted in different rock types, Geochim Cosmochim Ac, doi:10.1016/j.gca.2011.07.041

Anagnostou, John, et int, Pearson, 2016: Changing atmospheric CO_2 concentration was the primary driver of early Cenozoic climate, Nature, doi:10.1038/nature17423

Arrieta, Jesus, et int, Duarte, 2015: Dilution limits dissolved organic carbon utilization in the deep ocean, Science, doi:10.1126/science.1258955 (Dittmar)

Bach, 2016: Some compositional and kinetic controls on the bioenergetic landscapes in oceanic basement, Front Microbiol, doi:10.3389/fmicb.2016.00107

Bachmayer and Claus, 2012: Hybrid Glider: Motivation, Design and Evaluation. In: Further Advances in Unmanned Marine Vehicles, Institution of Engineering and Technology, doi:10.1049/PBCE077E_ch13

Bauer, Cai, et int, Regnier, 2013: The changing carbon cycle of the coastal ocean, Nature, doi:10.1038/nature12857

Bayrakci, Minshull, et int, Morgan, 2016: Fault-controlled hydration of the upper mantle during continental rifting, Nature Geosci, doi:10.1038/ngeo2671 (Pérez-Gussinyé)

Becker, Scheffel, et int, Hehemann, 2017: Accurate quantification of Laminarin in marine organic matter with enzymes from marine microbes, Appl Env Microbiol, doi:10.1128/AEM.03389-16

Beerling and Royer, 2011: Convergent Cenozoic CO_2 history, Nature Geosci, doi:10.1038/ngeo1186

Boetius, Albrecht, et int, Wenzhöfer, 2013: Export of algal biomass from the melting Arctic sea ice, Science, doi:10.1126/science.1231346

Boetius and Wenzhöfer, 2013: Seafloor oxygen consumption fuelled by methane from cold seeps, Nature Geosci, doi:10.1038/ngeo1926

Botts, Percivall, et int, Davidson, 2008: OGC® Sensor Web Enablement: Overview and High Level Architecture. In: GeoSensor Networks. Springer, doi:10.1007/978-3-540-79996-2_10

Bourke, Marriot, et int, Cook, 2017: Metabolism in anoxic permeable sediments is dominated by eukaryotic dark fermentation, Nature Geosci, doi:10.1038/ngeo2843

Bowles, Mogollon, et int, Hinrichs, 2014: Global rates of marine sulfate reduction and implications for sub-sea-floor metabolic activities, Science, doi:10.1126/science.1249213 (Kasten, Zabel)

Clarkson, Kasemann, et int, Tipper, 2015: Ocean acidification and the Permo-Triassic mass extinction, Science, doi:10.1126/science.aaa0193.

Coggon, Teagle, et int, Cooper, 2010: Reconstructing past seawater Mg / Ca and Sr / Ca from mid-ocean ridge flank calcium carbonate veins, Science, doi:10.1126/science.1182252

Cyr, van Haren, et int, Bourgault, 2016: On the influence of cold-water coral mound size on flow hydrodynamics, and vice versa, Geophys Res Lett, doi:10.1002/2015GL067038

Dall'Olmo, Dingle, et int, Claustre, 2016: Substantial energy input to the mesopelagic ecosystem from the seasonal mixed-layer pump, Nature Geosci, doi:10.1038/ngeo2818

Davies, Morales Maqueda, et int, Ganopolski, 2017: Millenial-scale shifts in the methane hydrate stability zone due to Quaternary climate change, Geology, doi:10.1130/G39611.1

DeConto and Pollard, 2016: Contribution of Antarctica to past and future sea-level rise, Nature, doi:10.1038/nature17145

de Vernal and Hillaire-Marcel, 2008: Natural variability of Greenland climate, vegetation, and ice volume during the past million years, Science, doi:10.1126/science.1153929

De Vleeschouwer, Vahlenkamp, et int, Pälike, 2017: Alternating Southern and Northern Hemisphere climate response to astronomical forcing during the past 35 my, Geology, doi:10.1130/G38663.1

Dittmar and Paeng, 2009: A heat-induced molecular signature in marine dissolved organic matter, Nature Geosci, doi:10.1038/ngeo440

Donohue, Hillebrand, et int, Yang, 2016: Navigating the complexity of ecological stability, Ecol Lett doi:10.1111/ele.12648

Dubilier, Bergin, Lott, 2008: Symbiotic diversity in marine animals: the art of harnessing chemosynthesis, Nature Rev Microbiol, doi:10.1038/nrmicro1992

Dubois-Dauphin, Colin, et int, Frank, 2017: Fingerprinting Northeast Atlantic water masses using neodynium isotopes, Geoch Cosmoch Acta, doi:10.1016/j.gca.2017.04.002 (Hebbeln, Wienberg)

Edwards, Fisher, Wheat, 2012: The deep subsurface biosphere in igneous ocean crust: Frontier habitats for microbiological exploration, Front Microbiol, doi:10.3389/fmicb.2012.00008

Escartín, Mével, et int, Garcia, 2017: Tectonic structure, evolution, and the nature of oceanic core complexes and their detachment fault zones (13°20′N and 13°30′N, Mid Atlantic Ridge), Geochem Geophy Geosy, doi:10.1002/2016GC006775

Fischer and Lüttge, 2017: Beyond the conventional understanding of water-rock reactivity, Earth Planet Sci Lett, doi:10.1016/j.epsl.2016.10.019

Fischer, Romero, et int, Wefer, 2016: Deep ocean particle flux in the coastal upwelling off Mauritania from 1988 to 2012: variability on seasonal to decadal timescales, Biogeosci, doi:10.5194/bg-13-3071-2016 (Iversen)

Fisher, 2005: Marine hydrogeology: recent accomplishments and future opportunities, Hydrogeol J, doi:10.1007/s10040-004-0400-y
Follows, Dutkiewicz, et int, Chisholm, 2007: Emergent biogeography of microbial communities in a model ocean, Science, doi:10.1126/science.1138544
Freudenthal and Wefer, 2013: Drilling cores on the sea floor with the remote-controlled sea floor drilling rig MeBo, Geoscientific Instrumentation, doi:10.5194/gi-2-329-2013
German and Seyfried, 2014: Hydrothermal processes. In: Treatise on Geochemistry, Elsevier, doi:10.1016/B978-0-08-095975-7.00607-0
Giraud and Paul, 2010: Interpretation of the paleo-primary production record in the NW African coastal upwelling system as potentially biased by sea level change, Paleoceanogr, doi:10.1029/2009PA001795
Gray, Zonneveld, Versteegh, 2017: Species-specific sensitivity of dinoflagellate cysts to aerobic degradation: A five-year natural exposure experiment, Rev Pal Pal, doi:10.1016/j.revpalbo.2017.09.002
Guidi, Chaffron, et int, Gorsky, 2016: Plankton networks driving carbon export in the oligotrophic ocean, Nature, doi:10.1038/nature16942
Gutjahr, Ridgwell, et int, Foster, 2017: Very large release of mostly volcanic carbon during the Palaeocene-Eocene Thermal Maximum. Nature, doi:10.1038/nature23646 (Pälike)
Hain, Sigman, Haug, 2014: The Biological Pump in the Past. In: Treatise on Geochemistry, Elsevier, doi:10.1016/B978-0-08-095975-7.00618-5
Hansell and Carlson, 2013: Localized refractory dissolved organic carbon sinks in the deep ocean, Glob Biogeochem Cycl, doi:10.1002/gbc.20067
Hansen, Sato, et int, Kharecha, 2013: Climate sensitivity, sea level and atmospheric carbon dioxide, Phil Trans R Soc A, doi:10.1098/rsta.2012.0294
Hasenclever, Knorr, et int, Hall, 2017: Sea level fall during glaciation stabilized atmospheric CO_2 by enhanced volcanic degassing, Nature Comm, doi:10.1038/ncomms15867 (Lohmann)
Hehemann, Arevalo, et int, Polz, 2016: Adaptive radiation by waves of gene transfer leads to fine-scale resource partitioning in marine microbes, Nature Comm, doi:10.1038/ncomms12860
Hehemann, Correc, et int, Michel, 2010: Transfer of carbohydrate-active enzymes from marine bacteria to Japanese gut microbiota, Nature, doi:10.1038/nature08937
Hillebrand and Matthiessen, 2009: Biodiversity in a complex world: consolidation and progress in functional biodiversity research, Ecol Lett, doi:10.1111/j.1461-0248.2009.01388.x
Hinrichs, Hmelo, Sylva, 2003: Molecular fossil record of elevated methane levels in late Pleistocene coastal waters, Science, doi:10.1126/science.1079601
Hinrichs and Inagaki, 2012: Downsizing the deep biosphere, Science, doi:10.1126/science.1229296
Hönisch, Ridgwell, et int, Williams, 2012: The geological record of ocean acidification, Science, doi:10.1126/science.1208277
Huettel, Berg, et int, Giovannoni, 2014: Benthic exchange and biogeochemical cycling in permeable sediments, Ann Rev Mar Sci, doi:10.1146/annurev-marine-051413-012706
Hülse, Arndt, et int, Ridgwell, 2017: Understanding the causes and consequences of past marine carbon cycling variability through models, Earth Sci Rev, doi:10.1016/j.earscirev.2017.06.004
Ikari, Ito, et int, Kopf, 2015: Spectrum of slip behaviour in Tohoku fault zone samples at plate tectonic slip rates, Nature Geosci, doi:10.1038/NGEO2547
Inagaki, Hinrichs, et int, Yamada, 2015: Exploring deep microbial life in coal-bearing sediment down to ~2.5 km below the ocean floor, Science, doi:10.1126/science.aaa6882 (Elvert, Heuer)
IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press (Rhein, Schulz)
IPCC, 2014: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press
Iversen, Pakhomov, et int, Klaas, 2017: Sinkers or floaters? Contribution from salp pellets to the export flux during a large bloom event in the Southern Ocean, Deep-Sea Res II, doi:10.1016/j.dsr2.2016.12.004
John, Pearson, et int, Foster, 2013: Warm ocean processes and carbon cycling in the Eocene, Phil Trans R Soc A, doi:10.1098/rsta.2013.0099.
Kahl, Hansen, Bach, 2016: A new X-ray-transparent flow-through reaction cell for a μ-CT-based concomitant surveillance of the reaction progress of hydrothermal mineral-fluid interactions, Solid Earth, doi:10.5194/se-7-651-2016
Kallmeyer, Pockalny, et int, D'Hondt, 2012: Global distribution of microbial abundance and biomass in subseafloor sediment, P Natl Acad Sci USA, doi:10.1073/pnas.1203849109
Karakas, Nowald, et int, Schlitzer, 2009: Impact of particle aggregation on vertical fluxes of organic matter, Prog Oceanogr, doi:10.1016/j.pocean.2009.07.047 (Iversen)
Kellermann, Wegener, et int, Hinrichs, 2012: Autotrophy as predominant mode of carbon fixation in thermophilic anaerobic methane-oxidizing microbial communities, P Natl Acad Sci USA, doi:10.1073/pnas.1208795109 (Elvert)
Kirtland Turner, Ridgwell, 2013: Recovering the true size of an Eocene hyperthermal from the marine sedimentary record, Paleoceanogr, doi:10.1002/2013PA002541
Klein, Bach, et int, Berquó, 2014: Magnetite in seafloor serpentinite – some like it hot, Geology, doi:10.1130/G35068.1
Klein, Humphris, et int, Orsi, 2015: Fluid mixing and the deep biosphere of a fossil Lost City-type hydrothermal system at the Iberia Margin, P Natl Acad Sci USA, doi:10.1073/pnas.1504674112 (Schubotz)
Kopf, Hammerschmidt, et int Kido, 2011: The SmartPlug and GeniusPlug: Simple retrievable observatory systems for NanTroSEIZE borehole monitoring. Proc. IODP, doi:10.2204/iodp.proc.332.105.2011
Kopf, Freudenthal, et int, Wefer, 2015: Simple, affordable, and sustainable borehole observatories for complex monitoring objectives, Geosci Instrum, doi:10.5194/gi-4-99-2015

Kurahashi-Nakamura, Paul, Losch, 2017: Dynamical reconstruction of the global ocean state during the Last Glacial Maximum, Paleoceanogr, doi:10.1002/2016PA003001

Kurahashi-Nakamura, Losch, Paul, 2014: Can sparse proxy data constrain the strength of the Atlantic meridional overturning circulation?, Geosci Model Dev, doi:10.5194/gmd-7-419-2014

Lalonde, Mucci, et int, Gélinas, 2012: Preservation of organic matter in sediments promoted by iron, Nature, doi:10.1038/nature10855

Laso-Pérez, Wegener, et int, Musat, 2016: Thermophilic archaea activate butane via alkyl-coenzyme M formation, Nature, doi:10.1038/nature20152

Lee, Mavridou, et al., Rickaby, 2016: The uronic acid content of coccolith-associated polysaccharides provides insight into coccolithogenesis and past climate Nature Comm, doi:10.1038/ncomms13144

Lipp, Morono, et int, Hinrichs, 2008: Significant contribution of Archaea to extant biomass in marine subsurface sediments, Nature, doi:10.1038/nature07174

Littler, Röhl., et int, Zachos, 2014: A high-resolution benthic stable-isotope record for the South Atlantic: Implications for orbital-scale changes in Late Paleocene-Early Eocene climate and carbon cycling, Earth Planet Sci Lett, doi:10.1016/j.epsl.2014.05.054

Lund, Asimow, et int, Durham, 2016: Enhanced East Pacific Rise hydrothermal activity during the last two glacial terminations, Science, doi:10.1126/science.aad4296

Lynch-Stieglitz, Schmidt, et int, Chang, 2014: Muted change in Atlantic overturning circulation over some glacial-aged Heinrich events, Nature Geosci, doi:10.1038/ngeo2045 (Mulitza)

Marchant, Ahmerkamp, et int, Kuypers, 2017: Denitrifying community in coastal sediments performs aerobic and anaerobic respiration simultaneously, ISME Journal, doi:10.1038/ismej.2017.51 (Holtappels)

Marchant, Holtappels, et int Kuypers, 2016: Coupled nitrification-denitrification leads to extensive N loss in subtidal permeable sediments, Limnol Oceanogr, doi:10.1002/lno.10271

MARGO Project Members, 2009: Constraints on the magnitude and patterns of ocean cooling at the Last Glacial Maximum, Nature Geosci, doi:10.1038/NGEO411 (Kučera, Mulitza, Paul)

McCollom and Bach, 2009: Thermodynamic constraints on hydrogen generation during serpentinization of ultramafic rocks, Geochim Cosmochim Ac, doi:10.1016/j.gca.2008.10.032

Mewes, Mogollón, et int, Kasten, 2016: Diffusive transfer of oxygen from seamount basaltic crust into overlying sediments: An example from the Clarion-Clipperton Fracture Zone, Earth Planet Sc Lett, doi:10.1016/j.epsl.2015.10.028

Middleton, Langmuir, et int, Mitrovica, 2016: Hydrothermal iron flux variability following rapid sea level changes, Geophys Res Lett, doi:10.1002/2016GL068408

Mohtadi, Prange, et int, Jennerjahn, 2017: Late Holocene slowdown of the Indian Ocean Walker circulation, Nature Comm, doi:10.1038/s41467-017-00855-3 (Schefuß)

Mora, Tittensor, et int, Worm, 2011: How many species are there on Earth and in the ocean?, PLOS Biology, doi:10.1371/journal.pbio.1001127

Müller, Wagner, et int, Lohmann, 2011: Towards quantitative sea ice reconstructions in the northern North Atlantic: A combined biomarker and numerical modelling approach, Earth Planet Sci Lett, doi:10.1016/j.epsl.2011.04.011 (Prange)

Munhoven, 2007: Glacial-interglacial rain ratio changes: Implications for atmospheric CO_2 and ocean-sediment interaction, Deep Sea Res, Part II, doi:10.1016/j.dsr2.2007.01.008

Niu, Hong, et int, Zhang, 2014: Global trends in sediment-related research in earth science during 1992–2011: a bibliometric analysis, Scientometrics, doi:10.1007/s11192-013-1065-x

O'Connor, Knublauch, et int, Musen, 2005: Supporting rule system interoperability on the semantic web with SWRL. In: The Semantic Web, Springer, doi:10.1007/11574620_69

Orcutt, Wheat, et int, Bach, 2013: Oxygen consumption rates in subseafloor basaltic crust derived from a reaction transport model, Nature Comm, doi:10.1038/ncomms3539

Orsi, Coolen, et int, Giosan, 2017: Climate oscillations reflected within the microbiome of Arabian Sea sediments, Sci Rep, doi:10.1038/s41598-017-05590-9

Pälike, Lyle, et int, Zeebe, 2012: A Cenozoic record of the equatorial Pacific carbonate compensation depth, Nature, doi:10.1038/nature11360

Pape, Bahr, et int, Bohrmann, 2010: Molecular and isotopic partitioning of low- molecular-weight hydrocarbons during migration and gas hydrate precipitation in deposits of a high-flux seepage site, Chem Geol, doi:10.1016/j.chemgeo.2009.10.009 (Sahling, Hinrichs)

Penman, Turner, et int, Röhl, 2016: An abyssal carbonate compensation depth overshoot in the aftermath of the Palaeocene-Eocene Thermal Maximum. Nature Geosci, doi:10.1038/ngeo2757

Petersen, Zielinski, et int, Dubilier, 2011: Hydrogen is an energy source for hydrothermal vent symbioses, Nature, doi:10.1038/nature10325 (Pape, Amann, Bach)

Ranero and Pérez-Gussinyé, 2010: Sequential faulting explains the asymmetry and extension discrepancy of conjugate margins, Nature, doi:10.1038/nature09520

Ratmeyer and Rigaud, 2009: Europe's Growing Fleet of Scientific Deepwater ROVs: Emerging Demands for Interchange, Workflow Enhancement and Training. OCEANS, IEEE, doi:10.1109/OCEANSE.2009.5278157

Resing, Sedwick, et int, Tagliabue, 2015: Basin-scale transport of hydrothermal dissolved metals across the South Pacific Ocean, Nature, doi:10.1038/nature14577

Ridgwell and Schmidt, 2010: Past constraints on the vulnerability of marine calcifiers to massive carbon dioxide release, Nature Geosci, doi:10.1038/NGEO755

Riedinger, Formolo, et int, Kasten, 2014: An inorganic geochemical argument for coupled anaerobic oxidation of methane and iron reduction in marine sediments, Geobiol, doi:10.1111/gbi.12077

Roberts, Wheeler, Freiwald, 2006: Reefs of the deep: the biology and geology of cold-water coral ecosystems, Science, doi:10.1126/science.1119861
Robinson, Adkins, et int, van de Flierdt, 2014: The geochemistry of deep-sea coral skeletons: a review of vital effects and applications for palaeoceanography, Deep Sea Res II, doi:10.1016/j.dsr2.2014.05.001
Römer, Sahling, et int, Bohrmann, 2014: Methane fluxes and carbonate deposits at a cold seep area of the Central Nile Deep Sea Fan, Eastern Mediterranean Sea, Mar Geol, doi:10.1016/j.margeo.2013.10.011 (Boetius, Pape)
Ros, Pérez-Gussinyé, et int, Morgan, 2017: Lower crustal strength controls on melting and serpentinization at magma-poor margins: potential implications for the South Atlantic, Geochem Geophys Geosyst, doi:10.1002/2017GC007212
Rossel, Elvert, et int, Hinrichs, 2011: Factors controlling the distribution of anaerobic methanotrophic communities in marine environments: Evidence from intact polar membrane lipids, Geochim Cosmochim Ac, doi:10.1016/j.gca.2010.09.031 (Boetius)
Rothman, 2017: Thresholds of catastrophe in the Earth system, Sci Adv, doi:10.1126/sciadv.1700906
Rubin-Blum, Antony, et int, Dubilier, 2017: Short-chain alkanes fuel mussel and sponge Cycloclasticus symbionts from deep-sea gas and oil seeps, Nature Microbiol, doi:10.1038/nmicrobiol.2017.93 (Bohrmann, Pape, Sahling)
Ruppel and Kessler, 2017: The interaction of climate change and methane hydrates, Rev Geophys, doi:10.1002/2016RG000534
Sander and Koschinsky, 2011: Metal flux from hydrothermal vents increased by organic complexation, Nature Geosci, doi:10.1038/ngeo1088
Schefuß, Eglinton, et int, Schneider, 2016: Hydrologic control of carbon cycling and aged carbon discharge in the Congo River basin, Nature Geosci, doi:10.1038/ngeo2778
Schlindwein and Schmid, 2016: Mid-ocean-ridge seismicity reveals extreme types of ocean lithosphere, Nature, doi:10.1038/nature18277
Schwander, von Borzyskowski et int, Erb, 2016, A synthetic pathway for the fixation of carbon dioxide in vitro, Science, doi:10.1126/science.aah5237
Sokoll, Lavik, et int, Holtappels, 2016: Extensive nitrogen loss from permeable sediments off North-West Africa, J Geophys Res-Biogeosc, doi:10.1002/2015JG003298 (Kuypers)
Stams and Plugge, 2009: Electron transfer in syntrophic communities of anaerobic bacteria and archaea, Nature Rev Microbiol, doi:10.1038/nrmicro2166
Tagliabue, Bowie, et int, Saito, 2017: The integral role of iron in ocean biogeochemistry, Nature, doi:10.1038/nature21058
Völpel, Paul, et int, Schulz, 2017: Stable water isotopes in the MITgcm, Geosci Model Dev, doi:10.5194/gmd-10-3125-2017 (Mulitza)
von der Heydt et al., Dijkstra, et int, Ziegler, 2016: Lessons on climate sensitivity from past climate changes, Curr Clim Change Rep, doi:10.1007/s40641-016-0049-3 (Lohmann, Pälike)
Walker, Primeau, et int, McCarthy, 2016: Linked changes in marine dissolved organic carbon molecular size and radiocarbon age, Geophys Res Lett, doi:10.1002/2016GL070359
Wallace and Beavan, 2010: Diverse slow slip behavior at the Hikurangi subduction margin, New Zealand, J Geophys, doi:10.1029/2010JB007717
Wallmann, Pinero, et int, Ruepke, 2012: The global inventory of methane hydrate in marine sediments: A theoretical approach, Energies, doi:10.3390/en5072449
Wankel, Huang, et int, Girguis, 2012: Characterizing the distribution of methane sources and cycling in the deep sea via in situ stable isotope analysis. Environmental Science and Technology, doi:10.1021/es303661w
Wegener, Krukenberg, et int, Boetius, 2015: Intercellular wiring enables electron transfer between methanotrophic archaea and bacteria, Nature, doi:10.1038/nature15733
Wegener, Niemann, et int, Boetius, 2008: Assimilation of methane and inorganic carbon by microbial communities mediating the anaerobic oxidation of methane, Env Microbiol, doi:10.1111/j.1462-2920.2008.01653.x (Elvert, Hinrichs)
Willerslev, Hansen, et int, Cooper, 2003: Diverse plant and animal genetic records from Holocene and Pleistocene sediments, Science, doi:10.1126/science.1084114
Wörmer, Elvert, et int, Hinrichs, 2014: Ultra-high-resolution paleoenvironmental records via direct laser-based analysis of lipid biomarkers in sediment core samples, P Natl Acad Sci USA, doi:10.1073/pnas.1405237111 (Lipp, Zabel)
Yasuhara, Tittensor, et int, Worm, 2017: Combining marine macroecology and palaeoecology in understanding biodiversity: microfossils as a model, Biol Rev, doi:10.1111/brv.12223 (Hillebrand)
Yoshinaga, Holler, et int, Elvert, 2014: Carbon isotope equilibration during sulphate-limited anaerobic oxidation of methane, Nature Geosci, doi:10.1038/NGEO2069 (Hinrichs, Wegener)
Zachos, Dickens, Zeebe, 2008: An early Cenozoic perspective on greenhouse warming and carbon-cycle dynamics, Nature, doi:10.1038/nature06588
Zachos, Röhl, et int, Kroon, 2005: Rapid Acidification of the Ocean During the Paleocene-Eocene Thermal Maximum, Science, doi:10.1126/science.1109004
Zark, Christoffers, Dittmar, 2017: Molecular properties of deep-sea dissolved organic matter are predictable by the central limit theorem: evidence from tandem FT-ICR-MS, Mar Chem, doi:10.1016/j.marchem.2017.02.005
Zeebe and Zachos, 2007: Reversed deep-sea carbonate ion basin gradient during Paleocene-Eocene thermal maximum, Paleoceanogr, doi:10.1029/2006PA001395
Zhang, Cui, et int, Hanebuth, 2016: Storm-driven bottom sediment transport on a high-energy narrow shelf (NW Iberia) and development of mud depocenters, J Geophys Res-Oceans, doi:10.1002/2015JC011526
Zhou, Bachmayer, Young, 2016: Towards autonomous underwater iceberg profiling using a mechanical scanning sonar on a underwater Slocum glider, IEEE / OES AUV2016, Tokyo, doi:10.1109/AUV.2016.7778656

4 SUPPORTING STRUCTURES IN THE CLUSTER OF EXCELLENCE

4.1 SUPPORT OF EARLY CAREER RESEARCHERS (ECRs)

Coordinators: D. Hebbeln, J.-H. Hehemann, J. Müller

ECRs and Equal Opportunity Support Office: C. Klose

At a Glance

- Embedded in a stimulating interdisciplinary and international environment of outstanding research conditions, the support program for ECRs will offer training, resources and career guidance to enhance the ECR's sense of self-responsibility and academic independence, and to foster current and future excellence in ocean-floor research.
- The unique combination of specialized education in ocean-floor science, transferable skills training, international networking, and support of professional development aims to enhance the career prospects of ECRs, not only in academia but also on the broader job market.

Objectives – Early Career Researchers (ECRs), comprising PhD students and Postdocs within the first five years of completing their PhDs, are important drivers of scientific progress. While developing into highly skilled professionals in their fields, they increasingly assume responsibilities in student supervision and lab management. During this phase, ideally, ECRs are preparing to lead their own junior groups in universities and research institutions, or to take on similar kinds of responsibility elsewhere. At the same time, they need to plan their own personal careers during times of unpredictable perspectives in academia. The Cluster aims to provide a support program tailored to the specific needs of ECRs at different career stages, with special attention to major career transition phases. Based on the already existing, extensive experience in doctoral education (see Box 4), the Cluster will offer a **qualification program** and specialized courses to promote the advanced knowledge and skills required by ECRs for pursuing careers in academia, government, industry, NGOs, consulting, or other fields. The **individual mentoring** of ECRs will be a key aspect of their personal career development, and will include guidance by academic supervisors, alumni and other contact persons in the Cluster's professional network. Simultaneously, the Cluster will seek to stimulate an **exchange between supervisors**, thesis-committee members, and the leaders of junior research groups to ensure high quality in the supervision of ECRs, and to develop "best-practice approaches" for supervision-relevant topics. The satisfaction of ECRs with the support program and the success of the measures taken will be continuously evaluated through surveys. Meetings of the ECRs with the external Scientific Advisory Board (see Section 4.3) will provide an important additional feedback mechanism for quality assessment. The interdisciplinary and international environment of the Cluster, together with the culture of strong cooperative spirit at MARUM, will prepare the ECRs for their future, and at the same time raise their awareness for diversity and gender aspects.

Box 4: PhD Student Education in Marine Sciences in Bremen

Since foundation of MARUM, researchers placed a strong emphasis on the structural development of doctoral training in marine sciences. Since then, several graduate colleges and international research training groups have hosted and integrated PhD students from abroad. In 2006, the Bremen International Graduate School for Marine Sciences – GLOMAR was established as the only graduate school with a marine science focus in the Excellence Initiative's Graduate School funding line. By then, GLOMAR had already implemented many of the recommendations for doctoral education made in 2014 by the German *Wissenschaftsrat*. The Graduate School educates PhD students in marine sciences in a broader sense, including not only natural but also social, legal, and cultural sciences.

GLOMAR has served as a model for other graduate programs in the MARUM partner institutions of the Helmholtz and the Leibniz Associations and for the development of the University of Bremen Graduate Center, BYRD. In 2012, GLOMAR was integrated into the existing Cluster and by the end of 2018, it will be transferred to MARUM core funding.

GLOMAR has set the standards for PhD student education in marine sciences at the University of Bremen in terms of supervision, internationalization and interdisciplinary education. In terms of PhD student training, MARUM has defined the knowledge and skills that are expected to be acquired when graduating under the auspices of MARUM.

Qualification program – The Cluster aims to guide PhD students through their PhD terms while also providing the knowledge and skills necessary for future career development. Based on past experience, the following comprehensive portfolio of support measures is planned: (i) a qualification program of specialized courses with a distinct focus on ocean-floor research, complemented by skills and methods courses specifically addressing marine technology, advanced geochemical tracers and numerical modeling; (ii) transferable skills training that includes, for example, good scientific practice, data management, and public engagement; (iii) monthly seminars that focus on ocean-floor research topics, networking with peers, tackling the challenges of PhD projects, and fostering interdisciplinary exchange; and (iv) a mini-proposal program, including a review system, to provide funding for short- (i.e., active conference participation, etc.) and long-term (i.e., research residencies) international experiences that foster the PhD students' self-assurance and academic independence through practices such as project management, proposal writing, and administering of funds. For the Postdoc community, the program will be expanded to include: (i) courses and workshops tailored to address the special needs and skills that are relevant during the Postdoc phase (e.g., supervision, project management, sustainable data management, working / research in teams, networking, international cooperation, reviewing, public outreach); (ii) support in the development of their first independent research projects, such as information on research funding options, research-profile development, and a course in proposal writing. This course was implemented in 2011, and since then has helped ten ECRs to submit successful project proposals for which they served as PIs (seven women, three men; 90 % of all submitted proposals; submission primarily to the DFG). Since its establishment, we have particularly encouraged female ECRs to participate in the course; (iii) opportunities to gain experience in the teaching and supervision of students, which are considered to be major professional achievements at this career level. Postdocs will be encouraged to teach specialized courses related to their own fields of expertise in the PhD student program. This activity will be complemented by workshops on academic teaching that provide didactical background. Postdocs can also become involved in the supervision of master's and PhD students, e.g., by becoming members of PhD students' thesis committees or by acting as mentors; and (iv) guided peer-group supervision, an effective form of structured peer-group counseling, will bring together Postdocs to discuss key topics and professional issues with one another, thereby developing their counseling and coaching skills, fostering self-empowerment, and increasing professionalism inside and outside academia.

Individual mentoring – For PhD students, supervision by a thesis committee, consisting of three or more experienced scientists, is an already established, essential part of individual mentoring that will be continued in the Cluster. The PhD students will meet with their thesis committees at least twice a year. The committees will provide expertise and guidance to the PhD students and regularly discuss career options. Moreover, career counseling will also be offered by other PIs and by representatives from outside academia. The Cluster aims to establish an additional, new mentoring scheme for Postdocs during their first two years, to include bi-monthly meetings with a senior scientist to tackle challenges associated with their transition from PhD student to Postdoc, which represents a major step towards academic independence. Moreover, a career mentoring program, consisting of dedicated workshops and individual consultations between the Postdoc and a Professor, will help to prepare the Postdocs for their next career phases. This program will also raise the awareness of gender bias, as does the coaching program *navigare*, developed exclusively for female ECRs by the University of Bremen in close cooperation with MARUM (see Section 4.2).

Because many ECRs will not seek long-term academic careers, insights into the diversity of non-academic career paths are crucial for this group. Such insights will be provided through our existing and growing professional network, including professionals from outside academia, in the form of, e.g., fireside chats, career days, and round-table discussions. ECRs considering such a career path will be supported in (i) understanding the wide variety of career opportunities in areas such as industry, entrepreneurship, administration, communication, and science management, (ii) pursuing placements across these diverse career options (e.g., through contacts, financial support), (iii) preparing for such a new kind of working environment (e.g., CV and application preparation; job-hunting and interview skills), and (iv) obtaining additional relevant skills and knowledge (e.g., communication and knowledge transfer, entrepreneurship, intellectual property). A unique advantage of the training is the hands-on data-science education offered by PANGAEA – Data Publisher for Earth & Environmental Science (see Section 4.3).

Exchange between supervisors – To ensure high quality in the supervision of ECRs and to develop "best-practice approaches", regular workshops on supervision-relevant topics (e.g., "Role distribution – supervisor and PhD student", "Troubleshooting in the context of supervision", and "Gender aspects in staff selection and supervision") will be offered for supervisors and thesis-committee members ("train the trainer") and further developed according to the needs of the supervisors involved in the Cluster. Special focus will be given to supporting the leaders of junior research groups, as they are in a transition between being a leader for their staff while still needing guidance in terms of leadership and supervision skills themselves.

Cooperation and institutional integration – The Cluster's support of ECRs will be embedded in the Research Faculty MARUM and will build on the existing cooperation with the University's center for "Bremen Early Career Researcher Development" (BYRD), which combines all general University approaches in the field of personal, professional, and career development for PhD students and Postdocs. ECRs in this Cluster will have full access to the courses and personal counseling offered through BYRD, specifically with respect to transferable skills (e.g., program management, conflict management, leadership skills including gender / diversity competence, and presentation techniques). Close cooperation with the graduate schools at AWI, ZMT, MPI-MM, and the University of Oldenburg will generate synergies for the ECRs by providing additional opportunities for multidisciplinary academic exchange on the peer level. The cooperation will facilitate, for example, mutual access to courses, joint organization of career days, or implementation of joint education standards. The three existing Clusters of Excellence with links to marine sciences in northern Germany (Bremen, Hamburg, Kiel) are key locations for the education of early career marine researchers in Germany. In keeping with this responsibility, regular meetings between these institutions will be continued to target structural aspects of education and development, as well as expectations regarding the organization and outcome of PhD theses.

The Research Faculty MARUM hosts ECRs in all fields of marine sciences. With the Graduate School GLOMAR (see Box 4), two ongoing DFG-funded International Research Training Groups (INTERCOAST and ArcTrain), and international annual summer schools (e.g., the annual ECORD Summer Schools and Training Courses), MARUM has demonstrated a long-term commitment to providing comprehensive support for its PhD students. In the planned Cluster, MARUM aims to expand its commitment to the ECR community.

Table 4.1: Funding Request for Early Career Researchers Support

	2019	2020	2021	2022	2023	2024	2025
Funding category	**Totals per year in k€**						
Staff	88	91	94	145	149	153	158
Direct project costs (excl. staff)	79	109	109	109	109	109	109
Instrumentation	15	0	0	15	0	0	0

Justification: The personnel costs (one scientist) refer to the management and organization of the ECR program as well as equal opportunity support by the Cluster (see Section 4.2), and a manuscript completion extension (up to 3 months) that can be granted to PhD students who submit their thesis within three years. Direct project costs refer to running courses and workshops (incl. guest lecturer) (30 k€ / yr), supporting international mobility (50 k€ / yr), annual retreats of the ECRs (12 k€), mentoring / travel (12 k€), and student helpers (5 k€). Instrumentation refers to two sets of course laptops (2 × 15 k€).

4.2 SUPPORT OF EQUAL OPPORTUNITY

Coordinators: M. Schulz, N. Dubilier, K.-U. Hinrichs

ECRs and Equal Opportunity Support Office: C. Klose

At a Glance

- Promotion of equality of opportunity at all levels is embedded in the leadership and organizational culture of MARUM and will be extended to the Cluster. The Cluster will have a minimum of 40 % female members in the decision-making bodies and aims at a marked increase in the share of female scientists at the senior and professorial levels (see Section 2).
- Female MARUM alumni now in leadership positions attests to the fact that excellent female scientists have been attracted to MARUM and that support measures in place supported their career development.

Gender equality is one of the guiding principles at the University of Bremen. The gender-equality concept of the University of Bremen has achieved the highest possible rating in the *Forschungs-orientierte Gleichstellungsstandards* (research-oriented equality standards) of the *Deutsche Forschungsgemeinschaft* (DFG) three times in a row, and has been top-ranked by the Federal Ministry of Education and Research. At the University level, gender and diversity consulting for collaborative projects is in place to advance gender equality and diversity in the working environment and in the leadership culture. At the Research Faculty MARUM, promotion of gender equality and equal opportunity at all levels has been a central objective for many years and is embedded in the leadership and education culture.

The equal opportunity strategy of the Cluster will be overseen by the Spokespersons and will focus on five specific objectives: (i) to aim for a balanced gender ratio among all researchers,

(ii) to improve the gender balance in leadership positions and decision-making committees, (iii) to increase employment opportunities for female scientists in their next career phase, (iv) to increase awareness of gender bias in supervisory and staff selection processes, and (v) to further develop a gender-balanced academic culture. These goals will be pursued through a number of concrete measures. These include transparent recruitment procedures for scientists. Since 2012, all non-permanent positions at MARUM have also been advertised, and it is mandatory to involve the gender-equality representatives in the recruitment process. In addition, coaching programs for senior scientists are now in place to raise the awareness of gender bias in supervisory and staff-selection procedures. This new procedure is considered to be a model within the University of Bremen. To strengthen the existing gender-balanced culture, a minimum of 40 % female members in the decision-making bodies of the Cluster is envisioned. Together with the University, we will also develop and offer training courses for the senior staff addressing gender competency in leadership. Finally, the Cluster will make use of an existing coaching program for female ECRs pursuing a career in science. The bi-annual program *navigare* aims to professionalize women for their career management in science. Alumni of this program (and its forerunner) have obtained jobs as professors and leaders of junior research groups, and now themselves act as mentors for early career researchers.

Overlap exists between improving the work-life balance and concerns of gender equality. The University of Bremen has a long-term strategy to achieve a better work-life balance for its staff. Since 2007, the University has been certified as a family-friendly institution *(audit familiengerechte hochschule)*. The Cluster will also take into account family circumstances, and supports both female and male ECRs in combining work and family. Specific measures include the extension of contracts for up to 12 months for PhD students with children, temporary transfer to part-time contracts for postdocs, child-care support for members of the Cluster attending conferences and during expeditions, and additional student helpers for ECRs expecting children or who are parents. Dual-career couples are supported through regional networks of research institutions, through contacts with non-academic employers, and by special offers by the University of Bremen. Over the past five years, women have comprised on the average 59 % of the PhD students within GLOMAR, while for postdocs at MARUM the share was 39 %, and at the senior-scientist level it was 21 %. At the level of professorships, the proportion of women involved in MARUM is 25 % (36 % if the involved professorships funded by non-university institutions are also taken into account due to specific programs to increase the number of female professorships). In the proposed Cluster, 40 % of the principle investigators will be women (32 % in the present cluster “The Ocean in the Earth System”).

Through its leadership and organizational culture, the Cluster will support and encourage women to strive for leading positions in academia. At least 16 female scientists who were or are involved in MARUM have obtained professorships (10) or senior positions (6). These include three proponents of this Cluster (A. Boetius, N. Dubilier, H. Westphal), who have become directors of non-university research institutions. This increasing number of female alumni in leadership positions is a model situation, and represents a transformation toward a gender-balanced culture.

The measures that are already in place in the Research Faculty MARUM to increase the number of female scientists will be extended to include the Cluster. The goal is for 50 % of all ECR positions in the Cluster (PhD students and postdocs) to be filled by female scientists. The Research Units and Enablers share the responsibility for reaching these quotas. If quotas are not met, open positions will be re-advertised. Progress will be monitored through the annual reports of the Research Units and Enablers (see Section 4.3).

Finally, the Research Faculty MARUM is developing a personnel plan for all permanent positions (professorships, senior scientists, science-support staff) to increase the number of women through the course of retirement-related turnover during the next decade. Similar standards to support equal opportunity are in place at the partner institutions of the Cluster.

Table 4.2: Funding Request for Support of Equal Opportunity [1]

	2019	2020	2021	2022	2023	2024	2025
Funding category	**Totals per year in k€**						
Staff [2]	0	0	0	48	50	51	53
Direct project costs (excl. staff)	50	30	50	30	50	30	50
Instrumentation	0	0	0	0	0	0	0

[1] In addition to the funds requested here, the planned 50 % female quota for ECRs in the Cluster (see above), will result in a substantial contribution from the ECR-support budget (see Section 4.1) to support female scientists.

[2] The Cluster's equal opportunity program will be organized through a dual role of the ECR office (see Table 4.1).

Justification: The personnel costs refer to up to one year extensions for PhD students starting to raise a family during their PhD term, understanding that nurturing children requires a large amount of time and ultimately extends the length of the project. Direct project costs refer to a bi-annual mentoring program for female ECRs (20 k€ / yr), annual gender awareness workshops (5 k€ / yr), career coaching of female ECRs (15 k€ / yr), child-care support during conferences and expeditions, and student helpers to support parents (10 k€ / yr).

4.3 MANAGEMENT, QUALITY ASSURANCE, PUBLIC ENGAGEMENT

Coordinators: M. Schulz, N. Dubilier, K.-U. Hinrichs

At a Glance

- The proposed Cluster will be hosted by the Research Faculty MARUM of the University of Bremen. A lean management structure is envisioned for the Cluster that builds upon the efficient and effective structure of the ongoing Cluster and involves the partner institutions. It includes well-established measures for internal quality assurance.
- The data-management concept of the Cluster is based on more than two decades of in-house experience in operating a nationally and globally leading open-access data repository "PANGAEA – Data Publisher for Earth & Environmental Science".
- Public-engagement activities will transfer knowledge of marine environmental topics to the general public, stakeholders, and schools. Early career researchers will be involved in outreach activities at all levels.

Management

Within the University of Bremen, the Cluster will be hosted by the Research Faculty MARUM (Fig. 22). Fully established in 2012, the Research Faculty created a new and unique governance structure within the University. Based on its success, the Research Faculty became a permanent institution within the University in 2017. It operates at the same organizational level as the traditional faculties, but it also operates across disciplines and serves as a hub for marine sciences within the University and among the external partners. The Research Faculty has the same rights as, or in some cases even more extensive rights than, the University's other faculties with regard to management of personnel and budget. MARUM has been empowered to contract directly with external academic and industrial partners. The lean management and administrative structure of the proposed Cluster will take advantage of the well-established structure of the existing cluster.

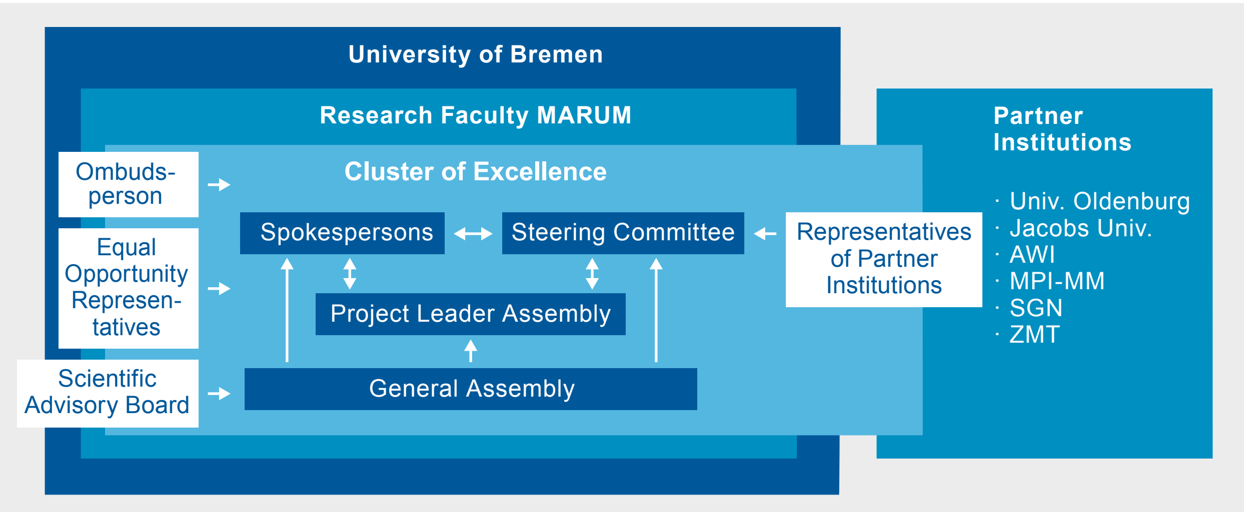

Figure 22 | Governance of the Cluster of Excellence and links to host university and partners.

Decisions in the proposed Cluster will be made by the General Assembly, the Project Leader Assembly, the Steering Committee, and the Spokespersons. The Spokesperson (M. Schulz) with Vice Spokespersons (N. Dubilier and K.-U. Hinrichs) have been appointed by the President of the University of Bremen. The Spokesperson will formally represent the Cluster within the University as well as in national and international governing bodies. He will chair meetings of all bodies, and will be in charge of the daily operative business of the Cluster. Promotion of equal opportunity in the Cluster will be overseen by the Spokespersons. The Steering Committee will be responsible for personnel matters, equal opportunity questions, and quality assurance, and will oversee the allocation of funds. Its membership will comprise the leaders of the Research Units and the Enablers, the head of the Early Career Researchers program, and the Spokesperson. It will meet at least quarterly. The Project Leader Assembly will consist of the leaders of the individual projects as well as PhD student, postdoc, and non-scientific staff representatives as full members, and will be responsible for the scientific program and its strategic development. This body will be key to maintaining a flat hierarchy throughout the Cluster and will allow bottom-up initiatives to thrive, as its members will provide direct interaction with the individual projects. Moreover, because the project leaders will be affiliated with all partner institutions, the Project Leader Assembly will further strengthen ties among the involved institutions. Meetings will be held every 4–6 weeks (in the ongoing DFG Research Center/Cluster of Excellence, 140 such meetings have been held since 2001). The General Assembly will consist of all scientific members of the Cluster, including doctoral researchers and postdocs, and will meet at least once a year and make suggestions on all matters of the Cluster. It elects the leaders of the Research Units, the Enablers, head of the Early Career Researchers program, and the Spokespersons. The elected Equal Opportunity Representatives of MARUM will also serve the Cluster. They will have the right to participate in all bodies of the Cluster and to submit proposals to these bodies and the Spokespersons. The Ombudsperson of MARUM, who is appointed by the President of the University, will also act on behalf of the Cluster by supporting problem solving in conflicts with regard to safeguarding good scientific practice.

Procedures for allocating funds

The distribution of funds for individual projects in the Research Units and cross-cutting Enablers will be decided by the Steering Committee. Consultation of the Project Leader Assembly in this process will ensure overall coherency and transparency of the research program across the entire Cluster while at the same time allowing it to react to new developments. The Research Units and cross-cutting Enablers will be responsible for updating ongoing projects or defining new ones; the process will be organized by the PIs of the Research Units involving all interested members of the Cluster. While the Cluster's research program will be evaluated internally and updated annually, individual projects will have an appropriate duration (e.g., 3 years for PhD projects; at least 2 years for postdoc projects). The annual interval is also appropriate for monitoring the progress regarding equal opportunity (see Section 4.2) and reacting to new developments.

Internal quality management

Based on its positive experience during the previous cluster, an internal reporting system will remain in place for quality assurance. The Research Units, cross-cutting Enablers and management will deliver annual scientific progress reports that also include information on achieving equal opportunity goals as well as information on data management. The reports will form the basis for updating annual budget plans across the Cluster. The Steering Committee will evaluate the reports with regard to the overall objectives (see Section 2) and make recommendations where necessary. Direct measures will be taken if the Committee's recommendations are not followed (ranging from warnings to exclusion of a responsible PI from the internal funding system). Evaluation of the progress reports of the Cluster will include input by the Vice President for Research of the University of Bremen. A Scientific Advisory Board, consisting of 15 leading international experts, will advise the Cluster regarding its long-term development and strategic goals, and will meet every 12 – 15 months. At every Scientific Advisory Board meeting, the President of the University of Bremen will meet with the external experts to discuss their views. Subsequently, trilateral meetings with the President, the Spokesperson and the Deans of the faculties involved will be held to advance support for early career researchers, gender equality, teaching matters and the strategic development of marine sciences at the University of Bremen.

Research-data management

To facilitate multidisciplinary data management at the national and international levels, MARUM and AWI jointly operate PANGAEA – Data Publisher for Earth & Environmental Science, which will form the backbone for research-data management in the Cluster. Established in 1994, PANGAEA is a nationally and globally leading open-access repository and data publisher, and is a member of the International Council for Science (ICSU) World Data System. Serving the environmental science community through a long history of data sharing, PANGAEA supports heterogeneous data from a variety of disciplines, from long-tail data to 'big data' collections acquired by long-term observation systems. The technical architecture of PANGAEA follows internationally recognized standards. In accordance with the most recent recommendations by funding organizations, PANGAEA follows the FAIR (Findable, Accessible, Interoperable, Re-usable) principles and hosts about 370,000 datasets. Each dataset includes a bibliographic citation and is persistently identified using a Digital Object Identifier (DOI), and data-set authors are identified using ORCID identifiers. All data publications in PANGAEA are forwarded to the Thomson Reuters Data Citation Index. Agreements with Elsevier and PubMed Central enable the cross-referencing of scientific publications and related datasets, and the display of data links on the webpages of these publishers. Furthermore, PANGAEA is a recommended repository for data supplements by most scientific journals. Based on its long experience, PANGAEA is also providing guidance for implementing the research-data concept at the University of Bremen. In order to support the interdisciplinary research of the Cluster, its data-management team will work hand in hand with PANGAEA to develop new data-management services: (i) *Custom portals and virtual research environments* for designated user groups in order to enhance data exploration, visualization, and statistical analysis. This task includes customization of search and retrieval features. The main focus is on data processing and analysis within a web-based virtual research environment that will serve all Research Units and Enablers. (ii) *Enhanced support for high-volume data* (e.g., ROV-based videos, bathymetric data) will be geared towards specific needs in the RECEIVER and REACTOR. Domain-specific front ends, workflows, and cloud-based virtual environments will be employed to allow fast access, exploration, and web-based annotation of these data types. (iii) *Enhanced support for biological, taxonomic, biogeochemical and -omics data*. This requires the internal revision of nomenclatures and ontologies for, e.g., taxa, fatty acids, or enzymes, and transfer to international conventions – the linkage of our terminologies with reference ontologies, as well as the establishment of cross-linking services with -omics databases. This work will be closely tied to the Marine Cheminformatics Node in the Enabler TRACERS (see Section 3.4.5).

Given the wide range of data types associated with the planned research, the data-management team of the Cluster will develop standards for handling heterogeneous data that will be implemented across the involved partner institutions.

Public engagement

The Cluster will implement a specific strategy to communicate knowledge of societal relevance from the Cluster to the general public and to stakeholders. The public engagement concept of the Cluster builds on approximately two decades of experience in science communication at MARUM and addresses a wide range of audiences (see Box 5 "Achievements in Public Engagement"). While the focus will be on topics that are rooted in the Cluster, we will also integrate scientific results from other collaborative projects and in close cooperation with the outreach activities at the partner institutions. Traditionally, science communication has focused on scientific results and their implications, but less on the scientific process itself. Therefore, public engagement in the proposed Cluster will also address this gap, especially by involving early-career researchers. Of equal importance is the consideration of gender awareness in the communication strategy of the Cluster. Gender-sensitive communication will consider language, image selection, and choice of speakers on the one hand, and consideration of diversified target groups on the other.

In order to communicate knowledge most effectively, scientific facts will be directly conveyed by the individuals involved. Dedicated topics will focus on researchers and their fields of research, their methods, and their scientific approaches. This will enable us to not only present research results but also to reveal the scientific processes. The selection of ocean-floor related topics for the next 3 to 5 years will include life in the deep sea, sea-level and climate change, humans and oceans, and the origins of life.

Box 5: Achievements in Public Engagement

The portfolio of existing science-communication activities consists of various elements: information via website and social media channels such as Twitter, Facebook and YouTube, hands-on exhibitions, school lab courses, and public media outlets. A number of distribution channels are used to efficiently address local, national, and international media. Social media channels are followed by a continuously increasing number of people.

The MARUM TV channel on YouTube with more than 100 clips plays an important part in communication, particularly with TV journalists and museums who are interested in using our underwater footage in documentaries and exhibitions. Scientists also follow news on MARUM TV and use footage in their lectures. Individual films, those about life in the deep, for example, have more than 50,000 views. Moreover, the films are presented by media websites such as National Geographic, Deutsche Welle TV (Berlin) or Focus magazine TV (Munich).

Exhibitions are growing in importance for public engagement. The travelling exhibition "Experience the Sea" (MeerErleben), which was on display between 2009 and 2017 in shopping centers across Germany and in neighboring countries, welcomed an estimated 800,000 visitors (based on 10 % of 8 million customers) – many of whom would normally not visit museums. Moreover, we closely cooperate with museums across Germany by supporting permanent (Deutsches Museum, Munich; Ozeaneum, Stralsund; International Maritime Museum, Hamburg) and temporary exhibitions (e.g., Bremerhaven, Münster, Bonn, Berlin).

For school classes and teachers, regular courses with a central focus on marine sciences have been offered by the MARUM UNISchool lab since 2001. The courses target classes from grades 3 to 12, with a focus on grades 5 to 8, to promote an interest in natural sciences. Presently, approximately 3,500 pupils participate annually. For several years the lab has maintained its participation in international cooperative projects (e.g., EMSEA and GIZ Bremen-Durban).

In addition to established formats in science communication, new interactive formats will be incorporated, such as dialogues with the public and stakeholders on controversial topics, as well as citizen science projects. For example, interested people not working directly in science could be involved by comparing old coastlines on maps with more recent photographs to create a data set. Such a data set would show how coastlines have changed over decades. In this way, we can combine the emotional attachment that people have to the sea with research, and raise the awareness of climate change. Cross-media activities are also part of this overall approach, including multimedia features, stop-motion films, and virtual-reality projects like the "Virtual Deep Sea", funded by the Federal Ministry of Education and Research. The virtual-reality module was presented across Germany in order to raise awareness of the importance of the ocean floor. An expansion of its content is planned. All activities will involve established and new partners in science and education, especially from the partner institutions (e.g., in Bremerhaven and Oldenburg), but also from schools and museums – expanding existing partnerships and seeking new ones. Similar to the processes and collaborations in scientific research, public communication and engagement are also based on cooperative work with international partners. To ensure sustainability, products generated within the framework of these targeted outreach activities will be available through the Cluster website.

Beginning at the ocean floor, hydrothermal vents, cold-water corals and the deep biosphere will be at the center of attention. With manifold public-engagement activities (see below), key questions shall be addressed and answered, including: How do we characterize life at the ocean floor? What conditions and processes enable life in the deep sea? How do ecosystems work in the deep sea? The science communication activities comprise diverse elements, e.g., talks, podcasts, social media, virtual reality, graphic elements and exhibits. This variety will allow us to prepare topics for specific target groups and convey versatile content. Each topic will be an opportunity to prepare teaching and working material for school classes. Our partnership in the European Marine Science Educator Association (EMSEA) will help us to integrate these efforts into an international framework.

The aim of our public engagement is to create points of contact between science and everyday life for all target groups and to increase the "ocean knowledge and literacy" of the general public. It is possible to pursue unconventional pathways toward this goal, bringing marine research ideas to people within the context of their daily lives, and discussing scientific topics in ways that they can relate to. This is important because, while politicians and journalists often seek direct contact with scientists and public-relations bodies, we approach the general public to arouse their curiosity and interest in the work of the Cluster, the marine sciences, and scientific research in general. Examples of this include the joint science-communication project in Bremen "Science goes public", co-organized by the MARUM science communication staff, and the virtual-reality exhibition "Virtual Deep Sea" presented in shopping malls across Germany.

Table 4.3: Funding Request for Management, Quality Assurance and Public Engagement

	2019	2020	2021	2022	2023	2024	2025
Funding category	**Totals per year in k€**						
Staff	815	840	865	891	918	945	974
Direct project costs (excl. staff)	205	211	217	224	231	238	245
Instrumentation	0	0	0	0	0	0	0

Justification: Support for Cluster-specific requirements in research-data management (2 scientists, 1 engineer) and public engagement (1 press officer [salary equivalent to scientist], 1 scientist for implementation of science communication, 1 technical assistant for support of online formats). Central management of the Cluster includes assistant to the spokesperson (1 scientist), IT support (2 engineers) and handling of finances and daily business (2 administrative positions, 1 secretary). **Direct project costs:** (costs for 2019; for subsequent years an annual increase of 3 % is assumed) include travel to represent the Cluster at conferences and for meetings of the Scientific Advisory Board (30 k€ / yr), language training for incoming scientists (5 k€ / yr), science communication (50 k€ / yr for online channels, print media, exhibitions and travel), software licenses for research-data management (10 k€ / yr), software licenses for scientists and consumables for existing IT equipment (40 k€ / yr), costs for open-access publications (25 k€ / yr), costs for job advertisements (15 k€ / yr), and business supplies for the entire Cluster (30 k€ / yr).

5 ENVIRONMENT OF THE CLUSTER OF EXCELLENCE

5.1 DEVELOPMENT PLANNING AT THE UNIVERSITY

The proposed Cluster will enhance the international visibility and development of the University of Bremen in several important ways. First, the Cluster will significantly strengthen the University of Bremen’s interdisciplinary high-profile area “Marine, Polar and Climate Research” (cf. Appendix A7) as well as the already solid ties between the University and its partners, with an impact on talent management, including activities such as joint strategic hiring, dual career opportunities, and diversity management. The Cluster will exploit the full research potential among its partner institutions and will enhance the national and international visibility of marine science in the region (cf. Table 5.1). Continuing support of this research area, which is also one of the five research foci of the State of Bremen, is evidenced by the large number of newly created professorships in the field of marine sciences (seven since 2001) and the construction of new buildings (see Section 5.2). This long-term development will be continued by the establishment of a professorship (see Section 3.4.7) and the provision of funds for expansion of the building infrastructure (see Section 5.2).

Second, the envisioned Excellence Chairs (see Section 3.4.7) are seen as a model for the University of Bremen to enhance its visibility and to attract outstanding international researchers to Bremen. The University has therefore decided to extend this model to other high-profile areas or emerging fields by means of the university allowance (see Appendix A7).

Third, the Cluster will provide important momentum for the University of Bremen toward its strategic goals to support early-career researchers and equal opportunity. Of special importance are the extension of the support program for early-career scientists to include postdoctoral researchers and the requisite plans to increase the number of women at all career levels. The Cluster will benefit greatly from the fruitful and long cooperation between the University’s equal opportunity department and MARUM, including its partners.

Fourth, the Cluster will pave the way for the new tenure-track system for outstanding researchers at the University of Bremen, for which the legal framework was created in 2017. While the transformation of existing personnel categories into the new framework will likely be a process lasting decades, the Cluster will promote this development by temporarily funding a significant number of such positions before their transfer to the core budget of the University/MARUM. The Cluster will use the new tenure-track option to attract and retain outstanding early career researchers. It is foreseen that up to 10 tenure-track positions will be filled at the University of Bremen by 2025 and that at least half of the positions will be filled by female researchers. Positions will either be advertised in response to new research developments or will be offered to outstanding early-career scientists originally hired as Postdocs in the Cluster. The Steering Committee will endorse scientists for tenure-track options based on at least three external reviews and by taking into account equal opportunity and diversity issues. The final decision on granting a tenure-track option lies with the President of the University of Bremen. Funding for the positions (before being transferred to the core-budget of the University) is implicitly included in the budgets of the Research Units and Enablers of this proposal.

Finally, the University is currently developing a research-data management strategy for the entire institution that builds heavily on our experience with complex data in PANGAEA, and that will greatly benefit from the planned developments in improving accessibility, explorability, and connectivity of a wide range of heterogeneous data generated in the Cluster (see Section 4.3).

Table 5.1 | Development potential within the framework of the Cluster together with the strengths and weaknesses.

<table>
<tr><th>Strengths</th><th>Weaknesses</th></tr>
<tr><td rowspan="3">
• Highly innovative, dynamic and productive staff at all levels
• A culture of strong cooperative spirit from the individual-to-institutional and national-to-international levels
• Track record of collaborative and interdisciplinary research and high-impact publications
• Demonstrated acquisition strength in highly competitive research-funding programs
• Science-driven technology developments in cooperation with industry
• World-class laboratory facilities, underwater vehicles, and platforms
• Well-established network of university and non-university partners with highly complementary profiles
• Long-term support of marine sciences by University and State of Bremen
• Constantly increasing success in diversity and talent management
• Exceptionally high level of autonomy and support within the University
</td><td>
• Several laboratory facilities and sea-going instruments will require large investments for modernization during the next decade
• Time lag of several years between planning and execution of sea-going expeditions
• Loss of knowledge due to high turnover of early career researchers having temporary positions
• Potential loss of technical know-how due to retirement of a cohort of highly skilled technical personnel during the next decade (will be compensated by timely transfer of knowledge to next generation of personnel that will partly overlap with existing positions)
</td></tr>
<tr><th>Development Potential</th></tr>
<tr><td>
• Providing flexibility towards new developments in marine research through process-oriented multidisciplinary research
• Attracting outstanding scientists through the new tenure-track option in Bremen
• Increasing the number of female scientists and preparing them for leadership positions
• Developing new scientific themes by attracting highly innovative early career researchers
• Transforming science by means of science-driven technological developments in collaboration with engineering
• Contributing to and co-leading the strategic development of international programs
• Streaming fundamental knowledge into ocean assessments and providing society with impartial knowledge
</td></tr>
</table>

5.2 BASIC FRAMEWORK

The Research Faculty MARUM is the University-based hub of a diverse marine-research landscape within the State of Bremen, which has the highest concentration of marine-research institutions in Germany. Approximately 40 % of all marine scientists in Germany are working in the State of Bremen (*Wissenschaftsrat*, 2010, *Empfehlungen zur zukünftigen Entwicklung der deutschen marinen Forschungsflotte,* Drs. 10330-10). This proportion increases to 44 % when the marine-research institutions in northern Lower Saxony (University of Oldenburg, SGN) are included.

The core funding for the Cluster will be provided by the University of Bremen as part of the support of the Research Faculty MARUM. This annual core funding amounts to approximately 8 million Euros. It includes 16 affiliated professorships with their own research groups and science-support staff (see Section 3.3) as well as 4 independent working groups led by senior scientists with permanent positions (J.-H. Hehemann, *Marine Glycobiology*; M. Ikari, *Experimental Geomechanics*; A. Rovere, *Sea Level and Coastal Changes*; M. Zabel, *Sediment Geochemistry*). Additional funding (currently 1.5 million Euros per year) is received from the Federal State of Bremen to support the Research Faculty. The State intends to increase its funding to 3.5 million Euros in 2019 and to 4 million Euros from 2020 onward to meet its commitment to sustainability associated with the transformation of MARUM into a Research Faculty. Finally, the proposed Cluster will benefit from the recently established "Innovation Center for Deep-Sea Observing Systems", which is funded for the next ten years by the private Werner-Siemens-Foundation (Switzerland) and includes a new professorship in "Underwater Technology / Deep-Sea Engineering" (filled in July 2017 by R. Bachmayer).

In addition to funding personnel, the University has provided the 5,100 m^2 MARUM building, completed in early 2005 and expanded by 1,300 m^2 in 2009, and by another 440 m^2 in 2015. This building complex provides space for the core repository, underwater equipment, laboratories and offices, and will house the main body of the proposed Cluster. The MARUM uses an additional ~1,000 m^2 of laboratory and office space in other University buildings on the campus. In order to accommodate the demand for space in the coming decade, the University and the State of Bremen have budgeted the necessary funds and submitted a building application to the federal-states program for an additional building (approx. 4,000 m^2) for MARUM (full proposal submitted in January 2018). High-performance computing for using comprehensive Earth-system models is available via the North-German Supercomputing Alliance, of which the State of Bremen is a member.

5.3 COLLABORATION, TEACHING, KNOWLEDGE TRANSFER

The Cluster will expand the levels of collaboration, teaching and knowledge transfer at the University of Bremen with the following specific measures.

Collaboration – The Cluster will expand the long-standing and successful collaborations among its partner institutions (Univ. Oldenburg, Jacobs Univ., AWI, MPI-MM, SGN, and ZMT), which have led to numerous joint publications, projects, and ship-based expeditions. Joint research activities among the partners have resulted in the existing DFG Research Center / Cluster of Excellence "The Ocean in the Earth System" and several collaborative research projects (including the two International Research Training Groups INTERCOAST and ArcTrain, both funded by the DFG).

New collaborations will involve marine chemistry, biology and ecosystem research (Univ. of Oldenburg and AWI) and marine robotics (Jacobs University). Within the University of Bremen, new collaborations have already been established in the fields of marine chemistry, engineering, and informatics that will strengthen the Cluster in the Enablers Tracers and Technology. In addition, the Helmholtz Association will support the Cluster through an Excellence Network, with the specific aim of creating and supporting links between seven existing junior-research groups in the wider framework of the Cluster.

Binding cooperative agreements are in place to ensure collaborative research between institutions. A template for the cooperative agreements was established as early as 1982 between the University of Bremen and AWI. It defines joint professorships and opens the opportunity for heads of sections at the AWI to become professors at the University of Bremen and, furthermore, for AWI staff to be engaged in teaching. It also allows for mutual access to research infrastructure. The AWI-MARUM Alliance (AMAR), established in 2010, develops strategies for opening new fields of collaboration (e.g., climate research, underwater technology, Earth-system data infrastructures) and has resulted in several joint projects. Similar bilateral agreements exist with all other non-university marine research institutions included in this proposal. Furthermore, cooperative agreements are in place between the University of Bremen and the University of Oldenburg (since 2000) and the private Jacobs University (since 2001).

MARUM and its partners are thoroughly integrated in the national marine research community. All partners of the proposed Cluster are members of the German Marine Research Consortium (KDM). For more than 10 years, the KDM has fostered strategic collaboration among its member institutions and collectively represented the interests of marine research to decision-makers in Germany and the European Union.

At the international level, active cooperative agreements in marine sciences are in place with universities in Montreal (Canada, representing a consortium of eight Canadian universities), Waikato (New Zealand), Tongji (China), Tokyo (Japan), as well as the institut français de recherche pour l'exploitation de la mer (Ifremer, France), the Royal Netherlands Institute for Sea Research (NIOZ), and the National Oceanography Centre, Southampton (NOC, UK). The agreements have the goals of personnel exchange and joint research activity. In the area of underwater technology, long-standing collaborations exist with Ifremer, the Woods Hole Oceanographic Institution (WHOI, USA), the Monterey Bay Aquarium Research Institute (MBARI, USA), and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC, Japan).

Teaching – Research-oriented teaching is a cornerstone of the educational strategy of the University of Bremen. Along these lines, international marine-oriented master's programs exist in marine geosciences, environmental physics, and marine (micro)biology. Development of these programs has benefitted greatly from the ongoing Excellence Initiative and the associated new professors, who are academic teachers in these programs. On average, 50 students obtain a master's degree under these marine-oriented programs each year. Within the Cluster we will expand research-oriented teaching to include the undergraduate level by creating, e.g., an interdisciplinary online course on ocean-floor related topics. The course will specifically address topics of societal relevance. The online course will build on our experience in the massive open online course on climate change, which was developed within the framework of the German Climate Consortium (DKK) and attracted more than 10,000 participants.

Knowledge transfer – For the development of new equipment and for improvements to complex analytical instruments, there is a need for knowledge transfer and cooperation with industry. An example is the construction of the MeBo sea-floor drill rigs. The rigs were planned by us and built according to our specifications in close cooperation with companies in the USA (Schilling Robotics) and Germany (Prakla Bohrtechnik, Peine and Bauer AG, Schrobenhausen). This novel drilling concept has generated considerable commercial interest in the offshore industry.

To foster collaborations with industry partners, the Cluster will initiate a bi-annual workshop series on "Innovation in Underwater Technology" with an eye toward transferring the scientific needs to industry partners and encouraging manufacturers to standardize equipment interfaces. In addition, we plan residencies by the Cluster's technical personnel with industry partners (e.g., Bauer, Schilling Robotics) to gain deeper insights into specific aspects of the use and application of equipment in ocean-floor settings.

Table 5.3: Funding Request for Collaboration, Teaching, Knowledge Transfer

	2019	2020	2021	2022	2023	2024	2025
Funding category	**Totals per year in k€**						
Staff	72	74	0	0	0	84	0
Direct project costs (excl. staff)	90	140	65	115	65	140	65
Instrumentation	0	0	0	0	0	0	0

Justification: Online course requires one scientist (implementation in years 2019/2020 and update to include findings from Cluster in 2024). **Direct projects costs** include travel for guest scientists and scientific workshops (60 k€/yr), costs for online course (25 k€/yr for external graphics and filming in 2019/2020/2024), costs for bi-annual knowledge-transfer workshops (50 k€ per workshop, in 2020/2022/2024), and costs for residencies with industry (5 k€/yr; one 3-month stay per year).

5.4 LINKS WITH PROJECTS CURRENTLY FUNDED THROUGH THE EXCELLENCE INITIATIVE

This proposal builds on the previous Cluster of Excellence "The Ocean in the Earth System" (funded since 2007; see Appendix A6 for a summary), which, in turn, was an extension of the already existing DFG Research Center "Ocean Margins – Research Topics in Marine Geosciences for the 21st Century" (funded since 2001). Furthermore, core elements of our PhD-student education program were established through the Graduate School "GLOMAR – Global Change in the Marine Realm", which was funded in the first phase of the Excellence Initiative and was integrated into the Cluster in 2012.

The proposed Cluster, while clearly benefitting from the developments in the Excellence Initiative, is distinctive in terms of its research focus, disciplinary range and its structural goals. Research in the previous Cluster encompassed the areas 'ocean and climate', 'geosphere-biosphere interactions', and 'sediment dynamics'. Accordingly, the thematic scope of the previous Cluster was much broader than the research agenda of the proposed Cluster with its focus on ocean-floor processes. The thematic shift and focusing is also reflected in the composition of the PI group. Thirteen of the 25 PIs in this proposal were not involved as PIs in the previous Cluster. This change in the composition of the PI group is related to the disciplinary scope, which has shifted from a concentration on geosciences to a more balanced representation of disciplines. In particular, the involvement of biologists will be strengthened with the new Cluster.

Building on the achievements of the previous Cluster, the planned Research Units will be distinctive in many aspects: For example, the intended work on particle transfer (RECEIVER) will consider the transformation of biogenic particles at a molecular level while the previous Cluster addressed primarily the net flux of particles. Similarly, the geodynamic forcing of geosphere-biosphere interactions (REACTOR) was beyond the scope of the previous Cluster. With respect to understanding past climate changes, the previous Cluster was instrumental in the integration of proxy-based reconstructions with climate modeling. The proposed Cluster will shift the research focus (RECORDER) from cold climate states to warm climate states and geologically toward older archives. While ecosystem research was not included in the previous Cluster, it will be an important aspect in the three planned Research Units, and enhanced by PIs of the new Helmholtz Institute on Functional Marine Biodiversity (HIFMB) in Oldenburg. Several lines of research that were central to the previous Cluster are not included in this proposal but will be continued through other projects hosted by the Research Faculty MARUM (e.g., coastal research, sedimentation processes in estuaries and on shelves, submarine landslides and geohazards, and mineral dust in the Earth system).

The previous Cluster was instrumental in setting up the analytical and technological research infrastructures (see Boxes 2 and 3) that provide the foundations for the planned work. With regard to underwater technology, the main scope of the previous phase was on the operation of the equipment, whereas the future Cluster will focus on the development of scientific payloads to exploit the full potential of the equipment.

By integrating the formerly independent Graduate School GLOMAR, the previous Cluster offered its education program to PhD students in marine sciences across all disciplines (including law, social sciences, and humanities). While this important component of education will be transferred to MARUM (see Section 4.1), the new Cluster will expand education to include early-career postdocs.

The major structural objective of the previous Cluster was to strengthen marine sciences at the University of Bremen, and the key outcome of this objective was the permanent establishment of MARUM as the first and only Research Faculty of the University of Bremen. The proposed Cluster will make full use of this new organizational and governance structure to achieve its overarching goals.

6 FUNDING REQUEST

Table 6.1: Total Funding Requested for the Research Program

Research Units, Enablers, etc.	Funding category	Total in k€ 2019 – 2025
Research Unit RECEIVER	Staff	5,979
	Direct project costs (excl. staff)	1,655
	Instrumentation	470
Research Unit REACTOR	Staff	7,126
	Direct project costs (excl. staff)	1,600
	Instrumentation	0
Research Unit RECORDER	Staff	5,647
	Direct project costs (excl. staff)	1,210
	Instrumentation	100
Enabler DEEP-SEA TECHNOLOGY AND OCEAN-FLOOR OBSERVING SYSTEMS	Staff	1,856
	Direct project costs (excl. staff)	630
	Instrumentation	750
Enabler MOLECULAR AND ISOTOPIC TRACERS	Staff	1,667
	Direct project costs (excl. staff)	535
	Instrumentation	330
Enabler OCEAN FLOOR MODELING FRAMEWORK	Staff	1,656
	Direct project costs (excl. staff)	345
	Instrumentation	120
CENTRAL RESEARCH SUPPORT	Staff	7,740
	Direct project costs (excl. staff)	6,184
	Instrumentation	0
Total		**45,600**

Table 6.2: Total Funding Requested for Structural Measures

Structural measures	**Amount in k€ 2019–2025**
Early career researchers	1,641
Equal opportunity [1]	492
Management and quality assurance	4,009
Research data	1,945
Public engagement	1,865
Collaboration (excluding Excellence Chairs)	420
Research-oriented teaching	305
Knowledge transfer	185
Total	**10,862**

[1] In addition to the funds requested here, the planned 50 % female quota for ECRs in the Cluster (see Section 4.2), will result in a substantial contribution from the ECR-support budget to support female scientists.

Table 6.3: Total Staff Requested [1]

	2019	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**
Staff category	**Number of persons**						
Professors	1	1	1	1	1	1	1
Excellence Chairs	3	3	3	3	3	3	3
Independent junior research group leaders [2]	0	0	0	0	0	0	0
Postdoctoral researchers [3]	32	40	40	40	39	39	38
Doctoral researchers [4]	15	23	26	27	27	26	22
Other staff	16	16	15	15	15	15	15

[1] Staff costs based on DFG staff-funding rates for 2018 and assuming an annual increase of 3 %.
[2] Due to the fact that several existing independent junior research groups would contribute to the proposed Cluster, we do not apply for additional groups. We intend to provide partial support to these groups and to new incoming groups through the Cluster.
[3] Approximately ⅓ of the positions in this category are for experienced scientists (incl. tenure-track positions). Salaries are based on real costs.
[4] PhD salary based on 66.6 % of full E13 salary.

Table 6.4: Total Funding Requested

	2019	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**Total**
Funding category	**Totals per year in k€**							
Staff	4,620	5,340	5,610	5,528	5,921	6,010	6,201	39,230
Direct project costs (excl. staff)	1,822	2,394	2,563	2,421	2,251	2,011	1,970	15,432
Instrumentation	1,145	180	20	245	20	170	20	1,800
Total project funding	**7,587**	**7,914**	**8,193**	**8,194**	**8,192**	**8,191**	**8,191**	**56,462**

APPENDIX

A 1 SUMMARY OF THE OVERALL CONCEPT OF THE CLUSTER OF EXCELLENCE

The proposed Cluster aims to initiate a new chapter in ocean-floor research by quantifying exchange processes at and within the ocean floor and their role in the Earth system. Making up 71 % of the Earth’s surface, the ocean floor is the largest solid interface on the planet. At and within the ocean floor, geological, physical, biological and chemical processes interact, thus influencing the climate system, the global carbon cycle, and biological productivity in the world ocean. While the ocean floor hosts unique ecosystems, such as chemosynthetic communities thriving at hot vents and cold seeps, or cold-water corals existing without light in the deep sea, it also incorporates an invaluable archive of Earth’s history, as environmental information is continuously recorded in the properties of accumulating sediment particles. On average, the ocean floor lies 3,700 meters beneath the ocean surface, and its exploration is dependent upon expeditions with research vessels and the use of highly specialized underwater equipment. As yet, only a tiny fraction of the ocean floor has been scientifically investigated. Because of its inaccessibility to humankind, the ocean floor is the last largely intact natural habitat on the planet. This situation is likely to change, with increasing pressure from climate-change dynamics, resource extraction, pollution and ocean acidification impairing the integrity of ocean-floor ecosystems. In this regard, a basic knowledge of ocean-floor processes, dynamics and resilience is crucial in order to inform policy makers, and to instill natural conservation values in future generations.

As one of the world’s leading hubs for marine Earth-system research, equipped with interdisciplinary expertise, cutting-edge seagoing technology, a unique analytical infrastructure, and advanced Earth-system modeling capabilities, we aim to **systematically transform ocean-floor research from a largely disciplinary level to an integrative research field**. Presently, we still know too little about ocean-floor processes to compile detailed global mass budgets, but this knowledge is essential for understanding the role of the ocean within the entire Earth system. Therefore, the Cluster will **elucidate and quantify the key processes that are responsible for the transfer of matter to, and its transformation at the ocean floor, and use marine sediment archives to constrain the rates and sensitivities of these processes to global changes and perturbations.** Our intended research will fill major knowledge gaps and **provide information for ocean governance within the framework of the United Nations Sustainable Development Goals and climate policies**. We are prepared to communicate the Cluster’s scientific findings to the public and to facilitate informed decision-making for the protection of the marine environment and sustainable use of the ocean and its resources.

Research in the proposed Cluster will address the following **overarching scientific objectives**:

To understand the processes that transform the properties and fluxes of biogenic particles on their transit to the ocean floor under changing climate conditions: The transfer of biogenic particles through the water column to the ocean floor and the partitioning of organic matter between the shelf and open ocean play a pivotal role in the climate system by affecting atmospheric carbon-dioxide (CO_2) content. The associated biological pump, that is, the rate of organic-matter transfer to the ocean floor, depends on the biological transformation during particle transit. Fundamental knowledge gaps regarding the transformation of biogenic particles result in grossly simplified representations of the biological pump in global biogeochemical models. The Cluster will significantly improve the understanding of how biogenic particles are transformed before and after reaching the ocean floor, and will use this information to critically enhance global biogeochemical models.

To quantify fluxes of carbon and other elements to and across the ocean floor and estimate their budgets under current and past states of the Earth system: The ocean floor is not only a receiver of particle fluxes from the overlying water column, but also a reactor, whose products may eventually escape into the ocean. Geodynamic and biogeochemical processes associated with oceanic plate boundaries and continental margins control the fluxes of biologically relevant elements across the ocean-floor interface on geological timescales. While many of the underlying mechanisms have been identified, a comprehensive picture of the interconnected element cycles and their feedbacks within the Earth system is only beginning to emerge. By acting globally, these processes ultimately also control the uptake of anthropogenic CO_2 by the oceans. The Cluster intends to provide pivotal knowledge towards the quantification of relevant element fluxes, and to develop modeling frameworks that integrate multidisciplinary observations into a global synthesis over a wide range of timescales.

To generate an in-depth understanding of how the structure and state of ocean-floor ecosystems are interrelated with local-scale biogeochemical processes and other environmental conditions: The ocean floor hosts diverse ecosystems, many of which occupy extreme environments. For example, hot vents and cold seeps support abundant chemosynthetic life at the ocean floor. Here, unique ecosystems are ultimately shaped by geological and tectonic processes. Microbial processes within the ocean floor are key drivers of biogeochemical element cycles. Neither the diversity nor the functioning of these ecosystems, nor their interactions with biogeochemical processes has yet reached a satisfactory level of quantitative understanding. Such an understanding is required to assess, for example, the potential impact of deep-sea mining on these ecosystems. Cold-water coral ecosystems, occurring at continental margins, are oases of life at the ocean floor. While these are globally threatened by human activities, e.g., by fishing, our knowledge about the environmental conditions that allow these ecosystems to thrive is far too limited to establish conservation concepts. The Cluster will greatly enhance the knowledge base related to these ocean-floor ecosystems, and facilitate a quantitative understanding of their role in shaping the ocean-floor environment at a global scale.

To derive scenarios for "warmer worlds" through comprehensive decoding of environmental signals from past warm climate conditions as recorded in ocean-floor archives: Instrumental records alone cannot provide reliable information about the potential consequences of global warming because climate conditions such as those now projected for the near future have never been directly observed. Since warming by more than 2 °C by the end of this century cannot be ruled out, it is of utmost importance to provide scenarios for warm climate conditions (> 2 °C) that include threshold processes, which are only incompletely captured in state-of-the-art climate models. By making full use of environmental information from warm periods in the Earth's history, which is archived in ocean-floor sediments, the Cluster will inform climate models and deliver critical new knowledge about changes in ocean circulation, the hydrological cycle, biological productivity, and the state of the cryosphere (incl. sea level) during periods with warmer climate conditions. In combination with Earth-system models, this paleoclimate information will greatly improve the robustness of climate scenarios for the future.

Achieving these scientific objectives will transform ocean-floor research from a largely disciplinary level to an integrative research field that will provide novel insights into the functioning of the largest solid interface on the planet and its role in the Earth system. A further key objective is to provide core underpinning methodologies that will enable us to reach our scientific goals. Innovative developments in the existing seagoing systems will enhance our capabilities for sampling particles in the water column, for example, or for conducting real-time 3D environmental mapping. Novel analytical approaches will increase our capabilities for deciphering environmental information encoded in organic molecules and in the isotopic compositions of matter at the ocean floor. Finally, model developments will target identified shortcomings regarding the representation of ocean-floor processes in existing modeling systems and provide the means for integrating local and regional information into a global framework.

Research approach and partner institutions – An interdisciplinary team of geoscientists, (micro) biologists, biogeochemists, and environmental physicists will jointly apply their expertise in combination with highly advanced research infrastructures to address the scientific challenges in ocean-floor research. By tightly linking seagoing expeditions with shore-based analyses, experiments, and numerical modeling, we will achieve significant advances in ocean-floor knowledge. Shore-based work will make full use of a unique array of state-of-the-art analytical instruments that enable us to decode crucial information captured in organic molecules, minerals, and the isotopic compositions of organic and inorganic matter.

The university and its partner institutions (Univ. Oldenburg, Jacobs Univ., AWI, MPI-MM, SGN, and ZMT), who will implement the work of the Cluster, are highly qualified for the proposed investigations, based on an array of extensive mutual preliminary work carried out over many years. Cooperative agreements are in place to ensure collaborative research between institutions. The proposed Cluster will be hosted by the Research Faculty MARUM – Center for Marine Environmental Sciences of the University of Bremen. Through decades of groundwork in national and international projects, a unique expertise exists among the Cluster partners to successfully carry out challenging interdisciplinary expeditions. For the subsequent generation of scientific data, a wide spectrum of methods and the most modern laboratory equipment, unrivaled worldwide, are available. The Cluster will make it possible to develop the full potential in ocean-floor research among the involved partners by building on a foundation of unique complementary expertise, long-term cooperation, and world-class analytical facilities and research infrastructures.

Early career researcher support – The integrated support program will offer training, resources and career guidance to enhance the early career researcher's sense of self-responsibility and academic independence. These offers will be embedded in an interdisciplinary and international environment of outstanding research conditions to foster excellence in ocean-floor research. The unique combination of specialized education in ocean-floor science, transferable skills training, international networking, and support of professional development will enhance the career prospects of early career researchers not only in academia but also in the broader job market.

Equal opportunity support – The Cluster will benefit from the existing leadership and organizational culture of MARUM to promote gender equality and diversity. Cluster-specific goals encompass a minimum of 40 % female members in the decision-making bodies and a marked increase in the share of female scientists at the senior and professorial levels. The equal opportunity strategy of the Cluster will be overseen by the Spokespersons and will focus on five specific objectives: (i) to aim for a balanced gender ratio among all researchers, (ii) to improve the gender balance in leadership positions and decision-making committees, (iii) to increase employment opportunities for female scientists in their next career phase, (iv) to increase awareness of gender bias in supervisory and staff selection processes, and (v) to further develop a gender-balanced academic culture.

Research-data management – To facilitate data management, MARUM and AWI jointly operate the World Data Center "PANGAEA – Data Publisher for Earth & Environmental Science", which will form the backbone for research-data management in the Cluster and is an asset in the growing field of data science. In order to support the interdisciplinary research of the Cluster, its data-management team will work hand in hand with PANGAEA to develop new data-management services.

Public engagement – Planned activities will promote dialog on marine environmental topics with the general public, stakeholders, and schools. Outreach activities in the Cluster will also include information on the scientific process itself. Early career researchers will be involved in outreach activities at all levels. Of equal importance is the consideration of gender and diversity awareness in the communication strategy of the Cluster. Gender- and diversity-sensitive communication will consider language, image selection, and choice of speakers on the one hand, and consideration of various target groups on the other.

Transfer of knowledge – To foster collaborations with industry partners, the Cluster will initiate a bi-annual workshop series on "Innovation in Underwater Technology" with an eye toward transferring the scientific needs to industry partners and encouraging manufacturers to standardize equipment interfaces. In addition, we plan residencies by the Cluster's personnel with industry partners.

Role of the Cluster for the University of Bremen – The proposed Cluster will enhance the development of the University of Bremen in several important ways. It will significantly strengthen the University of Bremen's interdisciplinary high-profile area "Marine, Polar and Climate Research" as well as the already solid ties between the University and its partners. Through the Cluster, the potential for ocean-floor research among all of the participating partner institutes can be strategically linked and fully exploited, resulting in enhanced visibility of marine science in the region at the national and international levels. The Cluster will also provide important momentum for the University of Bremen toward its strategic goals to support early-career researchers. Of special importance are the extension of the support program for early-career scientists to include postdoctoral researchers, and the requisite plans to increase the number of women at all career levels. To systematically strengthen our research profile, three "U Bremen Excellence Chairs" will be filled by distinguished international scientists who will work part-time in Bremen. The envisioned Excellence Chairs are seen as a model for the University of Bremen, to enhance its visibility and to attract outstanding international researchers to Bremen. The University has therefore decided to extend this model to other high-profile areas or emerging fields by means of the university allowance. Finally, the Cluster will pave the way for the new tenure-track system for outstanding researchers at the University of Bremen, for which the legal framework was created in 2017.

A 2 THE 25 MOST IMPORTANT PUBLICATIONS FOR THE CLUSTER OF EXCELLENCE

Principal investigator for the Cluster; *Members* of MARUM at the time of publication

1 **Boetius**, A. and F. *Wenzhöfer* (2013), Seafloor oxygen consumption fuelled by methane from cold seeps, Nature Geoscience, 6, 725–734. (A synthesis of chemical-flux measurements at ocean-floor cold-seep systems, arriving at an estimate of annual global methane emissions of up to 0.02 Gt; the methods used exemplify future budgeting approaches.)

2 *Bowles*, M. W., J. M. *Mogollon*, S. *Kasten*, M. *Zabel*, and K. U. **Hinrichs** (2014), Global rates of marine sulfate reduction and implications for sub-sea-floor metabolic activities, Science, 344, 889–891. (Estimate, using an artificial neural network, of the global flux of sulfate into the ocean floor, where it is utilized by microbes for the respiration of sedimentary organic matter; the study exemplifies future efforts to determine the fluxes of various chemicals across the ocean floor.)

3 **Dittmar**, T. and J. Paeng (2009), A heat-induced molecular signature in marine dissolved organic matter, Nature Geoscience, 2, 175–179. (Dissolved organic matter in the ocean contains compounds that bear signatures of the thermogenic alteration of organic matter that may have taken place in deeper, geothermally heated layers of the "ocean-floor reactor".)

4 **Freiwald**, A., L. Beuck, A. Rüggeberg, M. Taviani, and D. **Hebbeln** (2009), The white coral community in the Central Mediterranean Sea Revealed by ROV Surveys, Oceanography, 22, 58–74. (Discovery of previously unknown coral habitats using MARUM-based ocean-floor observing technology.)

5 **Hehemann**, J. H., P. Arevalo, M. S. Datta, X. Yu, C. H. Corzett, A. Henschel, S. P. Preheim, S. Timberlake, E. J. Alm, and M. F. Polz (2016), Adaptive radiation by waves of gene transfer leads to fine-scale resource partitioning in marine microbes. Nature Communications, 7, 12860. (Demonstrates that horizontal gene transfer in marine microbes is an important driver of niche filling through adaptive radiation. The resulting adaptation exerts an important control on the degradation of organic matter.)

6 **Hillebrand**, H. and B. Matthiessen (2009), Biodiversity in a complex world: consolidation and progress in functional biodiversity research, Ecology Letters, 12, 1405–1419. (New conceptual framework, according to which the implementation of trait-based approaches will result in more realistic predictions of the consequences of altered biodiversity on ecosystem function.)

7 Inagaki, F., K. U. **Hinrichs**, Y. Kubo, M. W. *Bowles*, V. B. *Heuer*, W. L. Hong, T. Hoshino, A. Ijiri, H. Imachi, M. Ito, M. Kaneko, M. A. Lever, Y. S. Lin, B. A. Methe, S. Morita, Y. Morono, W. Tanikawa, M. Bihan, S. A. Bowden, M. *Elvert*, C. Glombitza, D. Gross, G. J. Harrington, T. Hori, K. Li, D. Limmer, C. H. Liu, M. Murayama, N. Ohkouchi, S. Ono, Y. S. Park, S. C. Phillips, X. *Prieto-Mollar*, M. Purkey, N. *Riedinger*, Y. Sanada, J. Sauvage, G. Snyder, R. Susilawati, Y. Takano, E. Tasumi, T. Terada, H. Tomaru, E. Trembath-Reichert, D. T. Wang, and Y. Yamada (2015), Exploring deep microbial life in coal-bearing sediment down to ~2.5 km below the ocean floor, Science, 349, 420–424. (Most deeply buried microbial ecosystem within the ocean floor thus far discovered and its characterization as a ~20-million year old remnant of a former forest soil community.)

8 **Iversen**, M. H. and H. Ploug (2010), Ballast minerals and the sinking carbon flux in the ocean: carbon-specific respiration rates and sinking velocity of marine snow aggregates, Biogeosciences, 7, 2613–2624. (The first comprehensive dataset of carbon-specific respiration rate in marine particles as a function of their size, sinking velocity and composition, measured directly in three different aggregate types representing key components of the biological pump.)

9 Kalvelage, T., G. *Lavik*, P. Lam, S. Contreras, L. Arteaga, C. R. Löscher, A. Oschlies, A. Paulmier, L. Stramma, and M. M. M. **Kuypers** (2013), Nitrogen cycling driven by organic matter export in the South Pacific oxygen minimum zone, Nature Geoscience, 6, 228–234. (The efficiency of the biological pump exerts a strong control on the rates of nitrogen cycling and ultimately on the loss of fixed nitrogen from oxygen minimum zones.)

10 **Kučera**, M., A. Rosell-Melé, R. Schneider, C. Waelbroeck, and M. Weinelt (2005), Multiproxy approach for the reconstruction of the glacial ocean surface (MARGO), Quaternary Science Reviews, 24, 813–819. (A leading international effort to globally reconstruct sea-surface temperatures at the Last Glacial Maximum, based on the species compositions of micro fossils and geochemical methods, and exemplifying the quantitative analysis of climate-biota interactions.)

11 *Lipp*, J. S., Y. Morono, F. Inagaki, and K. U. **Hinrichs** (2008), Significant contribution of Archaea to extant biomass in marine subsurface sediments, Nature, 454, 991–994. (The concentrations and compositional distributions of intact microbial membrane lipids in marine sediments suggest that archaea are major members of the deep biosphere and have been underestimated by previous studies.)

12 McCollom, T. M. and W. **Bach** (2009), Thermodynamic constraints on hydrogen generation during serpentinization of ultramafic rocks, Geochimica et Cosmochimica Acta, 73, 856–875. (Geochemical reaction path models were developed that consider the full range of iron partitioning among all the phases involved in serpentinization; these models are now a cornerstone for predicting hydrogen production during water-rock interactions.)

13 *Mulitza*, S., D. *Heslop*, D. *Pittauerova*, H. W. Fischer, I. *Meyer*, J. B. *Stuut*, M. *Zabel*, G. **Mollenhauer**, J. A. *Collins*, H. *Kuhnert*, and M. **Schulz** (2010), Increase in African dust flux at the onset of commercial agriculture in the Sahel region, Nature, 466, 226–228. (Assessing the link between dust deposition and precipitation in tropical West Africa on timescales of societal relevance and deciphering the human contribution to dust mobilization from ocean-floor archives.)

14 **Müller**, J., A. Wagner, K. Fahl, R. Stein, M. *Prange*, and G. **Lohmann** (2011), Towards quantitative sea ice reconstructions in the northern North Atlantic: A combined biomarker and numerical modelling approach, Earth and Planetary Science Letters, 306, 137–148. (First combined biomarker / climate-modeling approach to establish quantitative sea-ice reconstructions; to be applied in testing links between sea-ice variability and ice-sheet (in) stability.)

15 **Pälike**, H., M. W. Lyle, H. Nishi, I. Raffi, A. Ridgwell, K. Gamage, A. Klaus, G. Acton, L. Anderson, J. Backman, J. Baldauf, C. Beltran, S. M. Bohaty, P. Bown, W. Busch, J. E. T. Channell, C. O. J. Chun, M. Delaney, P. Dewangan, T. Dunkley Jones, K. M. Edgar, H. Evans, P. Fitch, G. L. Foster, N. Gussone, H. Hasegawa, E. C. Hathorne, H. Hayashi, J. O. Herrle, A. Holbourn, S. Hovan, K. Hyeong, K. Iijima, T. Ito, S. Kamikuri, K. Kimoto, J. Kuroda, L. Leon-Rodriguez, A. Malinverno, T. C. Moore, B. H. Murphy, D. P. Murphy, H. Nakamura, K. Ogane, C. Ohneiser, C. Richter, R. Robinson, E. J. Rohling, O. *Romero*, K. Sawada, H. Scher, L. Schneider, A. Sluijs, H. Takata, J. Tian, A. Tsujimoto, B. S. Wade, T. *Westerhold*, R. Wilkens, T. Williams, P. A. Wilson, Y. Yamamoto, S. Yamamoto, T. Yamazaki, and R. E. Zeebe (2012), A Cenozoic record of the equatorial Pacific carbonate compensation depth, Nature, 488, 609–614. (A major revision of Cenozoic shifts in the equatorial Pacific carbonate compensation depth and application of Earth-system models in a novel fashion, exemplifying planned efforts to determine carbon-cycle interactions with relevance to Earth-system sensitivity.)

16 *Pape*, T., A. *Bahr*, J. *Rethemeyer*, J. D. Kessler, H. *Sahling*, K. U. **Hinrichs**, S. A. *Klapp*, W. S. Reeburgh, and G. **Bohrmann** (2010), Molecular and isotopic partitioning of low-molecular-weight hydrocarbons during migration and gas hydrate precipitation in deposits of a high-flux seepage site, Chemical Geology, 269, 350–363. (Retrieval of pristine samples of hydrocarbon gases at the ocean floor using various dedicated MARUM-housed sampling technologies. Sampling enables linking of geological processes at and within the ocean floor to the chemical and isotopic compositions of the gas mixtures.)

17 *Petersen*, J. M., F. U. Zielinski, T. *Pape*, R. Seifert, C. Moraru, R. *Amann*, S. Hourdez, P. R. Girguis, S. D. Wankel, V. Barbe, E. Pelletier, D. Fink, C. *Borowski*, W. **Bach**, and N. **Dubilier** (2011), Hydrogen is an energy source for hydrothermal vent symbioses, Nature, 476, 176–180. (Discovery of symbiotic relationships between hydrothermal vent animals and bacteria fueled by hydrogen rather than hydrogen sulfide or methane.)

18 Ranero, C. R. and M. **Pérez-Gussinyé** (2010), Sequential faulting explains the asymmetry and extension discrepancy of conjugate margins, Nature, 468, 294–299. (Development of a novel balanced kinematic model of continental breakup that produces both fault-controlled crustal thinning, which progresses from a rift basin to the asymmetric structure, and extreme thinning of conjugate rifted margins.)

19 *Roessler,* A.*,* M. **Rhein***,* D. *Kieke, and* C. *Mertens* (2015)*,* Long-term observations of North Atlantic Current transport at the gateway between western and eastern Atlantic, Journal of Geophysical Research – Oceans, 120, 4003–4027*.* (First observational North Atlantic Current transport time series in the ocean's interior that allows assessments of natural variability and suggests the potential link between ocean circulation and warmer climates.)

20 **Röhl**, U., T. *Westerhold*, T. J. Bralower, and J. C. Zachos (2007), On the duration of the Paleocene-Eocene thermal maximum (PETM), Geochemistry Geophysics Geosystems, 8. Q12002. (A cyclostratigraphic estimate for the duration of the Paleocene-Eocene Thermal Maximum that forms the foundation for the planned extended study of hyperthermal events during the Paleogene for associated high atmospheric CO_2 levels.)

21 Rubin-Blum, M., C. P. Antony, C. Borowski, L. Sayavedra, T. *Pape*, H. *Sahling*, G. **Bohrmann**, M. Kleiner, M. C. Redmond, D. L. Valentine, and N. **Dubilier**, (2017), Short-chain alkanes fuel mussel and sponge Cycloclasticus symbionts from deep-sea gas and oil seeps. Nature Microbiology, *2, 17093.* (Discovery of a novel symbiosis in deep-sea mussels and sponges at asphalt volcanoes in the Gulf of Mexico. These invertebrates harbor bacteria that can use short-chain alkanes as energy and carbon sources, thus expanding the range of substrates known to power chemosynthetic symbioses.)

22 Sander, S. G. and A. **Koschinsky** (2011), Metal flux from hydrothermal vents increased by organic complexation, Nature Geoscience, 4, 145 – 150. (The complexation of hydrothermally derived chromium, iron, and copper by seawater-derived dissolved organic molecules contributes to the dispersal of these metals in the deep sea; geochemical model simulations suggest that 9 % and 14 % of deep-ocean iron and copper, respectively, could stem from hydrothermal sources.)

23 *Schefuß*, E., H. *Kuhlmann*, G. **Mollenhauer**, M. *Prange*, and J. *Pätzold* (2011), Forcing of wet phases in southeast Africa over the past 17,000 years, Nature, 480, 509 – 512. (First continuous record of hydrological variability for the past 17,000 years, from a marine sediment core off Africa, showing that hydrological conditions were influenced by local insolation and migrations of the intertropical convergence zone, probably driven by events in the northern hemisphere.)

24 Stein, R., K. Fahl, M. Schreck, G. Knorr, F. Niessen, M. Forwick, C. Gebhardt, L. Jensen, M. Kaminski, A. *Kopf*, J. Matthiessen, W. Jokat, and G. **Lohmann**, (2016) Evidence for ice-free summers in the late Miocene central Arctic Ocean. Nature Communications, 7, 11148. (First evidence for an ice-free summer season in the central Arctic Ocean during the warm late Miocene. The underlying proxy- and model-based approach exemplifies the understanding of forcings and feedbacks during periods of warm climate.)

25 *Wegener*, G., H. *Niemann*, M. *Elvert*, K. U. **Hinrichs**, and A. **Boetius** (2008), Assimilation of methane and inorganic carbon by microbial communities mediating the anaerobic oxidation of methane, Environmental Microbiology, 10, 2287 – 2298. (The first experimental demonstration that anaerobic methane-oxidizing archaea incorporate substantial fractions of CO_2 into lipid biosynthesis.)

A 3 THE 25 MOST IMPORTANT ADDITIONAL QUALIFICATION INDICATORS

No.	Awards	Person	Year
1	Gottfried Wilhelm Leibniz Prize, DFG	Antje Boetius	2009
2	Gottfried Wilhelm Leibniz Prize, DFG	Kai-Uwe Hinrichs	2011
3	Gottfried Wilhelm Leibniz Prize, DFG	Nicole Dubilier	2014
4	European Research Council, Advanced Grant	Kai-Uwe Hinrichs	2010
5	European Research Council, Advanced Grant	Antje Boetius	2011
6	European Research Council, Advanced Grant	Nicole Dubilier	2013
7	European Research Council, Advanced Grant	Kai-Uwe Hinrichs	2015
8	European Research Council, Consolidator Grant	Heiko Pälike	2014
9	Reinhart Kosselleck Award, DFG	Wolfgang Bach	2012
10	Investigator Award of the Gordon and Betty Moore Foundation Marine Microbiology Initiative, USA	Nicole Dubilier	2013
11	Asahiko Taira Prize of the American Geophysical Union and the Japan Geoscience Union	Heiko Pälike	2016
12	Tsungming Tu Award, Ministry of Science and Technology, Taiwan	Gerhard Bohrmann	2017
13	Clair C. Patterson Award of the Geochemical Society	Kai-Uwe Hinrichs	2017

No.	Scientific councils, panels, and coordinated projects	Person	Year
1	Chair, Science in Dialog (WiD)	Antje Boetius	since 2015
2	Scientific Vice President of the Leibniz Association	Hildegard Westphal	2011–2017
3	Member, Leopoldina, German National Academy of Sciences	Antje Boetius	since 2009
4	Member, Leopoldina, German National Academy of Sciences	Nicole Dubilier	since 2015
5	Chair, DFG Senate Commission on Oceanography	Michael Schulz	2011–2017
6	Speaker, DFG Geoforum	André Freiwald	2008–2011
7	Co-Chair, IODP Science Plan Writing Committee	Wolfgang Bach	2009–2012
8	Member, “JOIDES Resolution” Facility Board (IODP)	Wolfgang Bach	since 2016
9	Coordinating lead authors, IPCC working group I, Ch. 3	Monika Rhein	2009–2013
10	Coordinating lead authors, IPCC working group I, Ch. 5	Michael Schulz	2009–2013
11	Member, Past Global Changes (PAGES) Steering Committee	Michal Kučera	since 2014
12	Member, Board of Reviewing Editors for “Science”	Kai-Uwe Hinrichs	since 2011

A 4 THIRD-PARTY FUNDING

No.	Funding Body	Title	Proponent / Coordinator	Term	Volume (k€)
1	DFG / Excellence Initiative	Research Center / Cluster of Excellence "The Ocean in the Earth System"	Michael Schulz (Coordinator)	2012–2018	59,225
2	DFG	International Research Training Group "INTERCOAST – Integrated Coastal Zone and Shelf-Sea Research" (Phase II)	Katrin Huhn (Coordinator)	2014–2018	4,228
3	DFG	International Research Training Group "ArcTrain – Processes and impacts of climate change in the North Atlantic Ocean and the Canadian Arctic" (Phase I + II)	Michal Kučera (Coordinator)	2013–2022	7,588
4	DFG	Transregio Collaborative Research Center "Energy transfers in Atmosphere and Ocean"	Monika Rhein (Co-Coordinator)	2016–2020	1,666
5	BMBF	National Climate Modeling Initiative "PalMod – From the Last Interglacial to the Anthropocene: Modeling a Complete Glacial Cycle"	Michael Schulz (Co-Coordinator)	2015–2019	2,735
6	BMBF	Collaborative Project "RACE II – Regional Atlantic Circulation and Global Change"	Monika Rhein (Co-Coordinator)	2016–2018	752
7	ERC	Advanced Grant "ZOOMecular – Read the fine print: Zooming into paleoenvironmental and biogeochemical processes through molecular imaging of biomarker distributions in sediments"	Kai-Uwe Hinrichs	2015–2020	3,000
8	ERC	Consolidator Grant "EARTHSEQUENCING – A new approach to sequence Earth history at high resolution over the past 66 million years"	Heiko Pälike	2014–2019	1,998
9	ERC	Starting Grant "PREDATORS – Plate-rate experimental deformation: Aseismic, transient or seismic fault slip"	Matt Ikari	2017–2022	1,499
10	BMBF	MeBo 200 system, MeBo 70 upgrade	Gerold Wefer	2012–2018	6,515
11	BMBF	H-ROV Launch and Recovery System	Gerold Wefer	2015–2017	1,205
12	BMWi	SUGAR II – Submarine gas hydrate resources	Gerhard Bohrmann	2014–2017	1,225

No.	Funding Body	Title	Proponent / Coordinator	Term	Volume (k€)
13	EU	COOPEUS Strengthening the cooperation between the US and the EU in the field of environmental research infrastructures	Christoph Waldmann (Coordinator)	2012–2015	1,999
14	DFG	GFBio – German Federation for the Curation of Biological Data	Michael Diepenbroek (Co-Coordinator)	2013–2018	1,352
15	WSS	Innovation Center for Deep-Sea Environmental Observations	Michael Schulz	2016–2026	4,975

A 5 CURRICULA VITAE AND LISTS OF PUBLICATIONS

BACH, WOLFGANG, PROF. DR.

Personal Data	
Date and Place of birth	24 September 1964, Dillenburg
Nationality	German
Webpage	www.marum.de/en/Wolfgang_Bach.html
ORCID	0000-0002-3099-7142
Degrees	
1996	PhD, University of Gießen, Germany
1991	Diploma in Mineralogy, University of Gießen
Positions	
2005–present	Professor of Petrology, University of Bremen
2003–2005	Associate Scientist, Woods Hole Oceanographic Institution, USA
1999–2003	Assistant Scientist, Woods Hole Oceanographic Institution
1996–1999	Postdoctoral Researcher, Woods Hole Oceanographic Institution
1995–1996	Research Assistant, University of Potsdam, Germany
1991–1995	Research Assistant, University of Gießen, Germany
Scientific Awards	
2012	Reinhart Kosselleck Award, DFG
1996	Woods Hole Oceanographic Institution Postdoctoral Scholarship

Research Work

Trained in igneous petrology and inorganic geochemistry I began my scientific career with examining processes of mantle melting and magmatic differentiation in mid-ocean ridge and back-arc basin settings. In the past decade, the focus of my research has been on hydrothermal systems and their relevance in global geochemical cycles. My research approach is a combination of instrumental analytics, petrographic observations, and thermodynamic modeling. Specific emphasis has been on fluid-rock interactions and their role in metal-deposit formation and microbial habitat development.

Professional Activities	
2016–present	Member, IODP Joides Resolution Facility Board
2016–present	Member, DFG Proposal Evaluation Board
2012–present	Associate Editor, "Geochimica et Cosmochimica Acta"
2009	Co-chair of Steering Committee IODP New Ventures in Exploring Scientific Targets
2008–2010	Chair of Academic Programs, Faculty of Geosciences, University of Bremen
2003–2005	Representative of the IODP Science Steering and Evaluation Panel
2002–2005	Member of the Woods Hole Oceanographic Institution Marine Operations Committee

Most relevant publications

- **Bach, W.** (2016), Some Compositional and Kinetic Controls on the Bioenergetic Landscapes in Oceanic Basement, Frontiers in Microbiology, 7, 107.
- Hawkes, J. A., P. E. Rossel, A. Stubbins, D. Butterfield, D. P. Connelly, E. P. Achterberg, A. Koschinsky, V. Chavagnac, C. T. Hansen, **W. Bach**, and T. Dittmar (2015), Efficient removal of recalcitrant deep-ocean dissolved organic matter during hydrothermal circulation, Nature Geoscience, 8, 856–860.
- Türke, A., K. Nakamura, and **W. Bach** (2015), Palagonitization of Basalt Glass in the Flanks of Mid-Ocean Ridges: Implications for the Bioenergetics of Oceanic Intracrustal Ecosystems, Astrobiology, 15, 793–803.
- Klein, F., **W. Bach**, S. E. Humphris, W. A. Kahl, N. Jöns, B. Moskowitz, and T. S. Berquo (2014), Magnetite in seafloor serpentinite-Some like it hot, Geology, 42, 135–138.
- Orcutt, B. N., C. G. Wheat, O. Rouxel, S. Hulme, K. J. Edwards, and **W. Bach** (2013), Oxygen consumption rates in subseafloor basaltic crust derived from a reaction transport model, Nature Communications, 4, 2539.
- **Bach, W.**, M. Rosner, N. Jöns, S. Rausch, L. F. Robinson, H. Paulick, and J. Erzinger (2011), Carbonate veins trace seawater circulation during exhumation and uplift of mantle rock: Results from ODP Leg 209, Earth and Planetary Science Letters, 311, 242–252.
- **Bach, W.** and F. Klein (2009), The petrology of seafloor rodingites: Insights from geochemical reaction path modeling, Lithos, 112, 103–117.
- **Bach, W.**, H. Paulick, C. J. Garrido, B. Ildefonse, W. P. Meurer, and S. E. Humphris (2006), Unraveling the sequence of serpentinization reactions: petrography, mineral chemistry, and petrophysics of serpentinites from MAR 15 degrees N (ODP Leg 209, Site 1274), Geophysical Research Letters, 33, L13306.
- **Bach, W.**, B. Peuker-Ehrenbrink, S. R. Hart, and J. S. Blusztajn (2003), Geochemistry of hydrothermally altered oceanic crust: DSDP/ODP Hole 504B – Implications for seawater-crust exchange budgets and Sr- and Pb-isotopic evolution of the mantle, Geochemistry Geophysics Geosystems, 4, 8907.
- **Bach, W.** and K. J. Edwards (2003), Iron and sulfide oxidation within the basaltic ocean crust: Implications for chemolithoautotrophic microbial biomass production, Geochimica et Cosmochimica Acta, 67, 3871–3887.

BOETIUS, ANTJE, PROF. DR.

Personal Data	
Date and Place of birth	5 March 1967, Frankfurt am Main
Nationality	German
Webpage	www.awi.de/nc/en/about-us/organisation/staff/antje-boetius.html
ORCID	0000-0003-2117-4176
Degrees	
1996	PhD, University of Bremen
1992	Diploma in Biology, University of Hamburg, Germany
Positions	
2017 – present	Director, Alfred Wegener Institute, Helmholtz Center
2009 – present	Professor of Geomicrobiology, University of Bremen
2008 – present	Leader of the HGF-MPG Research Group on Deep Sea Ecology and Technology, MPI-MM, Bremen
2003 – 2008	Professor of Microbiology, Jacobs University Bremen
1995 – 1996	Research Assistant, University of Potsdam, Germany
1991 – 1995	Research Assistant, University of Gießen, Germany
Scientific Awards	
2017	Copernicus Medal
2016	European Academy of Sciences
2015	American Academy of Microbiology
2014	Elected Fellow of the American Geophysical Union (AGU)
2013	International Ecology Institute Ecology Prize
2012	ERC Advanced Grant (Abyss)
2009	Gottfried Wilhelm Leibniz Prize of the DFG

Research Work

My research focuses on carbon and sulfur cycling, methane biogeochemistry in the deep sea, and on marine microbial ecology of polar seas. My work has been essential in revealing the functioning of the anaerobic oxidation of methane, one of the largest sinks for methane on Earth; and recently in understanding future sea-ice productivity and export flux. My research group develops *in-situ* technologies for the study of biogeochemical processes at the ocean floor and under ice. We also study anthropogenic pressures on ocean ecosystems and marine biodiversity, including ocean warming and acidification, hypoxia, littering and deep-sea mining.

Professional Activities	
2016 – present	Head of the Commission "Wissenschaft im Dialog"
2015 – present	Senator of the DFG, Senator of the Leibniz Association
2014 – present	Coordinator HGF Infrastructure Program FRAM Arctic Monitoring
2012 – present	Vice-Director, MARUM – Center for Marine Environmental Sciences (incl. DFG Research Center / Cluster of Excellence)
2011 – present	Advisory Boards: Senckenberg Forschungsmuseen; *Naturkunde Museum* Berlin; Biology Dep., University of Copenhagen
2010 – present	External Scientific Member, Max Planck Society

Most relevant publications

- Jessen, G. L., A. Lichtschlag, A. Ramette, S. Pantoja, P. E. Rossel, C. J. Schubert, U. Struck, and **A. Boetius** (2017), Hypoxia causes preservation of labile organic matter and changes seafloor microbial community composition (Black Sea), Science Advances, 3, e1601897.
- Wegener, G., V. Krukenberg, D. Riedel, H. E. Tegetmeyer, and **A. Boetius** (2015), Intercellular wiring enables electron transfer between methanotrophic archaea and bacteria, Nature, 526, 587 – 590.
- **Boetius, A.**, A. M. Anesio, J. W. Deming, J. A. Mikucki, and J. Z. Rapp (2015), Microbial ecology of the cryosphere: sea ice and glacial habitats, Nature Reviews Microbiology, 13, 677 – 690.
- **Boetius, A.**, S. Albrecht, K. Bakker, C. Bienhold, J. Felden, M. Fernandez-Mendez, S. Hendricks, C. Katlein, C. Lalande, T. Krumpen, M. Nicolaus, I. Peeken, B. Rabe, A. Rogacheva, E. Rybakova, R. Somavilla, F. Wenzhöfer, and RV Polarstern ARK27-3-Shipboard Science Party (2013), Export of Algal Biomass from the Melting Arctic Sea Ice, Science, 339, 1430 – 1432.
- **Boetius, A.** and F. Wenzhöfer (2013), Seafloor oxygen consumption fuelled by methane from cold seeps, Nature Geoscience, 6, 725 – 734.
- Knittel, K. and **A. Boetius** (2009), Anaerobic oxidation of methane: progress with an unknown process, Annual Review of Microbiology, 63, 311 – 334.
- Jørgensen, B. B. and **A. Boetius** (2007), Feast and famine – microbial life in the deep-sea bed, Nature Reviews Microbiology, 5, 770 – 781.
- Niemann, H., T. Lösekann, D. de Beer, M. Elvert, T. Nadalig, K. Knittel, R. Amann, E. J. Sauter, M. Schlüter, M. Klages, J. P. Foucher, and **A. Boetius** (2006), Novel microbial communities of the Haakon Mosby mud volcano and their role as a methane sink, Nature, 443, 854 – 858.
- Inagaki, F., M. M. M. Kuypers, U. Tsunogai, J. Ishibashi, K. Nakamura, T. Treude, S. Ohkubo, M. Nakaseama, K. Gena, H. Chiba, H. Hirayama, T. Nunoura, K. Takai, B. B. Jørgensen, K. Horikoshi, and **A. Boetius** (2006), Microbial community in a sediment-hosted CO_2 lake of the southern Okinawa Trough hydrothermal system, Proceedings of the National Academy of Sciences of the United States of America, 103, 14164 – 14169.
- **Boetius, A.**, K. Ravenschlag, C. J. Schubert, D. Rickert, F. Widdel, A. Gieseke, R. Amann, B. B. Jørgensen, U. Witte, and O. Pfannkuche (2000), A marine microbial consortium apparently mediating anaerobic oxidation of methane, Nature, 407, 623 – 626.

BOHRMANN, GERHARD, PROF. DR.

Personal Data	
Date and Place of birth	30 March 1956, Sankt Ingbert
Nationality	German
Webpage	www.marum.de/Gerhard_Bohrmann.html
ORCID	0000-0001-9976-4948
Degrees	
1988	PhD, University of Kiel, Germany
1984	Diploma in Earth Sciences, University of Darmstadt, Germany
Positions	
2002 – present	Professor of General / Marine Geology, University of Bremen
1999 – 2002	Head of Central Service "Lithothek", GEOMAR, Kiel, Germany
1992 – 1998	Assistant Professor of Marine Geology, GEOMAR, Kiel
1991 – 1992	Research Associate, GEOMAR, Kiel
1988 – 1991	Research Associate, AWI, Bremerhaven
1984 – 1987	Research Associate, University of Kiel, Germany
Scientific Awards	
2016	Tsungming Tu Award, Ministry of Science and Technology, Taiwan, with A.v.H. Foundation
2001	Philip-Morris-Science Award
1991	Herman-Credener-Award, German Geological Society

Research Work

My research focuses on natural methane and methane hydrates in ocean sediments, and related biogeochemical and geological processes. We are developing new technologies to better study seepage at the ocean floor, and quantifying gas emissions by acoustic sonar or optical methods. My research projects include the use of AUV, ROV, and MeBo technologies, for which we are using adopted payload. Ocean-floor fluid dynamics and diagenesis of mineral precipitates, specifically at colds seeps and gas-hydrate locations, are the major interests.

Professional Activities	
2013 – 2015	Member, scientific committee of experts for RV POLARSTERN II
2007 – 2011	Dean, Earth Sciences Department, University of Bremen
2006 – present	Member, scientific advisory board RV POLARSTERN
2005 – 2017	Member, steering group medium-sized research vessels Germany
2005 – present	Vice-Director, MARUM – Center for Marine Environmental Sciences (incl. DFG Research Center / Cluster of Excellence)
2004 – 2011	Deputy Chair of the Academic Advisory Board "HWK" Institute for Advanced Studies, Delmenhorst, Germany
1996 – present	Chief scientist of more than 30 international cruises (e.g., ODP 204)

Most relevant publications

- Wallmann, K., M. Riedel, W. L. Hong, H. Patton, A. Hubbard, T. Pape, C. W. Hsu, C. Schmidt, J. E. Johnson, M. E. Torres, K. Andreassen, C. Berndt, and **G. Bohrmann** (2018), Gas hydrate dissociation off Svalbard induced by isostatic rebound rather than global warming, Nature Communications, 9, 83.
- Sahling, H., M. Römer, T. Pape, B. Berges, C. D. Fereirra, J. Boelmann, P. Geprägs, M. Tomczyk, N. Nowald, W. Dimmler, L. Schroedter, M. Glockzin, and **G. Bohrmann** (2014), Gas emissions at the continental margin west of Svalbard: mapping, sampling, and quantification, Biogeosciences, 11, 6029–6046.
- Fischer, D., J. M. Mogollón, M. Strasser, T. Pape, **G. Bohrmann**, N. Fekete, V. Spiess, and S. Kasten (2013), Subduction zone earthquake as potential trigger of submarine hydrocarbon seepage, Nature Geoscience, 6, 647–651.
- Römer, M., H. Sahling, T. Pape, **G. Bohrmann**, and V. Spieß (2012), Quantification of gas bubble emissions from submarine hydrocarbon seeps at the Makran continental margin (offshore Pakistan), Journal of Geophysical Research-Oceans, 117, C10015.
- Himmler, T., W. Bach, **G. Bohrmann**, and J. Peckmann (2010), Rare earth elements in authigenic methane-seep carbonates as tracers for fluid composition during early diagenesis, Chemical Geology, 277, 126–136.
- **Bohrmann, G.**, W. F. Kuhs, S. A. Klapp, K. S. Techmer, H. Klein, M. M. Murshed, and F. Abegg (2007), Appearance and preservation of natural gas hydrate from Hydrate Ridge sampled during ODP Leg 204 drilling, Marine Geology, 244, 1–14.
- MacDonald, I. R., **G. Bohrmann**, E. Escobar, F. Abegg, P. Blanchon, V. Blinova, W. Brückmann, M. Drews, A. Eisenhauer, X. Han, K. Heeschen, F. Meier, C. Mortera, T. Naehr, B. Orcutt, B. Bernard, J. Brooks, and M. de Farago (2004), Asphalt volcanism and chemosynthetic life in the Campeche Knolls, Gulf of Mexico, Science, 304, 999–1002.
- Torres, M. E., K. Wallmann, A. M. Tréhu, **G. Bohrmann**, W. S. Borowski, and H. Tomaru (2004) Gas hydrate growth, methane transport, and chloride enrichment at the southern summit of Hydrate Ridge, Cascadia margin off Oregon, Earth and Planetary Science Letters, 226, 225–241.
- Tréhu, A. M., P. E. Long, M. E. Torres, **G. Bohrmann**, F. R. Rack, T. S. Collett, D. S. Goldberg, A. V. Milkov, M. Riedel, P. Schultheiss, N. L. Bangs, S. R. Barr, W. S. Borowski, G. E. Claypool, M. E. Delwiche, G. R. Dickens, E. Gràcia, G. Guerin, M. Holland, J. E. Johnson, Y. J. Lee, C. S. Liu, X. Su, B. Teichert, H. Tomaru, M. Vanneste, M. Watanabe, and J. L. Weinberger (2004), Three-dimensional distribution of gas hydrate beneath southern Hydrate Ridge: constraints from ODP Leg 204, Earth and Planetary Science Letters, 222, 845–862.
- **Bohrmann, G.**, J. Greinert, E. Suess, and M. Torres (1998), Authigenic carbonates from the Cascadia subduction zone and their relation to gas hydrate stability, Geology, 26, 647–650.

DITTMAR, THORSTEN, PROF. DR.

Personal Data	
Date and Place of birth	10 August 1970, Konstanz
Nationality	German
Webpage	www.icbm.de/en/marine-geochemistry/staff/prof-dr-thorsten-dittmar
ORCID	0000-0002-3462-0107
Degrees	
1999	PhD, University of Bremen
1996	Diploma in Geoecology, University of Bayreuth, Germany
Positions	
2013 – present	Professor for Marine Geochemistry, University of Oldenburg
2008 – 2013	Head of the Max Planck Research Group for Marine Geochemistry at MPI-MM, Bremen
2003 – 2008	Assistant Professor for Chemical Oceanography, Florida State University, Tallahassee, Florida, USA
2001 – 2003	Research Fellow, School of Oceanography, University of Washington, Seattle, USA
2000 – 2001	Postdoctoral Researcher, AWI, Bremerhaven
1996 – 1999	Doctoral Researcher, ZMT, Bremen
Scientific Awards	
2009	Courtesy Professor, Florida State University, USA
2007	Courtesy Professor, Florida Agricultural and Mechanical University, USA
2000	Wilhelmshaven Award for Marine Research
1986	Federal Young Researcher Award

Research Work

My research focus is the organic geochemistry of the oceanic water column. Most of the organic matter in the ocean resides there in dissolved form, and the oceans are among the largest organic-carbon pools on the Earth's surface. The reason behind the accumulation of this material is one of my main research interests. I also study mechanistic aspects of the formation and turnover of organic matter by diverse microbial communities. I introduced novel ultrahigh-resolution mass spectrometry techniques in the marine sciences to address long-standing open questions in the oceanic carbon cycle.

Professional Activities	
2016 – present	Member, DFG review panel for physics, chemistry and biology of the ocean
2011 / 2014 – present	Editorial Board Member: Marine Chemistry (Elsevier), Scientific Reports (Nature Publishing Group), Scientific Data (Nature Publishing Group)

Most relevant publications

- Hawkes, J. A., C. T. Hansen, T. Goldhammer, W. Bach, and **T. Dittmar** (2016), Molecular alteration of marine dissolved organic matter under experimental hydrothermal conditions, Geochimica et Cosmochimica Acta, 175, 68–85.
- Osterholz, H., G. Singer, B. Wemheuer, R. Daniel, M. Simon, J. Niggemann, and **T. Dittmar** (2016), Deciphering associations between dissolved organic molecules and bacterial communities in a pelagic marine system, ISME Journal, 10, 1717–1730.
- Arrieta, J. M., E. Mayol, R. L. Hansman, G. J. Herndl, **T. Dittmar**, and C. M. Duarte (2015), Dilution limits dissolved organic carbon utilization in the deep ocean, Science, 348, 331–333.
- Hawkes, J. A., P. E. Rossel, A. Stubbins, D. Butterfield, D. P. Connelly, E. P. Achterberg, A. Koschinsky, V. Chavagnac, C. T. Hansen, W. Bach, and **T. Dittmar** (2015), Efficient removal of recalcitrant deep-ocean dissolved organic matter during hydrothermal circulation, Nature Geoscience, 8, 856–860.
- Osterholz, H., J. Niggemann, H. A. Giebel, M. Simon, and **T. Dittmar** (2015), Inefficient microbial production of refractory dissolved organic matter in the ocean, Nature Communications, 6, 7422.
- Zark, M., U. Riebesell, and **T. Dittmar** (2015), Effects of ocean acidification on marine dissolved organic matter are not detectable over the succession of phytoplankton blooms, Science Advances, 1, 9.
- Jaffé, R., Y. Ding, J. Niggemann, A. V. Vahatalo, A. Stubbins, R. G. M. Spencer, J. Campbell, and **T. Dittmar** (2013), Global Charcoal Mobilization from Soils via Dissolution and Riverine Transport to the Oceans, Science, 340, 345–347.
- Riedel, T., D. Zak, H. Biester, and **T. Dittmar** (2013), Iron traps terrestrially derived dissolved organic matter at redox interfaces, Proceedings of the National Academy of Sciences of the United States of America, 110, 10101–10105.
- **Dittmar, T.**, C. E. de Rezende, M. Manecki, J. Niggemann, A. R. C. Ovalle, A. Stubbins, and M. C. Bernardes (2012), Continuous flux of dissolved black carbon from a vanished tropical forest biome, Nature Geoscience, 5, 618–622.
- **Dittmar, T.**, and J. Paeng (2009), A heat-induced molecular signature in marine dissolved organic matter, Nature Geoscience, 2, 175–179.

DUBILIER, NICOLE, PROF. DR.

Personal Data	
Date and Place of birth	16 January 1957, New York City
Nationality	USA
Webpage	www.mpi-bremen.de/Nicole-Dubilier.html
ORCID	0000-0002-9394-825X
Degrees	
1992	PhD, University of Hamburg, Germany
1986	Diploma in Zoology, Biochemistry, Microbiology, University of Hamburg
Positions	
2013 – present	Director MPI-MM, Head of the Symbiosis Department, Bremen
2012 – present	Professor for Microbial Symbiosis, University of Bremen
2007 – 2012	Research Group Leader at MPI-MM and MARUM PI, Bremen
1997 – 2007	Research Scientist at MPI-MM, Bremen
1997	Parental leave
1995 – 1996	Research Scientist at the University of Hamburg, Germany
1992 – 1994	Postdoc Harvard University, USA
Scientific Awards	
2015	Elected Fellow of Leopoldina (German National Academy of Sciences), European Academy of Microbiology
2014	Gottfried Wilhelm Leibniz Prize of the DFG
2013	ERC Advanced Grant, Elected Fellow of American Academy of Microbiology
2013	Investigator Award of the Gordon and Betty Moore Foundation Marine Microbiology Initiative, USA

Research Work

My lab studies the diversity, ecology, and evolution of symbioses between bacteria and marine invertebrates from chemosynthetic environments such as deep-sea hydrothermal vents, cold seeps, whale and wood falls, upwelling regions, and coastal sediments. My group uses a wide array of methods to study chemosynthetic symbioses that range from deep-sea *in-situ* tools to molecular, 'omic' and imaging analyses. My research has led to the discovery that the diversity of chemosynthetic symbionts is much higher than previously recognized, that chemosynthetic bacteria have been highly successful in independently establishing symbioses with many animal hosts in convergent evolution, and that numerous animal groups benefit from such associations.

Professional Activities	
2014 – 2017	Chair / Vice-Chair of the American Society of Microbiology annual meeting
2015	Chair Gordon Research Conference Animal-Microbe Symbiosis

Most relevant publications

- Rubin-Blum M., C. P. Antony, C. Borowski, L. Sayavedra, T. Pape, H. Sahling, G. Bohrmann, M. Kleiner, M. C. Redmond, D. L. Valentine, and **N. Dubilier** (2017), Short-chain alkanes fuel mussel and sponge *Cycloclasticus* symbionts from deep-sea gas and oil seeps, Nature Microbiology, 2, 17093.
- Sayavedra, L., M. Kleiner, R. Ponnudurai, S. Wetzel, E. Pelletier, V. Barbe, N. Satoh, E. Shoguchi, D. Fink, C. Breusing, T. B. H. Reusch, P. Rosenstiel, M. B. Schilhabel, D. Becher, T. Schweder, S. Markert, **N. Dubilier**, and J. M. Petersen (2015), Abundant toxin-related genes in the genomes of beneficial symbionts from deep-sea hydrothermal vent mussels, eLife, 4, e07966.
- Kleiner, M., J. C. Young, M. Shah, N. C. VerBerkmoes, and **N. Dubilier** (2013), Metaproteomics reveals abundant transposase expression in mutualistic endosymbionts, mBio, 4, e00223-13.
- McFall-Ngai, M., M. G. Hadfield, T. C. G. Bosch, H. V. Carey, T. Domazet-Loso, A. E. Douglas, **N. Dubilier**, G. Eberl, T. Fukami, S. F. Gilbert, U. Hentschel, N. King, S. Kjelleberg, A. H. Knoll, N. Kremer, S. K. Mazmanian, J. L. Metcalf, K. Nealson, N. E. Pierce, J. F. Rawls, A. Reid, E. G. Ruby, M. Rumpho, J. G. Sanders, D. Tautz, and J. J. Wernegreen (2013), Animals in a bacterial world, a new imperative for the life sciences, Proceedings of the National Academy of Sciences of the United States of America, 110, 3229–3236.
- Wentrup, C., A. Wendeberg, J. L. Y. Huang, C. Borowski, and **N. Dubilier** (2013), Shift from widespread symbiont infection of host tissues to specific colonization of gills in juvenile deep-sea mussels, ISME Journal, 7, 1244–1247.
- Kleiner, M., C. Wentrup, C. Lott, H. Teeling, S. Wetzel, J. Young, Y. J. Chang, M. Shah, N. C. VerBerkmoes, J. Zarzycki, G. Fuchs, S. Markert, K. Hempel, B. Voigt, D. Becher, M. Liebeke, M. Lalk, D. Albrecht, M. Hecker, T. Schweder, and **N. Dubilier** (2012), Metaproteomics of a gutless marine worm and its symbiotic microbial community reveal unusual pathways for carbon and energy use, Proceedings of the National Academy of Sciences of the United States of America, 109, 1173–1182.
- Petersen, J. M., F. U. Zielinski, T. Pape, R. Seifert, C. Moraru, R. Amann, S. Hourdez, P. R. Girguis, S. D. Wankel, V. Barbe, E. Pelletier, D. Fink, C. Borowski, W. Bach, and **N. Dubilier** (2011), Hydrogen is an energy source for hydrothermal vent symbioses, Nature, 476, 176–180.
- **Dubilier, N.**, C. Bergin, and C. Lott (2008), Symbiotic diversity in marine animals: the art of harnessing chemosynthesis, Nature Reviews Microbiology, 6, 725–740.
- Woyke, T., H. Teeling, N. N. Ivanova, M. Huntemann, M. Richter, F. O. Gloeckner, D. Boffelli, I. J. Anderson, K. W. Barry, H. J. Shapiro, E. Szeto, N. C. Kyrpides, M. Mussmann, R. Amann, C. Bergin, C. Ruehland, E. M. Rubin, and **N. Dubilier** (2006), Symbiosis insights through metagenomic analysis of a microbial consortium, Nature, 443, 950–955.
- **Dubilier, N.**, C. Mülders, T. Ferdelman, D. de Beer, A. Pernthaler, M. Klein, M. Wagner, C. Erséus, F. Thiermann, J. Krieger, O. Giere, and R. Amann (2001), Endosymbiotic sulphate-reducing and sulphide-oxidizing bacteria in an oligochaete worm, Nature, 411, 298–302.

FREIWALD, ANDRÉ, PROF. DR.

Personal Data	
Date and Place of birth	12 August 1961, Kiel
Nationality	German
Webpage	www.senckenberg.de/root/index.php?page_id=13366
ORCID	0000-0002-2335-4042
Degrees	
1993	PhD, University of Kiel, Germany
1989	Diploma in Geology, University of Kiel
Positions	
2018	Director of Senckenberg at the Sea, Wilhelmshaven
2010 – present	Professor of Marine Geology, University of Bremen
2010 – present	Head of Marine Research Department, SGN, Wilhelmshaven
2002 – 2010	Professor of Paleontology, University of Erlangen, Germany
2000 – 2002	Professor of Paleoclimatology, University of Tübingen, Germany
1999	DFG Heisenberg Fellow, University of Bremen
1993 – 1999	Postdoc, University of Bremen
Scientific Awards	
2016	Gustav-Steinmann Medal (The German Geological Society)
2015	North-German Science Award
1999	DFG Heisenberg Fellowship

Research Work

My scientific career is devoted to interdisciplinary studies of biosedimentary systems in high latitudes (cold-water carbonate factories) and deep-water coral ecosystems.

Professional Activities	
2010 – present	Head of Marine Research, SGN, Wilhelmshaven
2013 – present	Speaker, advisory boards for the German research vessels METEOR and MARIA S. MERIAN
2013 – present	Member, advisory board for the German research vessel SONNE
2008 – 2011	Speaker, DFG GeoForum (FK 314, FK 315, FK 316)
2010 – present	Member, Executive Board German Marine Research Consortium (KDM)
2008 – 2009	Founding Director, GeoZentrum Nordbayern, Erlangen
2004 – 2010	Chief Editor, FACIES
2001 – 2006	Member, DFG Senate Commission on Oceanography

Most relevant publications

- Titschack, J., H. G. Fink, D. Baum, C. Wienberg, D. Hebbeln, and **A. Freiwald** (2016), Mediterranean cold-water corals – an important regional carbonate factory?, Depositional Record, 2, 74 – 96.
- Titschack, J., D. Baum, R. De Pol-Holz, M. López Correa, N. Forster, S. Flögel, D. Hebbeln, and **A. Freiwald** (2015), Aggradation and carbonate accumulation of Holocene Norwegian cold-water coral reefs, Sedimentology, 62, 1873 – 1898.
- Fabri, M. C., L. Pedel, L. Beuck, F. Galgani, D. Hebbeln, and **A. Freiwald** (2014), Megafauna of vulnerable marine ecosystems in French mediterranean submarine canyons: Spatial distribution and anthropogenic impacts, Deep-Sea Research Part II-Topical Studies in Oceanography, 104, 184 – 207.
- Teichert, S. and **A. Freiwald** (2014), Polar coralline algal $CaCO_3$-production rates correspond to intensity and duration of the solar radiation, Biogeosciences, 11, 833 – 842.
- Wisshak, M., C. H. L. Schönberg, A. Form, and **A. Freiwald** (2014), Sponge bioerosion accelerated by ocean acidification across species and latitudes?, Helgoland Marine Research, 68, 253 – 262.
- Wisshak, M., C. H. L. Schönberg, A. Form, and **A. Freiwald** (2013), Effects of ocean acidification and global warming on reef bioerosion-lessons from a clionaid sponge, Aquatic Biology, 19, 111 – 127.
- Wisshak, M., C. H. L. Schönberg, A. Form, and **A. Freiwald** (2012), Ocean acidification accelerates reef bioerosion, Plos One, 7, e45124.
- Frank, N., **A. Freiwald**, M. López Correa, C. Wienberg, M. Eisele, D. Hebbeln, D. Van Rooij, J. P. Henriet, C. Colin, T. van Weering, H. de Haas, P. Buhl-Mortensen, J. M. Roberts, B. De Mol, E. Douville, D. Blamart, and C. Hatte (2011), Northeastern Atlantic cold-water coral reefs and climate, Geology, 39, 743 – 746.
- **Freiwald, A.**, L. Beuck, A. Rüggeberg, M. Taviani, and D. Hebbeln (2009), The white coral community in the Central Mediterranean Sea Revealed by ROV Surveys, Oceanography, 22, 58 – 74.
- Roberts, J. M., A. J. Wheeler, and **A. Freiwald** (2006), Reefs of the deep: The biology and geology of cold-water coral ecosystems, Science, 312, 543 – 547.

FRIEDRICH, MICHAEL W., PROF. DR.

Personal Data	
Date and Place of birth	23 May 1964, Hagen
Nationality	German
Webpage	www.uni-bremen.de/de/microecophys/head-of-the-group.html
ORCID	0000-0002-8055-3232
Degrees	
1994	PhD, University of Tübingen, Germany
1990	Diploma in Biology, University of Tübingen
Positions	
2008 – present	Professor of Microbial Ecophysiology, University of Bremen
1997 – 2008	Group Leader, Max Planck Institute for Terrestrial Microbiology, Marburg, Germany
1995 – 1996	Postdoc, Montana State University, Bozeman, USA
1990 – 1994	Research Assistant (PhD), University of Tübingen and Konstanz, Germany

Research Work

Understanding what uncultivated microorganisms do in their natural (mostly) anaerobic habitats is my main research topic. My group has refined tools for identifying microorganisms based on the incorporation of the stable carbon isotope ^{13}C into DNA and RNA, which are widely used in the community of microbial ecologists. Our current focus is on iron-reducing microbial populations and how they impact carbon cycling in marine sediments.

Professional Activities	
2009 – present	Editor, Archaea
2017 – present	Editor, PeerJ
2009 – present	Editorial board member: Applied and Environmental Microbiology

Most relevant publications

- Reyes, C., D. Schneider, A. Thürmer, A. Kulkarni, M. Lipka, S. Y. Sztejrenszus, M. E. Böttcher, R. Daniel, and **M. W. Friedrich** (2017), Potentially active iron, sulfur, and sulfate reducing bacteria in Skagerrak and Bothnian Bay sediments, Geomicrobiology Journal, 34, 840–850.
- Oni, O., T. Miyatake, S. Kasten, T. Richter-Heitmann, D. Fischer, L. Wagenknecht, A. Kulkarni, M. Blumers, S. I. Shylin, V. Ksenofontov, B. F. O. Costa, G. Klingelhöfer, and **M. W. Friedrich** (2015), Distinct microbial populations are tightly linked to the profile of dissolved iron in the methanic sediments of the Helgoland mud area, North Sea, Frontiers in Microbiology, 6, 365.
- Oni, O. E., F. Schmidt, T. Miyatake, S. Kasten, M. Witt, K.-U. Hinrichs, and **M. W. Friedrich** (2015), Microbial communities and organic matter composition in surface and subsurface sediments of the Helgoland Mud Area, North Sea, Frontiers in Microbiology, 6, 1290.
- Bruun, A. M., K. Finster, H. P. Gunnlaugsson, P. Nornberg, and **M. W. Friedrich** (2010), A Comprehensive Investigation on Iron Cycling in a Freshwater Seep Including Microscopy, Cultivation and Molecular Community Analysis, Geomicrobiology Journal, 27, 15–34.
- Hori, T., A. Muller, Y. Igarashi, R. Conrad, and **M. W. Friedrich** (2010), Identification of iron-reducing microorganisms in anoxic rice paddy soil by C-13-acetate probing, ISME Journal, 4, 26–278.
- Kittelmann, S. and **M. W. Friedrich** (2008), Novel uncultured Chloroflexi dechlorinate perchloroethene to trans-dichloroethene in tidal flat sediments, Environmental Microbiology, 10, 1557–1570.
- Lueders, T., M. Manefield and **M. W. Friedrich** (2004), Enhanced sensitivity of DNA- and rRNA-based stable isotope probing by fractionation and quantitative analysis of isopycnic centrifugation gradients, Environmental Microbiology, 6, 73–78.
- Lueders, T., B. Pommerenke, and **M. W. Friedrich** (2004), Stable-isotope probing of microorganisms thriving at thermodynamic limits: Syntrophic propionate oxidation in flooded soil, Applied and Environmental Microbiology, 70, 5778–5786.
- **Friedrich, M. W.** (2002), Phylogenetic analysis reveals multiple lateral transfers of adenosine-5'-phosphosulfate reductase genes among sulfate-reducing microorganisms, Journal of Bacteriology, 184, 278–289.
- Schink, B. and **M. W. Friedrich** (2000), Bacterial metabolism – Phosphite oxidation by sulphate reduction, Nature, 406, 37–37.

HEBBELN, DIERK, PROF. DR.

Personal Data	
Date and Place of birth	26 November 1962, Flensburg
Nationality	German
Webpage	www.marum.de/en/Dierk_Hebbeln.html
ORCID	0000-0001-5099-6115
Degrees	
2002	Habilitation, University of Bremen
1991	PhD, University of Bremen
1988	Diploma in Geology, University of Bremen
Positions	
2006–present	Director of GLOMAR, the International Bremen Graduate School for Marine Sciences
2006–present	Professor of Marine Geology at University of Bremen
1999–2006	Senior Scientist at University of Bremen
1993–1999	Assistant Professor at University of Bremen
1991–1999	Postdoc, University of Bremen, Faculty of Geosciences
1988–1991	Research Assistant (PhD), University of Bremen
Scientific Awards	
2015	North-German Science Award

Research Work

Being a paleoceanographer by training, I studied Late Quaternary paleoceanography mainly in the Nordic Seas/Arctic, the SE-Pacific and around the Indonesian archipelago, thereby also considering sedimentation processes by linking plankton net, sediment-trap and surface-sediment investigations. Over the last 15 years, I have extended my scope towards cold-water corals and coral mounds as new paleoarchives with a focus on the Atlantic Ocean.

Professional Activities	
2012–present	Vice-Director, MARUM – Center for Marine Environmental Sciences (incl. DFG Research Center/Cluster of Excellence)
2011–2017	Member, DFG Senate Commission on Oceanography
2009–present	Vice-Speaker, DFG International Graduate College INTERCOAST
2005–2016	Member, Board of ZMT, Bremen
2006–2010	Member, editorial board of the open source journal *eEarth*
2005–2015	Co-Chairman, Netherlands-Bremen-Oceanography Cooperation NEBROC

Most relevant publications

- **Hebbeln, D.** and E. Samankassou (2015), Where did ancient carbonate mounds grow – In bathyal depths or in shallow shelf waters?, Earth-Science Reviews, 145, 56–65.
- **Hebbeln, D.**, C. Wienberg, P. Wintersteller, A. Freiwald, M. Becker, L. Beuck, C. Dullo, G. P. Eberli, S. Glogowski, L. Matos, N. Forster, H. Reyes-Bonilla, M. Taviani, and M. S. M. S. S. Party (2014), Environmental forcing of the Campeche cold-water coral province, southern Gulf of Mexico, Biogeosciences, 11, 1799–1815.
- Mohtadi, M., D. W. Oppo, S. Steinke, J. B. W. Stuut, R. De Pol-Holz, **D. Hebbeln**, and A. Lückge (2011), Glacial to Holocene swings of the Australian-Indonesian monsoon, Nature Geoscience, 4, 540–544.
- De Pol-Holz, R., L. Keigwin, J. Southon, **D. Hebbeln**, and M. Mohtadi (2010), No signature of abyssal carbon in intermediate waters off Chile during deglaciation, Nature Geoscience, 3, 192–195.
- **Hebbeln, D.**, F. Lamy, M. Mohtadi, and H. Echtler (2007), Tracing the impact of glacial-interglacial climate variability on erosion of the southern Andes, Geology, 35, 131–134.
- Dorschel, B., **D. Hebbeln**, A. Rüggeberg, W. C. Dullo, and A. Freiwald (2005), Growth and erosion of a cold-water coral covered carbonate mound in the Northeast Atlantic during the Late Pleistocene and Holocene, Earth and Planetary Science Letters, 233, 33–44.
- Lamy, F., J. Kaiser, U. Ninnemann, **D. Hebbeln**, H. W. Arz, and J. Stoner (2004), Antarctic timing of surface water changes off Chile and Patagonian ice sheet response, Science, 304, 1959–1962.
- Dowdeswell, J. A., A. Elverhøi, J. T. Andrews, and **D. Hebbeln** (1999), Asynchronous deposition of ice-rafted layers in the Nordic seas and North Atlantic Ocean, Nature, 400, 348–351.
- **Hebbeln, D.**, T. Dokken, E. S. Andersen, M. Hald, and A. Elverhøi (1994), Moisture supply to northern ice sheet growth during the Last Glacial Maximum, Nature, 370, 357–360.
- **Hebbeln, D.** and G. Wefer (1991), Effects of ice coverage and ice-rafted material on sedimentation in the Fram Strait, Nature, 350, 409–411.

HEHEMANN, JAN-HENDRIK, DR.

Personal Data	
Date and Place of birth	21 February 1979, Georgsmarienhütte
Nationality	German
Webpage	www.marum.de/en/Jan-Hendrik_Hehemann.html
ORCID	0000-0002-8700-2564
Degrees	
2010	PhD, Pierre and Marie Curie University Paris VI, France
2005	Diploma in Biochemistry and Molecular Biology, University of Hamburg, Germany
Positions	
2015 – present	Junior Research Group Leader, University of Bremen and MPI-MM, Bremen
2012 – 2015	Postdoc, Massachusetts Institute of Technology, USA
2010 – 2012	Postdoc, University of Victoria, Canada
2009 – 2010	Postdoc, Station Biologique de Roscoff, France
2006 – 2009	Research Assistant (PhD), UPMC, France
Scientific Awards	
2014	DFG Emmy Noether Research Award
2012	Human Frontiers Science Program Long Term Fellowship
2010	European Molecular Biology Organization Long Term Fellowship
2010	Award from the French Academy of Science

Research Work

I am a structural biologist and biochemist by training. I am studying carbon cycling at atomic detail by visualizing and resolving the mechanism of organic matter degrading enzymes with protein X-ray crystallography. I apply the gained knowledge regarding substrate specificity by using enzymes as new, analytic research tools to quantify specific types of polysaccharides in the oceans. I am also studying microbial evolution and how horizontal gene transfer adapts bacteria to consume new carbon sources. I discovered that horizontal gene transfer can transfer organic matter degrading pathways between ecosystems (marine → human intestine). To conclude, my laboratory combines biochemical work with environmental research and microbial evolution studies to investigate organic matter degradation from molecular to ecosystem scales.

Professional Activities	
2015 – present	Faculty Member, MarMic PhD school at the MPI-MM
2015 – present	Head, Junior Research Group Marine Glycobiology, MARUM

Most relevant publications

- Becker, S., A. Scheffel, M. F. Polz, and **J.-H. Hehemann** (2017), Accurate quantification of laminarin in marine organic matter with enzymes from marine microbes, Applied and Environmental Microbiology, 83, e03389-16.
- **Hehemann, J.-H.**, P. Arevalo, M. S. Datta, X. Q. Yu, C. H. Corzett, A. Henschel, S. P. Preheim, S. Timberlake, E. J. Alm, and M. F. Polz (2016), Adaptive radiation by waves of gene transfer leads to fine-scale resource partitioning in marine microbes, Nature Communications, 7, 12860.
- Hobbs, J. K., S. M. Lee, M. Robb, F. Hof, C. Barr, K. T. Abe, **J.-H. Hehemann**, R. McLean, D. W. Abbott, and A. B. Boraston (2016), KdgF, the missing link in the microbial metabolism of uronate sugars from pectin and alginate, Proceedings of the National Academy of Sciences of the United States of America, 113, 6188 – 6193.
- Yawata, Y., O. X. Cordero, F. Menolascina, **J.-H. Hehemann**, M. F. Polz, and R. Stocker (2014), Competition-dispersal tradeoff ecologically differentiates recently speciated marine bacterioplankton populations, Proceedings of the National Academy of Sciences of the United States of America, 111, 5622 – 5627.
- Labourel, A., M. Jam, A. Jeudy, **J.-H. Hehemann**, M. Czjzek, and G. Michel (2014), The beta-glucanase ZgLamA from *Zobellia galactanivorans* evolved a bent active site adapted for efficient degradation of algal laminarin, Journal of Biological Chemistry, 289, 2027 – 2042.
- **Hehemann, J.-H.**, A. G. Kelly, N. A. Pudlo, E. C. Martens, and A. B. Boraston (2012), Bacteria of the human gut microbiome catabolize red seaweed glycans with carbohydrate-active enzyme updates from extrinsic microbes, Proceedings of the National Academy of Sciences of the United States of America, 109, 19786 – 19791.
- **Hehemann, J.-H.**, G. Correc, F. Thomas, T. Bernard, T. Barbeyron, M. Jam, W. Helbert, G. Michel, and M. Czjzek (2012), Biochemical and structural characterization of the complex agarolytic enzyme system from the marine bacterium *Zobellia galactanivorans*, Journal of Biological Chemistry, 287, 30571 – 30584.
- **Hehemann, J.-H.**, L. Smyth, A. Yadav, D. J. Vocadlo, and A. B. Boraston (2012), Analysis of keystone enzyme in agar hydrolysis provides Insight into the degradation of a polysaccharide from red seaweeds, Journal of Biological Chemistry, 287, 13985 – 13995.
- Correc, G., **J.-H. Hehemann**, M. Czjzek, and W. Helbert (2011), Structural analysis of the degradation products of porphyran digested by *Zobellia galactanivorans* β-porphyranase A, Carbohydrate Polymers, 83, 277 – 283.
- **Hehemann, J.-H.**, G. Correc, T. Barbeyron, W. Helbert, M. Czjzek and G. Michel (2010), Transfer of carbohydrate-active enzymes from marine bacteria to Japanese gut microbiota, Nature, 464, 908 – 912.

HILLEBRAND, HELMUT, PROF. DR.

Personal Data	
Date and Place of birth	3 August 1966, Papenburg
Nationality	German
Webpage	www.icbm.de/en/planktology/staff/helmut-hillebrand
ORCID	0000-0001-7449-1613
Degrees	
2003	Docent qualification, Limnology, University of Uppsala, Sweden
1999	PhD, University of Kiel, Germany
1994	Diploma in Biology, University of Oldenburg
Positions	
2017 – present	Director, Helmholtz-Institute for Functional Marine Biodiversity at the University of Oldenburg (HIFMB)
2008 – present	Professor of Pelagic Ecology, Institute for Chemistry and Biology of the Marine Environment (ICBM), University of Oldenburg
2004 – 2008	Associate Professor of Aquatic Ecology, University of Cologne, Germany
2002 – 2004	Assistant Professor of Marine Ecology, Institute for Marine Science (IfM), University of Kiel, Germany
2001 – 2002	Marie Curie Research Fellow, Department of Limnology, University of Uppsala, Sweden
1999 – 2001	Postdoc, Erken Laboratory, University of Uppsala
1996 – 1999	PhD-student, Institute for Marine Science (IfM), University of Kiel, Germany
1994 – 1996	Research assistant, University of Oldenburg
Scientific Awards	
2017	Innovation in Sustainability Science Award, Ecological Society of America
2014 – 2015	Highly Cited Researcher by Thomson Reuters

Research Work

A main characteristic of my research experience is an effort towards generality and synthesis of mechanisms structuring biological interactions, communities and ecosystems. Therewith, it unifies major fields of ecology such as ecological stoichiometry, metacommunity ecology, and causes and consequences of biodiversity. The latter has become a major aspect of my research focusing on the analysis of trends in biodiversity through time and the effects of such changes on ecosystem functions.

Professional Activities	
2008 – 2016 and 2018 – present	Member, DFG Senate Commission on Biodiversity
2013 – present	Member, DFG Review Board Zoology: Ecology, Evolution and Biodiversity
2014 – present	Head, Biodiversity strategy group, German Marine Research Consortium (KDM)

Most relevant publications

- **Hillebrand, H.**, B. Blasius, E. T. Borer, J. M. Chase, J. A. Downing, B. K. Eriksson, C. T. Filstrup, W. S. Harpole. D. Hodapp, S. Larsen, A. M. Lewandowska, E. W. Seabloom, D. B. Van de Waal, and A. B. Ryabov (2018), Biodiversity change is uncoupled from species richness trends: consequences for conservation and monitoring, Journal of Applied Ecology, 55, 169–184.
- Yasuhara, M., D. P. Tittensor, **H. Hillebrand**, and B. Worm (2017), Combining marine macroecology and palaeoecology in understanding biodiversity: microfossils as a model, Biological Reviews, 92, 199–215.
- Grace, J. B., T. M. Anderson, E. W. Seabloom, E. T. Borer, P. B. Adler, W. S. Harpole, Y. Hautier, **H. Hillebrand**, E. M. Lind, M. Pärtel, J. D. Bakker, Y. M. Buckley, M. J. Crawley, E. I. Damschen, K. F. Davies, P. A. Fay, J. Firn, D. S. Gruner, A. Hector, J. M. H. Knops, A. S. MacDougall, B. A. Melbourne, J. W. Morgan, J. L. Orrock, S. M. Prober, and M. D. Smith (2016), Integrative modelling reveals mechanisms linking productivity and plant species richness, Nature, 529, 390–393.
- Hodapp, D., **H. Hillebrand**, B. Blasius, and A. B. Ryabov (2016), Environmental and trait variability constrain community structure and the biodiversity-productivity relationship, Ecology, 97, 1463–1474.
- Hautier, Y., E. W. Seabloom, E. T. Borer, P. B. Adler, W. S. Harpole, **H. Hillebrand**, E. M. Lind, A. S. MacDougall, C. J. Stevens, J. D. Bakker, Y. M. Buckley, C. J. Chu, S. L. Collins, P. Daleo, E. I. Damschen, K. F. Davies, P. A. Fay, J. Firn, D. S. Gruner, V. L. Jin, J. A. Klein, J. M. H. Knops, K. J. La Pierre, W. Li, R. L. McCulley, B. A. Melbourne, J. L. Moore, L. R. O'Halloran, S. M. Prober, A. C. Risch, M. Sankaran, M. Schuetz, and A. Hector (2014), Eutrophication weakens stabilizing effects of diversity in natural grasslands, Nature, 508, 521–525.
- **Hillebrand, H.**, G. Steinert, M. Boersma, A. Malzahn, C. L. Meunier, C. Plum, and R. Ptacnik (2013), Goldman revisited: Faster-growing phytoplankton has lower N : P and lower stoichiometric flexibility, Limnology and Oceanography, 58, 2076–2088.
- Logue, J. B., N. Mouquet, H. Peter, **H. Hillebrand**, and The Metacommunity Working Group (2011), Empirical approaches to metacommunities: a review and comparison with theory, Trends in Ecology & Evolution, 26, 482–491.
- **Hillebrand, H.**, E. T. Borer, M. E. S. Bracken, B. J. Cardinale, J. Cebrian, E. E. Cleland, J. J. Elser, D. S. Gruner, W. S. Harpole, J. T. Ngai, S. Sandin, E. W. Seabloom, J. B. Shurin, J. E. Smith, and M. D. Smith (2009), Herbivore metabolism and stoichiometry each constrain herbivory at different organizational scales across ecosystems, Ecology Letters, 12, 516–527.
- **Hillebrand, H.** and B. Matthiessen (2009), Biodiversity in a complex world: consolidation and progress in functional biodiversity research, Ecology Letters, 12, 1405–1419.
- Elser, J. J., M. E. S. Bracken, E. E. Cleland, D. S. Gruner, W. S. Harpole, **H. Hillebrand**, J. T. Ngai, E. W. Seabloom, J. B. Shurin, and J. E. Smith (2007), Global analysis of nitrogen and phosphorus limitation of primary producers in freshwater, marine and terrestrial ecosystems, Ecology Letters, 10, 1135–1142.

HINRICHS, KAI-UWE, PROF. DR.

Personal Data	
Date and Place of birth	6 November 1963, Oldenburg
Nationality	German
Webpage	www.marum.de/en/Kai-Uwe_Hinrichs.html
ORCID	0000-0002-0739-9291
Degrees	
1997	PhD, University of Oldenburg
1994	Diploma in Chemistry, University of Oldenburg
Positions	
2002 – present	Professor of Organic Geochemistry, University of Bremen
2004 – 2010	Adjunct Scientist, Woods Hole Oceanographic Institution, USA
2000 – 2002	Assistant Scientist, Woods Hole Oceanographic Institution, USA
1997 – 2000	Postdoc, Woods Hole Oceanographic Institution, USA
1994 – 1997	Research Assistant, University of Oldenburg
Scientific Awards	
2017	Clair C. Patterson Award, Geochemical Society
2017	Fellow, Geochemical Society
2015	European Research Council, Advanced Grant (*ZOOMecular*)
2011	Gottfried Wilhelm Leibniz Prize of the DFG
2011 – 2012	ECORD, Distinguished Lecturer
2010	European Research Council, Advanced Grant (*DARCLIFE*)
2000 – 2002	Fellow, Hanse Institute of Advanced Studies, Germany

Research Work

My research group studies the interactions between microbial life and the carbon cycle on a range of spatial and temporal scales. We are interested in how and which microbes shape element cycles and what the related environmental consequences are. To this end, we study the information encoded in distributions and isotopic compositions of organic molecules in sediments and water. We combine these environmental observations with experimental approaches. Systems studied include the deep subseafloor biosphere, cold seeps and hydrothermal environments, microbial mats, suspended particulate matter in the ocean, sedimentary pore fluids and gases, paleoenvironments, and the microbial lipidome.

Professional Activities	
2017 – present	Chair, Scientific Advisory Board, Hanse Institute of Advanced Studies; since 2013 member and vice-Chair
2013 – present	Co-Chair, Deep Life Steering Committee of the Deep Carbon Observatory (DCO) and member, Executive Committee, DCO
2011 – present	Board of Reviewing Editors, Science
2012	Co-Chief Scientist, IODP Exp. 337, Deep Coalbed Biosphere

Most relevant publications

- Inagaki, F., **K.-U. Hinrichs**, Y. Kubo, M. W. Bowles, V. B. Heuer, W. L. Hong, T. Hoshino, A. Ijiri, H. Imachi, M. Ito, M. Kaneko, M. A. Lever, Y. S. Lin, B. A. Methe, S. Morita, Y. Morono, W. Tanikawa, M. Bihan, S. A. Bowden, M. Elvert, C. Glombitza, D. Gross, G. J. Harrington, T. Hori, K. Li, D. Limmer, C. H. Liu, M. Murayama, N. Ohkouchi, S. Ono, Y. S. Park, S. C. Phillips, X. Prieto-Mollar, M. Purkey, N. Riedinger, Y. Sanada, J. Sauvage, G. Snyder, R. Susilawati, Y. Takano, E. Tasumi, T. Terada, H. Tomaru, E. Trembath-Reichert, D. T. Wang, and Y. Yamada (2015), Exploring deep microbial life in coal-bearing sediment down to similar to 2.5 km below the ocean floor, Science, 349, 420–424.
- Wormer, L., M. Elvert, J. Fuchser, J. S. Lipp, P. L. Buttigieg, M. Zabel, and **K.-U. Hinrichs** (2014), Ultra-high-resolution paleoenvironmental records via direct laser-based analysis of lipid biomarkers in sediment core samples, Proceedings of the National Academy of Sciences of the United States of America, 111, 15669–15674.
- Bowles, M. W., J. M. Mogollón, S. Kasten, M. Zabel, and **K.-U. Hinrichs** (2014), Global rates of marine sulfate reduction and implications for sub-sea-floor metabolic activities, Science, 344, 889–891.
- Xie, S. T., J. S. Lipp, G. Wegener, T. G. Ferdelman, and **K.-U. Hinrichs** (2013), Turnover of microbial lipids in the deep biosphere and growth of benthic archaeal populations, Proceedings of the National Academy of Sciences of the United States of America, 110, 6010–6014.
- Kellermann, M. Y., G. Wegener, M. Elvert, M. Y. Yoshinaga, Y. S. Lin, T. Holler, X. P. Mollar, K. Knittel, and **K.-U. Hinrichs** (2012), Autotrophy as a predominant mode of carbon fixation in anaerobic methane-oxidizing microbial communities, Proceedings of the National Academy of Sciences of the United States of America, 109, 19321–19326.
- Sepúlveda, J., J. E. Wendler, R. E. Summons, and **K.-U. Hinrichs** (2009), Rapid resurgence of marine productivity after the Cretaceous-Paleogene mass extinction, Science, 326, 129–132.
- Lipp, J. S., Y. Morono, F. Inagaki, and **K.-U. Hinrichs** (2008), Significant contribution of Archaea to extant biomass in marine subsurface sediments, Nature, 454, 991–994.
- **Hinrichs, K.-U.**, J. M. Hayes, W. Bach, A. J. Spivack, L. R. Hmelo, N. G. Holm, C. G. Johnson, and S. P. Sylva (2006), Biological formation of ethane and propane in the deep marine subsurface, Proceedings of the National Academy of Sciences of the United States of America, 103, 14684–14689.
- **Hinrichs, K.-U.**, L. R. Hmelo, and S. P. Sylva (2003), Molecular fossil record of elevated methane levels in late pleistocene coastal waters, Science, 299, 1214–1217.
- **Hinrichs, K.-U.**, J. M. Hayes, S. P. Sylva, P. G. Brewer, and E. F. DeLong (1999), Methane-consuming archaebacteria in marine sediments, Nature, 398, 802–805.

IVERSEN, MORTEN HVITFELDT, DR.

Personal Data	
Date and Place of birth	8 August 1979, Guldborgsund
Nationality	Danish
Webpage	www.marum.de/Morten_Hvitfeldt_Iversen.html
ORCID	0000-0002-5287-1110
Degrees	
2009	PhD, University of Bremen
2006	MSc, The University of Southern Denmark, Odense, Denmark
Positions	
2014 – present	Group leader, AWI, MARUM, University of Bremen
2009 – 2014	Postdoc, MARUM, University of Bremen
2008	Visiting Researcher, National Institute of Aquatic Resources (DTU-Aqua), Denmark
2006 – 2009	Research Assistant (PhD), AWI and MPI-MM, Bremerhaven
2005 – 2006	Research Assistant Danish Fisheries Institute, Denmark
2003 – 2004	Research Assistant, European working group POCEFF, Roskilde, Denmark
Scientific Awards	
2017	Mary B. Ansari Best Geoscience Research Resource Work Award of The Geoscience Information Society
2014	Helmholtz Young Investigator Group Award
2009	MARUM Research Award for Marine Geosciences
2009	ASLO Outstanding Student Presentation Award
2008	Feature Paper in MEPS (doi:10.3354/meps07611)

Research Work

As a biological oceanographer I combine laboratory experiments with field observations to study the functioning of the ocean's biological pump. I have developed new methods to quantify how food-web composition influences particle export dynamics and the efficiency of the biological pump. Field work is done across different latitudinal regions and seasons to identify the effect of changing key organisms on export and attenuation processes. This provides a detailed understanding of how changing food webs affect the biological pump and allows better predictions for the future ocean. For long-term annual observations, I develop new optical systems that can perform daily measurements of particle properties such as size, numbers and sinking velocities in the deep ocean. I have participated in 23 ship cruises of which I have planned and co-proposed 13.

Professional Activities	
2016 – present	Member, Scientific Committee on Oceanic Research (SCOR) working group "TOMCAT"
2014 – present	Head, Helmholtz Young Investigator Group "SeaPump"

Most relevant publications

- **Iversen, M. H.**, E. A. Pakhomov, B. P. V. Hunt, H. van der Jagt, D. Wolf-Gladrow, and C. Klaas (2016), Sinkers or floaters? Contribution from salp pellets to the export flux during a large bloom event in the Southern Ocean, Deep Sea Research Part II: Topical Studies in Oceanography, 138, 116–125.
- **Iversen, M. H.** and M. L. Robert (2015), Ballasting effects of smectite on aggregate formation and export from a natural plankton community, Marine Chemistry, 175, 18–27.
- Nowald, N., **M. H. Iversen**, G. Fischer, V. Ratmeyer, and G. Wefer (2015), Time series of in-situ particle properties and sediment trap fluxes in the coastal upwelling filament off Cape Blanc, Mauritania, Progress in Oceanography, 137, 1–11.
- Thiele, S., B. M. Fuchs, R. Amann, and **M. H. Iversen** (2015), Colonization in the photic zone and subsequent changes during sinking determine bacterial community composition in marine snow, Applied and Environmental Microbiology, 81, 1463–1471.
- **Iversen, M. H.**, and H. Ploug (2013), Temperature effects on carbon-specific respiration rate and sinking velocity of diatom aggregates – potential implications for deep ocean export processes, Biogeosciences, 10, 4073–4085.
- Gärdes, A., **M. H. Iversen**, H. P. Grossart, U. Passow, and M. S. Ullrich (2011), Diatom-associated bacteria are required for aggregation of *Thalassiosira weissflogii*, ISME Journal, 5, 436–445.
- **Iversen, M. H.** and H. Ploug (2010), Ballast minerals and the sinking carbon flux in the ocean: carbon-specific respiration rates and sinking velocity of marine snow aggregates, Biogeosciences, 7, 2613–2624.
- **Iversen, M. H.**, N. Nowald, H. Ploug, G. A. Jackson, and G. Fischer (2010), High resolution profiles of vertical particulate organic matter export off Cape Blanc, Mauritania: Degradation processes and ballasting effects, Deep-Sea Research Part I: Oceanographic Research Papers, 57, 771–784.
- Poulsen, L. K. and **M. H. Iversen** (2008), Degradation of copepod fecal pellets: key role of protozooplankton, Marine Ecology Progress Series, 367, 1–13.
- **Iversen, M. H.** and L. K. Poulsen (2007), Coprorhexy, coprophagy, and coprochaly in the copepods *Calanus helgolandicus*, *Pseudocalanus elongatus*, and *Oithona similis*, Marine Ecology Progress Series, 350, 79–89.

KOSCHINSKY, ANDREA, PROF. DR.

Personal Data	
Date and Place of birth	5 April 1964, Bad Lauterberg
Nationality	German
Webpage	akoschinsk.user.jacobs-university.de
ORCID	0000-0002-9224-0663
Degrees	
2002	Habilitation, Free University of Berlin, Germany
1993	PhD, Free University of Berlin
1989	Diploma in Chemistry, TU Clausthal, Germany
Positions	
2011–present	Professor of Geosciences, Jacobs University Bremen (former International University Bremen)
2005–2011	Associate Professor of Geosciences, Jacobs University Bremen
2003–2005	Senior Research Associate at the International University Bremen (now Jacobs University Bremen)
2002–2005	Assistant Professor, Free University of Berlin, Germany
1992–2001	Research Scientist, Free University of Berlin
1989–1992	Research Scientist, TU Clausthal, Germany
Scientific Awards	
2017	Mary B. Ansari Best Geoscience Research Resource Work Award of The Geoscience Information Society
2014	Helmholtz Young Investigator Group Award
2009	ASLO Outstanding Student Presentation Award
2008	Feature Paper in MEPS (doi:10.3354/meps07611)

Research Work

My main research area is the geochemistry of hydrothermal fluids and geo-bio interactions between organisms and fluids in hydrothermal systems. I focus on the role of the chemical speciation of trace metals for these interactions. My interest in trace metals is also reflected in my involvement in the GEOTRACES program investigating the distribution of trace metals in the world oceans. Another field of research deals with high-tech elements in marine ferromanganese crusts and nodules and the potential impact of future deep-sea mining on the geochemical equilibrium at the ocean floor.

Professional Activities	
2017–present	Member, DFG Senate Commission on Earth System Research
2014–present	Chair, Strategy Group Marine Mineral Resources of KDM (German Marine Research Consortium)
2011–2017	Member, DFG Senate Commission on Oceanography

Most relevant publications

- Nasemann, P., M. Gault-Ringold, C. Stirling, **A. Koschinsky**, and S. Sander (2017), Processes affecting the isotopic composition of dissolved iron in hydrothermal plumes: A case study from the Vanuatu back-arc, Chemical Geology, 476, 70–84.
- Pöhle, S. and **A. Koschinsky** (2017), Depth distribution of Zr and Nb in seawater: The potential role of colloids or organic complexation to explain non-scavenging-type behavior, Marine Chemistry, 188, 18–32.
- Kleint, C., J. A. Hawkes, S. G. Sander, and **A. Koschinsky** (2016), Voltammetric investigation of hydrothermal iron speciation, Frontiers in Marine Science, 3, 75.
- Sander, S. G. and **A. Koschinsky** (2016), The export of iron and other trace metals from hydrothermal vents and the impact on their marine biogeochemical cycle, in Trace Metal Biogeochemistry and Ecology of Deep-Sea Hydrothermal Vent Systems, edited by L. L. Demina and S. V. Galkin, pp. 9–24, Springer International Publishing, Cham.
- Hawkes, J. A., P. E. Rossel, A. Stubbins, D. Butterfield, D. P. Connelly, E. P. Achterberg, **A. Koschinsky**, V. Chavagnac, C. T. Hansen, W. Bach, and T. Dittmar (2015), Efficient removal of recalcitrant deep-ocean dissolved organic matter during hydrothermal circulation, Nature Geoscience, 8, 856–860.
- Kleint, C., S. Kuzmanovski, Z. Powell, S. I. Bühring, S. G. Sander, and **A. Koschinsky** (2015), Organic Cu-complexation at the shallow marine hydrothermal vent fields off the coast of Milos (Greece), Dominica (Lesser Antilles) and the Bay of Plenty (New Zealand), Marine Chemistry, 173, 244–252.
- **Koschinsky, A.**, M. Kausch, and C. Borowski (2014), Metal concentrations in the tissues of the hydrothermal vent mussel *Bathymodiolus*: Reflection of different metal sources, Marine Environmental Research, 95, 62–73.
- Sander, S. G. and **A. Koschinsky** (2011), Metal flux from hydrothermal vents increased by organic complexation, Nature Geoscience, 4, 145–150.
- **Koschinsky, A.**, D. Garbe-Schönberg, S. Sander, K. Schmidt, H. H. Gennerich, and H. Strauß (2008), Hydrothermal venting at pressure-temperature conditions above the critical point of seawater, 5 degrees S on the Mid-Atlantic Ridge, Geology, 36, 615–618.
- Sander, S. G., **A. Koschinsky**, G. Massoth, M. Stott, and K. A. Hunter (2007), Organic complexation of copper in deep-sea hydrothermal vent systems, Environmental Chemistry, 4, 81–89.

KUČERA, MICHAL, PROF. DR.

Personal Data	
Date and Place of birth	23 May 1971, Ceske Budejovice
Nationality	Czech
Webpage	www.marum.de/Michal_Kucera.html
ORCID	0000-0002-7817-9018
Degrees	
1998	PhD, University of Gothenburg, Sweden
1994	MSc in Geology, Charles University, Prague, Czech Republic
Positions	
2012–present	Professor of Micropaleontology/Paleoceanography, University of Bremen
2004–2012	Professor of Micropaleontology, University of Tübingen, Germany
2000–2004	Professor (2004), Reader (2003–2004) and Lecturer (2000–2003), Royal Holloway University of London, UK
1998–2000	Postdoctoral Fellow, University of California, Santa Barbara, USA

Research Work

My research combines the study of biological and ecological processes in marine organisms with the transfer of this knowledge to the development of proxies for past oceanic environments based on their microfossil record and the study of patterns of biotic response to global change in the marine realm. This involves integrated studies of Quaternary paleoclimatology in marginal oceanic basins and the Arctic, syntheses of paleoclimate records and trends serving to bench-mark climate models, understanding the sensitivity of calcification and productivity to global change and the reaction of marine organisms to stress.

Professional Activities	
2017–present	Member, DFG Senate Commission on Earth-System Research
2015–present	Member, Steering Group of the German National Climate Modeling Initiative "From the Last Interglacial to the Anthropocene: Modeling a Complete Glacial Cycle"
2014–present	Member, Scientific Steering Committee of the Future Earth/IGBP core project Past Global Changes (PAGES)
2013–present	Speaker, International Research Training Group ArcTrain: Processes and impacts of climate change in the North Atlantic Ocean and the Canadian Arctic (DFG, GRK 1904)
2009–present	Member, PMIP (Paleoclimate Modeling Intercomparison Project) steering board
2011–2016	Co-chair, SCOR/IGBP Working Group 138 "Modern Planktonic Foraminifera and Ocean Changes"
2008–2010	President, The Micropalaeontological Society
2004–2007	Fellow, National Environmental Research Council (NERC, UK) Peer Review College

Most relevant publications

- Morard, R., F. Lejzerowicz, K. F. Darling, B. Lecroq-Bennet, M. Winther Pedersen, L. Orlando, J. Pawlowski, S. Mulitza, C. de Vargas, and **M. Kučera** (2017), Planktonic foraminifera-derived environmental DNA extracted from abyssal sediments preserves patterns of plankton macroecology, Biogeosciences, 14, 2741–2754.
- Oksman, M., K. Weckström, A. Miettinen, S. Juggins, S. Divine, R. Jackson, R. Telford, and **M. Kučera** (2017), Younger Dryas ice margin retreat triggered by ocean surface warming in central-eastern Baffin Bay, Nature Communications, 8, 1017.
- Kretschmer, K., **M. Kučera**, and M. Schulz (2016), Modeling the distribution and seasonality of *Neogloboquadrina pachyderma* in the North Atlantic Ocean during Heinrich Stadial 1, Paleoceanography, 31, 986–010.
- Jonkers, L. and **M. Kučera** (2015), Global analysis of seasonality in the shell flux of extant planktonic Foraminifera, Biogeosciences, 12, 2207–2226.
- Lopes, C., **M. Kučera**, and A. C. Mix (2015), Climate change decouples oceanic primary and export productivity and organic carbon burial, Proceedings of the National Academy of Sciences of the United States of America, 112, 332–335.
- Weinkauf, M. F. G., T. Moller, M. C. Koch, and **M. Kučera** (2014), Disruptive selection and bet-hedging in planktonic Foraminifera: shell morphology as predictor of extinctions, Frontiers in Ecology and Evolution, 2, 64.
- Rohling, E. J., K. Grant, M. Bolshaw, A. P. Roberts, M. Siddall, C. Hemleben, and **M. Kučera** (2009), Antarctic temperature and global sea level closely coupled over the past five glacial cycles, Nature Geoscience, 2, 500–504.
- Waelbroeck, C., A. Paul, **M. Kučera**, A. Rosell-Melee, M. Weinelt, R. Schneider, A. C. Mix, A. Abelmann, L. Armand, E. Bard, S. Barker, T. T. Barrows, H. Benway, I. Cacho, M. T. Chen, E. Cortijo, X. Crosta, A. de Vernal, T. Dokken, J. Duprat, H. Elderfield, F. Eynaud, R. Gersonde, A. Hayes, M. Henry, C. Hillaire-Marcel, C. C. Huang, E. Jansen, S. Juggins, N. Kallel, T. Kiefer, M. Kienast, L. Labeyrie, H. Leclaire, L. Londeix, S. Mangin, J. Matthiessen, F. Marret, M. Meland, A. E. Morey, S. Mulitza, U. Pflaumann, N. G. Pisias, T. Radi, A. Rochon, E. J. Rohling, L. Sbaffi, C. Schafer-Neth, S. Solignac, H. Spero, K. Tachikawa, J. L. Turon (2009), Constraints on the magnitude and patterns of ocean cooling at the Last Glacial Maximum, Nature Geoscience, 2, 127–132.
- Kuhlemann, J., E. J. Rohling, I. Krumrei, P. Kubik, S. Ivy-Ochs, and **M. Kučera** (2008), Regional synthesis of Mediterranean atmospheric circulation during the last glacial maximum, Science, 321, 1338–1340.
- **Kučera, M.**, A. Rosell-Melé, R. Schneider, C. Waelbroeck, and M. Weinelt (2005), Multiproxy approach for the reconstruction of the glacial ocean surface (MARGO), Quaternary Science Reviews, 24, 813–819.

KUYPERS, MARCEL, PROF. DR.

Personal Data	
Date and Place of birth	6 June 1970, Hunsel
Nationality	Dutch
Webpage	www.mpi-bremen.de/Marcel_Kuypers.html
ORCID	0000-0001-7991-5091
Degrees	
2001	PhD, University of Utrecht, The Netherlands
1995	MSc in Chemistry, University of Nijmegen, The Netherlands
Positions	
2009 – present	Head, Biogeochemistry Department, MPI-MM, Bremen, and Professor for Biogeochemistry, University of Bremen
2005 – 2009	Head, independent Max Planck Research Group 'Nutrient', MPI-MM, Bremen
2001 – 2005	Scientist, MPI-MM, Bremen

Research Work

My research focuses on microbial processes that control the ocean's nitrogen and carbon cycles. Major areas of interest are anaerobic ammonium oxidation (anammox), dissimilatory nitrite reduction to ammonium (DNRA), denitrification and nitrification, carbon and nitrogen assimilation by bacterioplankton. My research interests have expanded to include nitrogen fixation and assimilation; single-cell environmental microbiology: coupling the identity of microorganisms with their activity in the environment (e.g., by combining nanoscale secondary isotope mass spectrometry (nanoSIMS) with fluorescence *in-situ* hybridization).

Professional Activities	
2009 – present	Director, Max Planck Institute for Marine Microbiology, Bremen

Most relevant publications

- Ahmerkamp, S., C. Winter, K. Kramer, D. de Beer, F. Janssen, J. Friedrich, **M. M. M. Kuypers**, and M. Holtappels (2017), Regulation of benthic oxygen fluxes in permeable sediments of the coastal ocean, Limnology and Oceanography, 62, 1935–1954.
- Marchant, H., K, S. Ahmerkamp, G. Lavik, H. E. Tegetmeyer, J. Graf, J. M. Klatt, M. Holtappels, E. Walpersdorf, and **M. M. M. Kuypers** (2017), Denitrifying community in coastal sediments performs aerobic and anaerobic respiration simultaneously, ISME Journal, 11, 1799–1812.
- Kalvelage, T., G. Lavik, P. Lam, S. Contreras, L. Arteaga, C. R. Löscher, A. Oschlies, A. Paulmier, L. Stramma, and **M. M. M. Kuypers** (2013), Nitrogen cycling driven by organic matter export in the South Pacific oxygen minimum zone, Nature Geoscience, 6, 228–234.
- Milucka, J., T. G Ferdelman, L. Polerecky, D. Franzke, G. Wegener, M. Schmid, I. Lieberwirth, M. Wagner, F. Widdel, and **M. M. M. Kuypers** (2012), Zero-valent sulphur is a key intermediate in marine methane oxidation, Nature, 491, 541–546.
- Gao, H., F. Schreiber, G. Collins, M. M. Jensen, O. Svitlica, J. E. Kostka, G. Lavik, D. de Beer, H. Y. Zhou, and **M. M. M. Kuypers** (2011), Aerobic denitrification in permeable Wadden Sea sediments, ISME Journal, 5, 776–776.
- Lam, P., G. Lavik, M. M. Jensen, J. van de Vossenberg, M. Schmid, D. Woebken, G. Dimitri, R. Amann, M. S. M. Jetten, and **M. M. M. Kuypers** (2009), Revising the nitrogen cycle in the Peruvian oxygen minimum zone, Proceedings of the National Academy of Sciences of the United States of America, 106, 4752–4757.
- Lavik, G., T. Stührmann, V. Brüchert, A. Van der Plas, V. Mohrholz, P. Lam, M. Mußmann, B. M. Fuchs, R. Amann, U. Lass, and **M. M. M. Kuypers** (2009), Detoxification of sulphidic African shelf waters by blooming chemolithotrophs, Nature, 457, 581–U586.
- Lam, P., M. M. Jensen, G. Lavik, D. F. McGinnis, B. Muller, C. J. Schubert, R. Amann, B. Thamdrup, and **M. M. M. Kuypers** (2007), Linking crenarchaeal and bacterial nitrification to anammox in the Black Sea, Proceedings of the National Academy of Sciences of the United States of America, 104, 7104–7109.
- **Kuypers, M. M. M.**, G. Lavik, D. Woebken, M. Schmid, B. M. Fuchs, R. Amann, B. B. Jørgensen, and M. S. M. Jetten (2005), Massive nitrogen loss from the Benguela upwelling system through anaerobic ammonium oxidation, Proceedings of the National Academy of Sciences of the United States of America, 102, 6478–6483.
- **Kuypers, M. M. M.**, A. O. Sliekers, G. Lavik, M. Schmid, B. B. Jørgensen, J. G. Kuenen, J. S. S. Sinninghe Damsté, M. Strous, and M. S. M. Jetten (2003), Anaerobic ammonium oxidation by anammox bacteria in the Black Sea, Nature, 422, 608–611.

LOHMANN, GERRIT, PROF. DR.

Personal Data	
Date and Place of birth	13 May 1965, Göttingen
Nationality	German
Webpage	www.awi.de/nc/ueber-uns/organisation/mitarbeiter/gerrit-lohmann.html
ORCID	0000-0003-2089-733X
Degrees	
1996	PhD, University of Bremen
1992	Diploma in Physics, Philipps University of Marburg / Lahn, Germany
Positions	
2004 – present	Professor of Physics of the Climate System, University of Bremen
2005 – present	Section head, Paleoclimate Dynamics, AWI, Bremerhaven
2001 – 2006	Head, Junior Research Group Earth System Modeling & Analysis, University of Hamburg, Meteorological Inst.; University of Bremen, MARUM
2000 – 2001	Postdoc, University of Bremen, Paleoceanographic Modeling
1996 – 2000	Postdoc, Max Planck Institute for Meteorology, Hamburg
1994	Visiting Scientist, Earth Science Center, University of Gothenburg, Sweden
1992 – 1995	Research Assistant, AWI, Bremerhaven
Scientific Awards	
2009	Romanian Academy Award "Stefan Hepites"

Research Work

I endeavor to identify the mechanisms of climate variations on timescales ranging from the interannual to millions of years. For this purpose, I combine the usage and development of Earth-system models with extensive statistical data analyses in order to draw conclusions regarding climate transitions. One particular scientific focus of my work is on detecting abrupt climate changes through the application of conceptual, prognostic and data-oriented modeling methods. I have been a regular contributor to national and international conferences, am collaborator in several interdisciplinary projects and, in addition to my work with the University of Bremen, enjoy teaching at summer / winter schools.

Professional Activities	
2016 – present	Guest Professor, First Institute of Oceanography, Qingdao, China
2013 – present	Topic Speaker at AWI, The Earth system from a polar perspective
2008 – 2016	Speaker, Earth System Science Research School at AWI
2004 – present	Editor: Climate Past (2004 – 2015); Earth System Dynamics (2010 – present)
2006 – 2009	European Geosciences Union (EGU): President of "Climate: Past, Present, Future"
2003 – 2006	Spokesperson, German climate research program DEKLIM

Most relevant publications

- Stein, R, K. Fahl, M. Schreck, G. Knorr, F. Niessen, M. Forwick, C. Gebhardt, L. Jensen, M. Kaminski, A. J. Kopf, J. Matthiessen, W. Jokat, and **G. Lohmann** (2016), Evidence for ice-free summers in the late Miocene central Arctic Ocean, Nature Communications, 7, 11148.
- Knorr, G., and **G. Lohmann** (2014), Climate warming during Antarctic ice sheet expansion at the Middle Miocene transition, Nature Geoscience, 7, 376–381.
- Zhang, X., **G. Lohmann**, G. Knorr, and C. Purcell (2014), Abrupt glacial climate shifts controlled by ice sheet changes, Nature, 512, 290–294.
- **Lohmann, G.**, M. Pfeiffer, T. Laepple, G. Leduc, and J. H. Kim (2013), A model-data comparison of the Holocene global sea surface temperature evolution, Climate of the Past, 9, 1807–1839.
- Laepple, T., M. Werner, and **G. Lohmann** (2011), Synchronicity of Antarctic temperatures and local solar insolation on orbital timescales, Nature, 471, 91–94.
- Drysdale, R. N., J. C. Hellstrom, G. Zanchetta, A. E. Fallick, M. F. Sánchez Gõni, I. Couchoud, J. McDonald, R. Maas, **G. Lohmann**, and I. Isola (2009), Evidence for obliquity forcing of glacial Termination II, Science, 325, 1527–1531.
- Felis, T., **G. Lohmann**, H. Kuhnert, S. J. Lorenz, D. Scholz, J. Pätzold, S. A. Al-Rousan, and S. M. Al-Moghrabi (2004), Increased seasonality in Middle East temperatures during the last interglacial period, Nature, 429, 164–168.
- **Lohmann, G**., N. Rimbu, and M. Dima (2004), Climate signature of solar irradiance variations: Analysis of long-term instrumental, historical, and proxy data, International Journal of Climatology, 24, 1045–1056.
- Knorr, G. and **G. Lohmann** (2003), Southern Ocean origin for the resumption of Atlantic thermohaline circulation during deglaciation, Nature, 424, 532–536.
- **Lohmann, G.** (2003), Atmospheric and oceanic freshwater transport during weak Atlantic overturning circulation, Tellus Series A: Dynamic Meteorology and Oceanography, 55, 438–449.

MOLLENHAUER, GESINE, PROF. DR.

Personal Data	
Date and Place of birth	22 October 1972, Frankfurt (Main)
Nationality	German
Webpage	www.awi.de/nc/ueber-uns/organisation/mitarbeiter/gesine-mollenhauer.html
ORCID	0000-0001-5138-564X
Degrees	
2002	PhD, University of Bremen
1999	Diploma in Geology, University of Bremen
Positions	
2011–present	Professor of Organic Sedimentology, University of Bremen
2006–present	Scientist, AWI
2005	Postdoc, University of Bremen
2005	Postdoc, Royal Netherlands Institute for Sea Research
2002–2004	Postdoc, Woods Hole Oceanographic Institution, USA
1999–2002	Research Assistant (doctoral student), University of Bremen
Scientific Awards	
2016	Helmholtz Recognition Award
2005	Helmholtz Young Investigator Group
2003	Annette Barthelt Prize for Marine Sciences, Germany
2002	Woods Hole Postdoctoral Fellowship

Research Work

My research activities have focus mainly on deposition of organic matter and organic source specific biomarkers in marine sediments. I am particularly interested in the timescales of carbon cycling, intermediate storage and of transport to the sediments, and the processes occurring during transport, all in context of climate as a controlling parameter. For this research, I apply compound-specific radiocarbon dating, for which I am one of a few experts worldwide. My second major field of research is in the development and application of organic palaeoproxies for reconstruction of environmental conditions, their origin, processes of their alteration, and application of their associated proxies in the high latitudes.

Professional Activities	
2016–present	Scientific coordinator of MICADAS ^{14}C-dating facility at Alfred Wegener Institute
2016–present	Topic speaker, PACES II research program, AWI
2014–present	Deputy head, Marine Geochemistry section, AWI

Most relevant publications

- Fischer, G., J. Karstensen, O. Romero, KH. Baumann, B. Donner, J. Hefter, **G. Mollenhauer**, M. Iversen, B. Fiedler, I. Monteiro, and A. Körtzinger (2016), Bathypelagic particle flux signatures from a suboxic eddy in the oligotrophic tropical North Atlantic: production, sedimentation and preservation, Biogeosciences, 13, 3203–3223.
- Meyer, V. D., L. Max, J. Hefter, R. Tiedemann, and **G. Mollenhauer** (2016), Glacial-to-Holocene evolution of sea surface temperature and surface circulation in the subarctic northwest Pacific and the Western Bering Sea, Paleoceanography, 31, 916–927.
- **Mollenhauer, G.**, A. Basse, J. H. Kim, J. S. S. Sinninghe Damsté, and G. Fischer (2015), A four-year record of U-37(K')- and TEX86-derived sea surface temperature estimates from sinking particles in the filamentous upwelling region off Cape Blanc, Mauritania, Deep-Sea Research Part I-Oceanographic Research Papers, 97, 67–79.
- Basse, A., C. Zhu, G. J. M. Versteegh, G. Fischer, K.-U. Hinrichs, and **G. Mollenhauer** (2014), Distribution of intact and core tetraether lipids in water column profiles of suspended particulate matter off Cape Blanc, NW Africa, Organic Geochemistry, 72, 1–13.
- Chen, W. W., M. Mohtadi, E. Schefuß, and **G. Mollenhauer** (2014), Organic-geochemical proxies of sea surface temperature in surface sediments of the tropical eastern Indian Ocean, Deep-Sea Research Part I-Oceanographic Research Papers, 88, 17–29.
- Ho, S. L., **G. Mollenhauer**, S. Fietz, A. Martínez-Garcia, F. Lamy, G. Rueda, K. Schipper, M. Méheust, A. Rosell-Melé, R. Stein, and R. Tiedemann (2014), Appraisal of TEX86 and TEX86L thermometries in subpolar and polar regions, Geochimica et Cosmochimica Acta, 131, 213–226.
- Kusch, S., J. Rethemeyer, E. Schefuß, and **G. Mollenhauer** (2010), Controls on the age of vascular plant biomarkers in Black Sea sediments, Geochimica et Cosmochimica Acta, 74, 7031–7047.
- **Mollenhauer, G.**, T. I. Eglinton, E. C. Hopmans, and J. S. S. Sinninghe Damsté (2008), A radiocarbon-based assessment of the preservation characteristics of crenarchaeol and alkenones from continental margin sediments, Organic Geochemistry, 39, 1039–1045.
- **Mollenhauer, G.**, and T. I. Eglinton (2007), Diagenetic and sedimentological controls on the composition of organic matter preserved in California Borderland Basin sediments, Limnology and Oceanography, 52, 558–576.
- **Mollenhauer, G.**, T. I. Eglinton, N. Ohkouchi, R. R. Schneider, P. J. Müller, P. M. Grootes, and J. Rullkötter (2003), Asynchronous alkenone and foraminfera records from the Benguela Upwelling System, Geochimica et Cosmochimica Acta, 67, 2157–2171.

MÜLLER, JULIANE, DR.

Personal Data	
Date and Place of birth	22 November 1981, Berlin
Nationality	German
Webpage	www.awi.de/en/about-us/organisation/staff/juliane-mueller.html
ORCID	0000-0003-0724-4131
Degrees	
2011	PhD, University of Bremen
2007	Diploma in Applied Geosciences, Technical University of Berlin, Germany
Positions	
2016–present	Leader of HGF Young Investigator Group PALICE, AWI, Bremerhaven and University of Bremen
2013–2016	Postdoc, AWI, Bremerhaven and Potsdam
2013	IODP Expedition Scientist, BGR, Hannover
2011–2013	Postdoc, AWI, Bremerhaven
2007–2011	Research Assistant, AWI, Bremerhaven
Scientific Awards	
2015	Helmholtz Young Investigator Group
2014	European Consortium for Ocean Research Drilling (ECORD) Research Grant
2014	IASC-ICARP III Research Fellowship
2012	German Thesis Award, *Körberstiftung*
2010	AWI Science Award

Research Work

My research specifically focuses on the reconstruction of past sea-ice conditions in the polar oceans during abrupt as well as long-term climate transitions. These studies are based on the application (and further development) of organic geochemical biomarker lipids preserved in marine sediments. With my HGF Young Investigator Group, I aim to assess sea ice/ocean/atmosphere interactions in the Southern Ocean and their impact on the biological and physical carbon pump. This project combines reconstructions of environmental conditions with numerical modeling approaches, which permit a testing of the proxy-derived hypotheses on climate feedbacks.

Professional Activities	
2016–present	Head of Young Investigator Group "PALICE"
2009–present	Head of 2nd Biomarker Laboratory at AWI (Marine Geology)

Most relevant publications

- Werner, K., **J. Müller**, K. Husum, R. F. Spielhagen, E. S. Kandiano, and L. Polyak (2016), Holocene sea subsurface and surface water masses in the Fram Strait – Comparisons of temperature and sea-ice reconstructions, Quaternary Science Reviews, 147, 194 – 209.
- Gulick, S. P. S., J. M. Jaeger, A. C. Mix, H. Asahi, H. Bahlburg, C. L. Belanger, G. B. B. Berbel, L. Childress, E. Cowan, L. Drab, M. Forwick, A. Fukumura, S. L. Ge, S. Gupta, A. Kioka, S. Konno, L. J. LeVay, C. März, K. M. Matsuzaki, E. L. McClymont, C. Moy, **J. Müller**, A. Nakamura, T. Ojima, F. R. Ribeiro, K. D. Ridgway, O. E. Romero, A. L. Slagle, J. S. Stoner, G. St-Onge, I. Suto, M. D. Walczak, L. L. Worthington, I. Bailey, E. Enkelmann, R. Reece, and J. M. Swartz (2015), Mid-Pleistocene climate transition drives net mass loss from rapidly uplifting St. Elias Mountains, Alaska, Proceedings of the National Academy of Sciences of the United States of America, 112, 15042 – 15047.
- Xiao, X. T., K. Fahl, **J. Müller**, and R. Stein (2015), Sea-ice distribution in the modern Arctic Ocean: Biomarker records from trans-Arctic Ocean surface sediments, Geochimica et Cosmochimica Acta, 155, 16 – 29.
- **Müller, J.** and R. Stein (2014), High-resolution record of late glacial and deglacial sea ice changes in Fram Strait corroborates ice-ocean interactions during abrupt climate shifts, Earth and Planetary Science Letters, 403, 446 – 455.
- Werner, K., M. Frank, C. Teschner, **J. Müller**, and R. F. Spielhagen (2014), Neoglacial change in deep water exchange and increase of sea-ice transport through eastern Fram Strait: evidence from radiogenic isotopes, Quaternary Science Reviews, 92, 190 – 207.
- Belt, S. T. and **J. Müller** (2013), The Arctic sea ice biomarker IP_{25}: a review of current understanding, recommendations for future research and applications in palaeo sea ice reconstructions, Quaternary Science Reviews, 79, 9 – 25.
- **Müller, J.**, K. Werner, R. Stein, K. Fahl, M. Moros, and E. Jansen (2012), Holocene cooling culminates in sea ice oscillations in Fram Strait, Quaternary Science Reviews, 47, 1 – 14.
- **Müller, J.**, A. Wagner, K. Fahl, R. Stein, M. Prange, and G. Lohmann (2011), Towards quantitative sea ice reconstructions in the northern North Atlantic: A combined biomarker and numerical modelling approach, Earth and Planetary Science Letters, 306, 137 – 148.
- **Müller, J.**, G. Massé, R. Stein, and S. T. Belt (2009), Variability of sea-ice conditions in the Fram Strait over the past 30,000 years, Nature Geoscience, 2, 772 – 776.

PÄLIKE, HEIKO, PROF. DR.

Personal Data	
Date and Place of birth	6 May 1974, Lemgo
Nationality	German
Webpage	www.marum.de/en/Heiko_Paelike.html
ORCID	0000-0003-3386-0923
Degrees	
2002	PhD, University of Cambridge, UK
1998	MSc (Distinction) in Hydrogeology, University College London, UK
Positions	
2012–present	Professor of Paleoceanography, University of Bremen
2011–2012	Professor, University of Southampton, UK
2004–2011	Lecturer, then Reader, University of Southampton
2002–2004	Research Scientist, Stockholm University, Sweden
Scientific Awards	
2016	Asahiko Taira Prize of the American Geophysical Union and the Japan Geoscience Union
2014	ERC Consolidator Grant
2012	Winner Wolfson Merit Award (declined due to move to Bremen)
2011	Winner Wollaston Fund, Geological Society, London, UK
2008	Winner Philip Leverhulme Prize, UK
2007	Apple Inc., ARTS Higher Education Laureate

Research Work

Reconstructing the paleoceanography and paleoclimatology of the Cenozoic using high-resolution paleoceanographic proxy time series. Investigating the carbonate saturation state of the oceans. Geology of polar regions with specific focus on the Arctic Ocean. Applying Earth-system models of intermediate complexity (cGENIE) to large climatic shifts during the Cenozoic. Events, causes and feedbacks during the extreme Cenozoic climatic events, including the Eocene / Oligocene transition from greenhouse to icehouse, Oligocene climate dynamics, and the Paleocene-Eocene thermal maximum.

Professional Activities	
2013–2017	Editor, Paleoceanography
2012–2015	Science Member, "JOIDES Resolution" Facility Board
2009–2012	Panel Member, IODP Science Plan Writing Committee
2008–2016	Member, Intl. Subcommission on Paleogene Stratigraphy
2014–present	Member, DFG Senate Commission on Oceanography

Most relevant publications

- **Pälike, H.**, M. W. Lyle, H. Nishi, I. Raffi, A. Ridgwell, K. Gamage, A. Klaus, G. Acton, L. Anderson, J. Backman, J. Baldauf, C. Beltran, S. M. Bohaty, P. Bown, W. Busch, J. E. T. Channell, C. O. J. Chun, M. Delaney, P. Dewangan, T. Dunkley Jones, K. M. Edgar, H. Evans, P. Fitch, G. L. Foster, N. Gussone, H. Hasegawa, E. C. Hathorne, H. Hayashi, J. O. Herrle, A. Holbourn, S. Hovan, K. Hyeong, K. Iijima, T. Ito, S. Kamikuri, K. Kimoto, J. Kuroda, L. Leon-Rodriguez, A. Malinverno, T. C. Moore, B. H. Murphy, D. P. Murphy, H. Nakamura, K. Ogane, C. Ohneiser, C. Richter, R. Robinson, E. J. Rohling, O. Romero, K. Sawada, H. Scher, L. Schneider, A. Sluijs, H. Takata, J. Tian, A. Tsujimoto, B. S. Wade, T. Westerhold, R. Wilkens, T. Williams, P. A. Wilson, Y. Yamamoto, S. Yamamoto, T. Yamazaki, and R. E. Zeebe (2012), A Cenozoic record of the equatorial Pacific carbonate compensation depth, Nature, 488, 609–615.
- Rohling, E. J., A. Sluijs, H. A. Dijkstra, P. Köhler, R. de Wal, A. S. von der Heydt, D. J. Beerling, A. Berger, P. K. Bijl, M. Crucifix, R. DeConto, S. S. Drijfhout, A. Fedorov, G. L. Foster, A. Ganopolski, J. Hansen, B. Hönisch, H. Hooghiemstra, M. Huber, P. Huybers, R. Knutti, D. W. Lea, L. J. Lourens, D. Lunt, V. Masson-Demotte, M. Medina-Elizalde, B. Otto-Bliesner, M. Pagani, **H. Pälike**, H. Renssen, D. L. Royer, M. Siddall, P. Valdes, J. C. Zachos, and R. E. Zeebe (2012), Making sense of palaeoclimate sensitivity, Nature, 491, 683–691.
- Liebrand, D., L. J. Lourens, D. A. Hodell, B. de Boer, R. S. W. van de Wal, and **H. Pälike** (2011), Antarctic ice sheet and oceanographic response to eccentricity forcing during the early Miocene, Climate of the Past, 7, 869–880.
- Sexton, P. F., R. D. Norris, P. A. Wilson, **H. Pälike**, T. Westerhold, U. Röhl, C. T. Bolton, and S. Gibbs (2011), Eocene global warming events driven by ventilation of oceanic dissolved organic carbon, Nature, 471, 349–352.
- Westbrook, G. K., K. E. Thatcher, E. J. Rohling, A. M. Piotrowski, **H. Pälike**, A. H. Osborne, E. G. Nisbet, T. A. Minshull, M. Lanoiselle, R. H. James, V. Huhnerbach, D. Green, R. E. Fisher, A. J. Crocker, A. Chabert, C. Bolton, A. Beszczynska-Moller, C. Berndt, and A. Aquilina (2009), Escape of methane gas from the seabed along the West Spitsbergen continental margin, Geophysical Research Letters, 36, L15608.
- DeConto, R. M., D. Pollard, P. A. Wilson, H. **Pälike**, C. H. Lear, and M. Pagani (2008), Thresholds for Cenozoic bipolar glaciation, Nature, 455, 652–656.
- Moran, K., J. Backman, H. Brinkhuis, S. C. Clemens, T. Cronin, G. R. Dickens, F. Eynaud, J. Gattacceca, M. Jakobsson, R. W. Jordan, M. Kaminski, J. King, N. Koc, A. Krylov, N. Martinez, J. Matthiessen, D. McInroy, T. C. Moore, J. Onodera, M. O'Regan, **H. Pälike**, B. Rea, D. Rio, T. Sakamoto, D. C. Smith, R. Stein, K. St John, I. Suto, N. Suzuki, K. Takahashi, M. Watanabe, M. Yamamoto, J. Farrell, M. Frank, P. Kubik, W. Jokat, and Y. Kristoffersen (2006), The Cenozoic palaeoenvironment of the Arctic Ocean, Nature, 441, 601–605.
- **Pälike, H.**, R. D. Norris, J. O. Herrle, P. A. Wilson, H. K. Coxall, C. H. Lear, N. J. Shackleton, A. K. Tripati, and B. S. Wade (2006), The heartbeat of the oligocene climate system, Science, 314, 1894–1898.
- Coxall, H. K., P. A. Wilson, **H. Pälike**, C. H. Lear, and J. Backman (2005), Rapid stepwise onset of Antarctic glaciation and deeper calcite compensation in the Pacific Ocean, Nature, 433, 53–57.
- **Pälike, H.**, J. Laskar, and N. J. Shackleton (2004), Geologic constraints on the chaotic diffusion of the solar system, Geology, 32, 929–932.

PÉREZ-GUSSINYÉ, MARTA, PROF. DR.

Personal Data	
Date and Place of birth	4 April 1972, Barcelona
Nationality	Spanish
Webpage	www.marum.de/Marta_Perez-Gussinye.html
ORCID	0000-0003-4109-1810
Degrees	
2000	PhD, University of Kiel, Germany
1996	Diploma in Physics, University of Barcelona, Spain
Positions	
2015–present	Professor of Geodynamics, University of Bremen
2015	Reader, Royal Holloway College, University of London, UK
2012–2014	Senior Lecturer, Royal Holloway College, University of London
2009–2011	Lecturer, Royal Holloway College, University of London
2005–2008	"Ramon y Cajal" Research Fellow, Spanish Research Council, Barcelona, Spain
2001–2005	NERC Research Fellow, Dept. Earth Sciences, University of Oxford, UK
2001–2003	Postdoc, Dept. Earth Sciences, University of Oxford, UK
2000–2001	Postdoc, GEOMAR, University of Kiel, Germany
1996–2000	Research Assistant (PhD), GEOMAR, University of Kiel

Research Work

My research focuses on understanding how lithospheric dynamics and its interaction with the convecting interior shape tectonics observed at the surface. To this end, I combine analyses of observational data, and the subsequent development of new conceptual models, with the numerical modeling of their dynamics. I work with a broad range of data, including multi-channel and wide-angle seismic, topography and gravity data, as well as with the development of dynamic models of deformation and inversion codes to retrieve lithospheric rheology.

Professional Activities	
2010–2012	Committee member, Young Scientist Award for the Tectonophysics Section of the European Geosciences Union (EGU)
2001–present	Reviewer for Nature Geoscience, J. Geophys. Res., G-cubed, Geology, Earth and Planet. Sci. Lett., Mar. and Petroleum Geology etc.

Most relevant publications

- Bayrakci, G., T. A. Minshull, D. S. Sawyer, T. J. Reston, D. Klaeschen, C. Papenberg, C. Ranero, J. M. Bull, R. G. Davy, D. J. Shillington, **M. Pérez-Gussinyé**, and J. K. Morgan (2016), Fault-controlled hydration of the upper mantle during continental rifting, Nature Geoscience, 9, 384–388.
- Brune, S., C. Heine, **M. Pérez-Gussinyé**, and S. V. Sobolev (2014), Rift migration explains continental margin asymmetry and crustal hyper-extension, Nature Communications, 5, 4014.
- Manea, V. C., **M. Pérez-Gussinyé**, and M. Manea (2012), Chilean flat slab subduction controlled by overriding plate thickness and trench rollback, Geology, 40, 35–38.
- Lowry, A. R. and **M. Pérez-Gussinyé** (2011), The role of crustal quartz in controlling Cordilleran deformation, Nature, 471, 353–357.
- Ranero, C. R. and **M. Pérez-Gussinyé** (2010), Sequential faulting explains the asymmetry and extension discrepancy of conjugate margins, Nature, 468, 294–299.
- **Pérez-Gussinyé, M.**, M. Metois, M. Fernández, J. Vergés, J. Fullea, and A. R. Lowry (2009), Effective elastic thickness of Africa and its relationship to other proxies for lithospheric structure and surface tectonics, Earth and Planetary Science Letters, 287, 152–167.
- **Pérez-Gussinyé, M.** and A. B. Watts (2005), The long-term strength of Europe and its implications for plate-forming processes, Nature, 436, 381–384.
- **Pérez-Gussinyé, M.**, A. R. Lowry, A. B. Watts, and I. Velicogna (2004), On the recovery of effective elastic thickness using spectral methods: Examples from synthetic data and from the Fennoscandian Shield, Journal of Geophysical Research-Solid Earth, 109, B10409.
- **Pérez-Gussinyé, M.**, C. R. Ranero, T. J. Reston, and D. Sawyer (2003), Mechanisms of extension at nonvolcanic margins: Evidence from the Galicia interior basin, west of Iberia, Journal of Geophysical Research-Solid Earth, 108, 2245.
- **Pérez-Gussinyé, M.** and T. J. Reston (2001), Rheological evolution during extension at nonvolcanic rifted margins: Onset of serpentinization and development of detachments leading to continental breakup, Journal of Geophysical Research-Solid Earth, 106, 3961–3975.

RHEIN, MONIKA, PROF. DR.

Personal Data	
Date and Place of birth	3 June 1956, Heidenheim
Nationality	German
Webpage	www.ocean.uni-bremen.de/mitarbeiter/mrhein/index_mr.html
ORCID	0000-0003-1496-2828
Degrees	
2004	Habilitation, University of Kiel, Germany
1986	PhD, University of Heidelberg, Germany
1982	Diploma in Physics, University of Heidelberg
Positions	
2000–present	Professor of Physical Oceanography, University of Bremen
1998–2000	Professor, Institute for Baltic Research, Rostock, Germany
1995–1998	Associate Professor and DFG Heisenberg Fellow, University of Kiel and IfM-GEOMAR, Kiel, Germany
1988–1995	Assistant Professor, University of Kiel
1986–1988	Research Scientist, University of Heidelberg and GKSS, Hamburg, Germany
Scientific Awards	
2016	A. Defant Medal, German Meteorological Society
2012	F. Schott Lecturer, RSMAS Miami and GEOMAR, Kiel
1995–1998	DFG Heisenberg Fellowship

Research Work

My main research topics are the climate-relevant processes in the ocean: variability of ventilation, formation and spreading of water masses, timescales, transport and pathways of circulation, changes in anthropogenic carbon storage in the ocean, link of oceanic variability to atmospheric modes.

Professional Activities	
2017–present	Review Editor for IPCC Special Report on Ocean and Cryosphere
2016–present	Co-Speaker, DFG Transregio TRR 181 "Energy transfers in atmosphere and oceans"
2016–present	Coordinator, BMBF program RACE: "Regional Atlantic circulation and global change"
2008–present	Directorate German Climate Consortium DKK
2015–present	Member, Scientific advisory board ICBM, Univ. Oldenburg
2006–present	Member, Advisory boards for the German research vessels SONNE (since 2008) and POLARSTERN
2012–present	Board of Trustees, GEOMAR, Kiel
2014–present	DFG National Committee SCAR/IASC, Co-Speaker since 2017
2008–2016	DFG review Board 313, co-speaker 2012–2014, speaker 2014–2016

Most relevant publications

- Hellmer, H. H., **M. Rhein**, G. Heinemann, J. Abalichin, W. Abouchami, O. Baars, U. Cubasch, K. Dethloff, L. Ebner, E. Fahrbach, M. Frank, G. Gollan, R. J. Greatbatch, J. Grieger, V. M. Gryanik, M. Gryschka, J. Hauck, M. Hoppema, O. Huhn, T. Kanzow, B. P. Koch, G. König-Langlo, U. Langematz, G. C. Leckebusch, C. Lupkes, S. Paul, A. Rinke, B. Rost, M. R. van der Loeff, M. Schröder, G. Seckmeyer, T. Stichel, V. Strass, R. Timmermann, S. Trimborn, U. Ulbrich, C. Venchiarutti, U. Wacker, S. Willmes, and D. Wolf-Gladrow (2016), Meteorology and oceanography of the Atlantic sector of the Southern Ocean – a review of German achievements from the last decade, Ocean Dynamics, 66, 1379–1413.
- Stendardo, I., **M. Rhein**, and R. Hollmann (2016), A high resolution salinity time series 1993–2012 in the North Atlantic from Argo and Altimeter data, Journal of Geophysical Research-Oceans, 121, 2523–2551.
- **Rhein, M.**, D. Kieke, and R. Steinfeldt (2015), Advection of North Atlantic Deep Water from the Labrador Sea to the southern hemisphere, Journal of Geophysical Research-Oceans, 120, 2471–2487.
- Roessler, A., **M. Rhein**, D. Kieke, and C. Mertens (2015), Long-term observations of North Atlantic Current transport at the gateway between western and eastern Atlantic, Journal of Geophysical Research-Oceans, 120, 4003–4027.
- Mertens, C., **M. Rhein**, M. Walter, C. W. Böning, E. Behrens, D. Kieke, R. Steinfeldt, and U. Stöber (2014), Circulation and transports in the Newfoundland Basin, western subpolar North Atlantic, Journal of Geophysical Research-Oceans, 119, 7772–7793.
- Bullister, J. L., **M. Rhein**, and C. Mauritzen (2013), Chapter 10 – Deepwater Formation, in International Geophysics, edited by G. Siedler, S. M. Griffies, J. Gould and J. A. Church, pp. 227–253, Academic Press.
- **Rhein, M.**, S. R. Rintoul, S. Aoki, E. Campos, D. Chambers, R. A. Feely, S. Gulev, G. C. Johnson, S. A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L. D. Talley, and F. Wang (2013), Observations: Ocean, in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, pp. 255–316, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- **Rhein, M.**, D. Kieke, S. Hüttl-Kabus, A. Roessler, C. Mertens, R. Meissner, B. Klein, C. W. Böning, and I. Yashayaev (2011), Deep-water formation, the subpolar gyre, and the meridional overturning circulation in the subpolar North Atlantic. Deep-Sea Research II, 58, 1819–1832.
- **Rhein, M.**, J. Fischer, W. M. Smethie, D. Smythe-Wright, R. F. Weiss, C. Mertens, D. H. Min, U. Fleischmann, and A. Putzka (2002), Labrador Sea Water: Pathways, CFC inventory, and formation rates, Journal of Physical Oceanography, 32, 648–665.
- Sy, A., **M. Rhein**, J. R. N. Lazier, K. P. Koltermann, J. Meincke, A. Putzka, and M. Bersch (1997), Surprisingly rapid spreading of newly formed intermediate waters across the North Atlantic Ocean, Nature, 386, 675–679.

RÖHL, URSULA, DR.

Personal Data	
Date and Place of birth	10 November 1959, Rheinberg
Nationality	German
Webpage	www.marum.de/en/Dr._Ursula_Roehl.html
ORCID	0000-0001-9469-7053
Degrees	
1988	PhD, University of Bonn, Germany
1985	Diploma in Geology, University of Bonn
Positions	
2001–present	Senior Scientist, University of Bremen, MARUM
1995–2001	Postdoc, University of Bremen
1994–1995	Visiting scientist, Purdue University, Earth and Atmospheric Science Department, West Lafayette, Indiana, USA
1989–1994	Postdoc, Federal Institute for Geosciences and Natural Resources (BGR), Hannover, and Assistant Director in the German ODP office, Germany
1985–1988	Research Assistant (PhD), University of Bonn, Germany
Scientific Awards	
2011	BIOMARIS Research Award for Marine Sciences

Research Work

Cenozoic paleoceanography: Paleocene-Eocene greenhouse climate, timescales, cyclo-stratigraphy, time-series analysis and orbital tuning, chronostratigraphy, inorganic sediment geochemistry, oxygen and carbon stable isotopes, physical properties of marine sediments, non-destructive core logging/XRF scanning methods, core-log integration, carbonate diagenesis.

Professional Activities	
2018	Co-Chief Scientist, IODP Exp. 378 (South Pacific Paleogene)
2014–present	Team Leader, El Kef Coring Program
2014–2016	Member, Editorial Board Geology
2013–present	Liaison to the ECORD Facility Board
2012–present	Member, Steering Committee of the British Ocean Sediment Core Research Facility, NOC, Southampton, UK
2011–present	Senior Personnel, Bighorn Basin Coring Project (BBCP)
2009–2010	Nominating host of Humboldt-Research Award winner Prof. James C. Zachos, UCSC, USA
2009	Co-organizer, DFG Round Table "Stratigraphy", Steinhude, Germany
2007–present	Editorial Board, "Newsletters on Stratigraphy"
2005–present	Manager, IODP group and Bremen Core Repository (BCR) at MARUM, University of Bremen
2003–present	ECORD Science Operator (ESO) Curation and Laboratory Manager

Most relevant publications

- Penman, D. E., S. K. Turner, P. F. Sexton, R. D. Norris, A. J. Dickson, S. Boulila, A. Ridgwell, R. E. Zeebe, J. C. Zachos, A. Cameron, T. Westerhold, and **U. Röhl** (2016), An abyssal carbonate compensation depth overshoot in the aftermath of the Palaeocene-Eocene Thermal Maximum, Nature Geoscience, 9, 575–580.
- Bowen, G. J., B. J. Maibauer, M. J. Kraus, **U. Röhl**, T. Westerhold, A. Steimke, P. D. Gingerich, S. L. Wing, and W. C. Clyde (2015), Two massive, rapid releases of carbon during the onset of the Palaeocene-Eocene thermal maximum, Nature Geoscience, 8, 44–47.
- Littler, K., **U. Röhl**, T. Westerhold, and J. C. Zachos (2014), A high-resolution benthic stable-isotope record for the South Atlantic: Implications for orbital-scale changes in Late Paleocene-Early Eocene climate and carbon cycling, Earth and Planetary Science Letters, 401, 18–30.
- Houben, A. J. P., P. K. Bijl, J. Pross, S. M. Bohaty, S. Passchier, C. E. Stickley, **U. Röhl**, S. Sugisaki, L. Tauxe, T. van de Flierdt, M. Olney, F. Sangiorgi, A. Sluijs, C. Escutia, H. Brinkhuis, and the Expedition 318 Scientists (2013), Reorganization of Southern Ocean Plankton Ecosystem at the Onset of Antarctic Glaciation, Science, 340, 341–344.
- Pross, J., L. Contreras, P. K. Bijl, D. R. Greenwood, S. M. Bohaty, S. Schouten, J. A. Bendle, **U. Röhl**, L. Tauxe, J. I. Raine, C. E. Huck, T. van de Flierdt, S. S. R. Jamieson, C. E. Stickley, B. van de Schootbrugge, C. Escutia, H. Brinkhuis, and Integrated Ocean Drilling Program Expedition 318 Scientists (2012), Persistent near-tropical warmth on the Antarctic continent during the early Eocene epoch, Nature, 488, 73–77.
- Westerhold, T., **U. Röhl**, B. Donner, H. K. McCarren, and J. C. Zachos (2011), A complete high-resolution Paleocene benthic stable isotope record for the central Pacific (ODP Site 1209), Paleoceanography, 26, Pa2216.
- **Röhl, U.**, T. Westerhold, T. J. Bralower, and J. C. Zachos (2007), On the duration of the Paleocene-Eocene thermal maximum (PETM), Geochemistry Geophysics Geosystems, 8, Q12002.
- Zachos, J. C., **U. Röhl**, S. A. Schellenberg, A. Sluijs, D. A. Hodell, D. C. Kelly, E. Thomas, M. Nicolo, I. Raffi, L. J. Lourens, H. McCarren, and D. Kroon (2005), Rapid acidification of the ocean during the Paleocene-Eocene thermal maximum, Science, 308, 1611–1615.
- **Röhl, U.**, T. J. Bralower, R. D. Norris, and G. Wefer (2000), New chronology for the late Paleocene thermal maximum and its environmental implications, Geology, 28, 927–930.
- Norris, R. D., and **U. Röhl** (1999), Carbon cycling and chronology of climate warming during the Palaeocene/Eocene transition, Nature, 401, 775–778.

SCHULZ, MICHAEL, PROF. DR.

Personal Data	
Date and Place of birth	11 May 1964, Kiel
Nationality	German
Webpage	www.marum.de/en/Michael_Schulz.html
ORCID	0000-0001-6500-2697
Degrees	
1999	PhD, University of Kiel, Germany
1995	Diploma in Geology, University of Kiel
Positions	
2002–present	Professor of Geosystem Modeling, University of Bremen
2001–2002	Junior Lecturer, University of Kiel, Institute for Geosciences, Germany
2001	Postdoc, University of Hamburg, Meteorological Institute, Germany
1999–2001	Postdoc, University of Kiel, Institute for Geosciences, Germany
1999	Postdoc, Scripps Institution of Oceanography, USA
1998–1999	Postdoc, University of Kiel, Institute for Geosciences, Germany
1995–1998	Research Assistant (PhD), University of Kiel

Research Work

The statistical analysis of paleoclimatic time series lay at the outset of my career and still is an important aspect of my research. I developed time-series analysis programs that are widely used in the paleoclimate community. While my focus has shifted towards Earth-system modeling, I am still involved in generating high-resolution reconstructions of past ocean changes. A red thread of my research is to combine paleoclimate reconstructions with results from Earth-system models.

Professional Activities	
2017–present	Member, DFG Senate Commission on Earth-System Research
2015–present	Co-Coordinator, German National Climate Modeling Initiative "From the Last Interglacial to the Anthropocene: Modeling a Complete Glacial Cycle" (with M. Latif and M. Claussen)
2015–present	Member, scientific advisory board "Netherlands Earth System Science Center"
2013–present	Member, Executive Board German Marine Research Consortium (KDM)
2012–present	Director, MARUM – Center for Marine Environmental Sciences (incl. DFG Research Center/Cluster of Excellence)
2011–present	Member, advisory boards for the German research vessels METEOR, MARIA S. MERIAN and SONNE (since 2013)
2011–2017	Chairperson, DFG Senate Commission on Oceanography

Most relevant publications

- Rachmayani, R., M. Prange, D. J. Lunt, E. J. Stone, and **M. Schulz** (2017), Sensitivity of the Greenland Ice Sheet to interglacial climate forcing: MIS 5e versus MIS 11, Paleoceanography, 32, 1089–1101.
- Kretschmer, K., M. Kučera, and **M. Schulz** (2016), Modeling the distribution and seasonality of *Neogloboquadrina pachyderma* in the North Atlantic Ocean during Heinrich Stadial 1, Paleoceanography, 31, 986–1010.
- Zhang, X., M. Prange, U. Merkel, and **M. Schulz** (2015), Spatial fingerprint and magnitude of changes in the Atlantic meridional overturning circulation during marine isotope stage 3, Geophysical Research Letters, 42, 1903–1911.
- Masson-Delmotte, V., **M. Schulz**, A. Abe-Ouchi, J. Beer, A. Ganopolski, J. F. González Rouco, E. Jansen, K. Lambeck, J. Luterbacher, T. Naish, T. Osborn, B. Otto-Bliesner, T. Quinn, R. Ramesh, M. Rojas, X. Shao, and A. Timmermann (2013), Information from Paleoclimate Archives, in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, pp. 383–464, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Mulitza, S., D. Heslop, D. Pittauerova, H. W. Fischer, I. Meyer, J. B. Stuut, M. Zabel, G. Mollenhauer, J. A. Collins, H. Kuhnert, and **M. Schulz** (2010), Increase in African dust flux at the onset of commercial agriculture in the Sahel region, Nature, 466, 226–228.
- Narayan, N., A. Paul, S. Mulitza, and **M. Schulz** (2010), Trends in coastal upwelling intensity during the late 20th century, Ocean Science, 6, 815–823.
- **Schulz, M.**, M. Prange, and A. Klocker (2007), Low-frequency oscillations of the Atlantic Ocean meridional overturning circulation in a coupled climate model, Climate of the Past, 3, 97–107.
- Holbourn, A., W. Kuhnt, **M. Schulz**, and H. Erlenkeuser (2005), Impacts of orbital forcing and atmospheric carbon dioxide on Miocene ice-sheet expansion, Nature, 438, 483–487.
- **Schulz, M.** (2002), The tempo of climate change during Dansgaard-Oeschger interstadials and its potential to affect the manifestation of the 1470-year climate cycle, Geophysical Research Letters, 29, 1002.
- **Schulz, M.** and M. Mudelsee (2002), REDFIT: estimating red-noise spectra directly from unevenly spaced paleoclimatic time series, Computers & Geosciences, 28, 421–426.

WESTPHAL, HILDEGARD, PROF. DR.

Personal Data	
Date and Place of birth	10 May 1968, Tübingen
Nationality	German
Webpage	www.leibniz-zmt.de/de/mitarbeiter/hildegard-westphal.html
ORCID	0000-0001-7324-6122
Degrees	
2004	Habilitation, University of Tübingen, Germany
1998	PhD, University of Kiel, Germany
1994	Diploma in Geology, University of Tübingen
Positions	
2010–present	Director, ZMT, Bremen and Professor of Geology of the Tropics, University of Bremen
2010	Chair of Sedimentology, University of Heidelberg, Germany
2005–2010	DFG Heisenberg Fellow, University of Bremen, MARUM
2003–2004	*Hochschul- und Wissenschaftsprogramm* Grant of the State of Bavaria, University of Erlangen-Nürnberg, Germany
1999–2003	Assistant Professor at University of Hannover, Germany
1998–1999	Post-Doctoral Research Associate at University of Miami, USA
Scientific Awards	
2004	Albert-Maucher-Preis 2004 (DFG)
2003	Hans-Cloos-Prize of the German Geological Society (GV)
2003	Walter-Schall-Prize of the Society of Naturalists of Württemberg
2005–2010	DFG Heisenberg Fellowship

Research Work

Carbonate sedimentology as a tool for understanding (paleo) ecology, in particular eutrophication and acidification and other anthropogenic and natural changes in tropical shallow-water environments. Coastal dynamics, sea-level rise and interaction with human interventions.

Professional Activities	
2016–present	Active Member, Class IV of the European Academy of Sciences and Arts
2014–present	Member, Foundation Board of *Zoologisches Forschungsmuseum Alexander König*
2013–present	Member, Board of Governors of Jacobs University Bremen
2012–present	Member, Board of Trustees of GEOMAR, Kiel
2011–2017	Scientific Vice President, Leibniz Association
2005–2010	Member, German Young Academy

Most relevant publications

- Humphreys, A. F., J. Halfar, F. Rivera, D. Manzello, C. E. Reymond, **H. Westphal**, and B. Riegl (2016), Variable El Nino-Southern Oscillation influence on biofacies dynamics of eastern Pacific shallow-water carbonate systems, Geology, 44, 571–574.
- Mann, T. and **H. Westphal** (2016), Multi-decadal shoreline changes on Takú Atoll, Papua New Guinea: Observational evidence of early reef island recovery after the impact of storm waves, Geomorphology, 257, 75–84.
- **Westphal, H.**, J. Lavi, and A. Munnecke (2015), Diagenesis makes the impossible come true: intersecting beds in calcareous turbidites, Facies, 61, 3.
- Wizemann, A., F. W. Meyer, L. C. Hofmann, C. Wild, and **H. Westphal** (2015), Ocean acidification alters the calcareous microstructure of the green macro-alga *Halimeda opuntia*, Coral Reefs, 34, 941–954.
- Mann, T. and **H. Westphal** (2014), Assessing long-term changes in the beach width of reef islands based on temporally fragmented remote sensing data, Remote Sensing, 6, 6961–6987.
- **Westphal, H.**, J. Halfar, and A. Freiwald (2010), Heterozoan carbonates in subtropical to tropical settings in the present and past, International Journal of Earth Sciences, 99, 153–169.
- **Westphal, H.**, K. Heindel, M. Brandano, and J. Peckmann (2010), Genesis of microbialites as contemporaneous framework components of deglacial coral reefs, Tahiti (IODP 310), Facies, 56, 337–352.
- **Westphal, H.**, F. Hilgen, and A. Munnecke (2010), An assessment of the suitability of individual rhythmic carbonate successions for astrochronological application, Earth-Science Reviews, 99, 19–30.
- **Westphal, H.** and A. Munnecke (2003), Limestone-marl alternations: A warm-water phenomenon?, Geology, 31, 263–266.
- Melim, L. A., **H. Westphal**, P. K. Swart, G. P. Eberli, and A. Munnecke (2002), Questioning carbonate diagenetic paradigms: evidence from the Neogene of the Bahamas, Marine Geology, 185, 27–53.

ZONNEVELD, KARIN, PD. DR.

Personal Data	
Date and Place of birth	8 September 1965, Almelo
Nationality	Dutch
Webpage	www.marum.de/Karin_Zonneveld.html
ORCID	0000-0002-3390-1572
Degrees	
2003	Habilitation, University of Bremen
1996	PhD, University of Utrecht, The Netherlands
1990	MSc in Biology, University of Utrecht
Positions	
2013–present	Senior Scientist, University of Bremen, MARUM
2003–2012	Senior Scientist, University of Bremen, Faculty of Geosciences
1998–2003	Assistant Professor, University of Bremen
1996–1998	Postdoc, University of Bremen

Research Work

My research activities focus on the study of biological and ecological processes in organisms forming organic-walled microfossils of marine and terrestrial origin called marine palynomorphs. In particular, I study the transport, alteration and preservation/degradation between their initial presence in the upper water column and fossilization in the ocean floor. These research activities are carried out in the context of climate as a controlling parameter. Special attention is given to the effects these processes have on the application of marine palynomorphs as proxies to reconstruct past oceanographic, environmental and climatic conditions. Additionally, I use fossil archives of these palynomorphs to reconstruct human-induced and naturally influenced changes in past marine environmental conditions.

Professional Activities	
2001–2011	Vice speaker of the DFG International Graduate College "Proxies in Earth History"

Most relevant publications

- Gray, D., **K. A. F. Zonneveld**, and G. J. M. Versteegh (2017). Species-specific sensitivity of dinoflagellate cysts to aerobic degradation: a 5 years natural exposure experiment, Review of Palaeobotany and Palynology, 247, 175–187.
- Poliakova, A., **K. A. F. Zonneveld**, C. Kwiatkowski, M. A. Suryoko, and H. Behling (2017), Marine environment, vegetation and land use changes during the late Holocene in South Kalimantan and East Java reconstructed based on pollen and organic-walled dinoflagellate cysts analysis, Review of Palaeobotany and Palynology, 238, 105–121.
- **Zonneveld, K. A. F.** and M. Siccha (2016), Dinoflagellate cyst based modern analogue technique at test – A 300 year record from the Gulf of Taranto (Eastern Mediterranean), Palaeogeography, Palaeoclimatology, Palaeoecology, 450, 17–37.
- Bogus, K., K. N. Mertens, J. Lauwaert, I. C. Harding, H. Vrielinck, **K. A. F. Zonneveld**, and G. J. M. Versteegh (2014), Differences in the chemical composition of organic-walled dinoflagellate resting cysts from phototrophic and heterotrophic dinoflagellates, Journal of Phycology, 50, 254–266.
- **Zonneveld, K. A. F.**, F. Marret, G. J. M. Versteegh, K. Bogus, S. Bonnet, I. Bouimetarhan, E. Crouch, A. de Vernal, R. Elshanawany, L. Edwards, O. Esper, S. Forke, K. Grøsfjeld, M. Henry, U. Holzwarth, J.-F. Kielt, S.-Y. Kim, S. Ladouceur, D. Ledu, L. Chen, A. Limoges, L. Londeix, S. H. Lu, M. S. Mahmoud, G. Marino, K. Matsouka, J. Matthiessen, D. C. Mildenhal, P. Mudie, H. L. Neil, V. Pospelova, Y. Qi, T. Radi, T. Richerol, A. Rochon, F. Sangiorgi, S. Solignac, J.-L. Turon, T. Verleye, Y. Wang, Z. Wang, and M. Young (2013), Atlas of modern dinoflagellate cyst distribution based on 2405 data points, Review of Palaeobotany and Palynology, 191, 1–197.
- Versteegh, G. J. M., P. Blokker, K. A. Bogus, I. C. Harding, J. Lewis, S. Oltmanns, A. Rochon, and **K. A. F. Zonneveld** (2012), Infra red spectroscopy, flash pyrolysis, thermally assisted hydrolysis and methylation (THM) in the presence of tetramethylammonium hydroxide (TMAH) of cultured and sediment-derived *Lingulodinium polyedrum* (Dinoflagellata) cyst walls, Organic Geochemistry, 43, 92–102.
- **Zonneveld, K. A. F.**, L. Chen, R. Elshanawany, H. W. Fischer, M. Hoins, M. I. Ibrahim, D. Pittauerova, and G. J. M. Versteegh (2012), The use of dinoflagellate cysts to separate human-induced from natural variability in the trophic state of the Po River discharge plume over the last two centuries, Marine Pollution Bulletin, 64, 114–132.
- Versteegh, G. J. M., **K. A. F. Zonneveld**, and G. J. de Lange (2010), Selective aerobic and anaerobic degradation of lipids and palynomorphs in the Eastern Mediterranean since the onset of sapropel S1 deposition, Marine Geology, 278, 177–192.
- **Zonneveld, K. A. F.**, G. J. M. Versteegh, S. Kasten, T. I. Eglinton, K. C. Emeis, C. Huguet, B. P. Koch, G. J. de Lange, J. W. de Leeuw, J. J. Middelburg, G. Mollenhauer, F. G. Prahl, J. Rethemeyer, and S. G. Wakeham (2010), Selective preservation of organic matter in marine environments; processes and impact on the sedimentary record, Biogeosciences, 7, 483–511.
- Versteegh, G. J. M. and **K. A. F. Zonneveld** (2002), Use of selective degradation to separate preservation from productivity, Geology, 30, 615–618.

A 6 SUMMARY OF PROJECTS CURRENTLY FUNDED THROUGH THE EXCELLENCE INITIATIVE[1]

Cluster of Excellence and DFG Research Center "The Ocean in the Earth System / MARUM – Center for Marine Environmental Sciences" (EXC 309 / FZT 15)

Over almost three decades a widely diverse potential in marine sciences has been developed in the State of Bremen. Parallel to the establishment of non-university research institutions (Alfred Wegener Institute for Polar and Marine Research in Bremerhaven, Max Planck Institute for Marine Microbiology in Bremen, and Leibniz Center for Marine Tropical Ecology in Bremen), the University of Bremen has introduced new curricula and research groups in the fields of marine geosciences, marine biology, marine chemistry, and physical oceanography. The closely networked fields of marine, polar, and climate research represent the largest area of natural sciences activity in Bremen. Marine geosciences in particular have achieved an international scope, both in terms of the science and with respect to providing international service facilities. Shortly after the founding of the Faculty of Geosciences (1986), the Sonderforschungsbereich 261 (Collaborative Research Project 261) of the German Research Foundation (DFG – Deutsche Forschungsgemeinschaft), "The South Atlantic in the Late Quaternary" (1989–2001) was established. Other examples include three DFG-funded (international) graduate training groups ("Mass Transport in Geosystems", "Proxies in Earth History", and "Integrated Coastal Zone and Shelf-Sea Research"), and the DFG Research Center MARUM, which was established in 2001. The Research Center has taken decisive initiatives and accepted important coordination responsibilities within the university and in the State of Bremen, for example, implementing a special training program for PhD students. In addition to support from the State of Bremen, external funding has been of great importance to the program.

At present, the Research Center is in its third funding period, which will last until 30 June 2013. In 2007 the Research Center was expanded to a Cluster of Excellence. Due to its start as a DFG Research Center, MARUM has a strong focus on marine geosciences. With its expansion to a Cluster of Excellence, the range of disciplines was widened, specifically in the directions of marine microbiology, mineralogy, and physical oceanography. The involvement of further disciplines (marine biology, social sciences, law, maritime history) was introduced through the "Bremen International Graduate School for Marine Sciences" (GLOMAR), which collaborates very closely with MARUM. GLOMAR has been funded separately since November 2006 as a Graduate School in the first round of the excellence initiative.

[1] Summary of the current cluster (2011–2017) word-for-word from the previous application as requested by the DFG.

Through the Research Center/Cluster of Excellence, the University of Bremen cooperates with working groups from the following institutions:

- Alfred Wegener Institute for Polar and Marine Research in Bremerhaven (AWI)
- Max Planck Institute for Marine Microbiology in Bremen (MPI)
- Senckenberg at the Sea in Wilhelmshaven (SGN)
- Jacobs University Bremen (JU)
- Leibniz Center for Marine Tropical Ecology in Bremen (ZMT)

Agreements of cooperation are in effect between the University of Bremen and the other participating research institutions. In February 2011 MARUM became the first research faculty within the University of Bremen. This new governance structure is similar to the faculties of the university, but more research oriented. With this new status, MARUM has taken on responsibility for the long-term development of the university's strategic focus in marine, polar and climate research. At the same time, the new status allows for exploring new directions in the governance of the university. A strategic-research alliance between the University of Bremen, represented by MARUM, and AWI was established 2010 (AMAR: AWI-MARUM Alliance). The alliance builds on almost three decades of successful cooperation between AWI and the University of Bremen. The goal of the binding agreement is to take the existing cooperation to a new level, which will involve joint long-term planning in research and development of infrastructure.

The Research Center/Cluster of Excellence has the following overarching goals:

- to carry out top-level research in an interdisciplinary and international framework,
- to train young scientists in an interdisciplinary and international "research environment",
- to develop/provide technologies and infrastructure for marine research in cooperation with industry,
- to communicate complex scientific issues to the public.

Specific goals of the new funding period are to strengthen the research portfolio, to develop novel interdisciplinary research directions among the Research Areas, to foster the careers of female scientists, and to establish MARUM as a leading global center for marine geoscience research and central hub for marine research in the State of Bremen.

With the proposed research, MARUM will advance our knowledge of the interactions of the ocean with other components of the Earth system. This knowledge will enhance predictive skills in anticipating future changes in the marine environment, specifically to better cope with the effects of human activities on the environment. For example, information about the ocean's role in climate change, the functioning of ecosystems in the deep sea, the distribution of mineral resources, and sediment stability will all contribute to sustainable use of the ocean. Ground-breaking new discoveries related to processes at or beneath the seafloor have been made during the past decade by means of direct observation and sampling. These findings include, for example, gas hydrates, cold seeps and hot vents and their accompanying ecosystems, deep-water corals, the deep biosphere, and microbial ecosystems that shape biogeochemical cycles. Moreover, new sampling technologies have allowed the reconstruction of past environmental conditions from marine archives at unprecedented temporal resolution and quality. It is only through the integration of marine geology, geophysics, geochemistry, marine (micro)biology, mineralogy, petrology, sedimentology, numerical modeling, and environmental physics that it becomes possible to achieve the research goals and disentangle the relevant processes of the Earth system.

After major expansions of the research portfolio in the second phase of the Research Center (2005–2009) and during the first phase of the Cluster of Excellence (2007–2012), the six Research Areas were reorganized in the proposal for the third phase of the Research Center (2009–2013). The resulting three new Research Areas are: Ocean and Climate, Geosphere-Biosphere Interactions and Sediment Dynamics. To foster interaction among the Research Areas, new cross-cutting projects between the areas will be established during the next funding period. New research perspectives will be realized through the planned inclusion of remote sensing (including a new professorship) in the research activities.

The expansion of the research portfolio since the founding of the Research Center in 2001 has been closely linked to the establishment of new professorships in various fields of marine geosciences. As many as nine professorships have been funded by the Research Center/Cluster of Excellence and Graduate School at a time. Most have already been transferred to the university budget; the remaining four will be transferred by 31.10.2012. With this proposal four new professorships will be established in the fields of Mineralogy, Micropaleontology/Paleoceanography, Paleoceanography, and Satellite-Based Earth-System Modeling. All positions are permanent and will be transferred to the university budget by November 2017.

Research Area "Ocean and Climate" aims to assess the role of the ocean in the climate system by testing hypotheses related to climate events and processes in modern times as well as in the geologic past. The overarching goal is to obtain a quantitative understanding of the processes determining and underlying climate variations that were significant in the past and are relevant for future climate change. Research activities will be guided by the following objectives: What is the role of the large-scale ocean circulation in generating and amplifying climate changes? What impacts do changes in ocean circulation have on terrestrial environments? How are atmosphere-ocean interactions and feedbacks in and between high and low latitudes related to global climate behavior at interannual to orbital timescales? These questions will be addressed by a joint effort of proxy-based reconstructions, observations, and modeling experiments. The existing interdisciplinary approach, encompassing paleoceanography, climate modeling and physical oceanography, will be broadened by the integration of satellite-based remote sensing data.

Research Area "Geosphere-Biosphere Interactions" focuses on biological, geochemical and geological processes, and will test hypotheses associated with the transformation of matter and extraction of energy by microbial communities in marine environments. The geosphere-biosphere interactions to be examined are intimately linked with the cycling of elements at various temporal and spatial scales. The relationship of some of these processes, such as benthic nitrogen cycling in presently expanding oxygen-minimum zones or carbon cycling in benthic, hydrothermal and sub-seafloor environments, to modern ecosystems and climate are poorly constrained. Understanding the associated feedback mechanisms is one of the broad long-term objectives of MARUM. This Research Area will draw on the considerable expertise in marine inorganic and organic (bio) geochemistry, marine geology, and microbiology, and take advantage of the marine-technology infrastructure at MARUM, which provides access to unique environments and sample materials.

The central focus of Research Area "Sediment Dynamics" is to understand and evaluate the driving forces, processes and interconnections of sediment dynamics between the shelves and continental slopes. The hypothesis-driven research program aims at a process-based understanding of ocean-margin sedimentary systems. These are controlled by the predominant or joint influences of waves, tides and coastal currents as well as climate and sea-level change and finally by tectonics and fluid flow. These three fundamental categories of environmental forcing factors act on distinct spatial and temporal scales, and change their expression with ambient geological settings. This Research Area will combine modern geoscientific methods with numerical modeling and focus on three guiding questions: What is the impact of small-scale sediment dynamics on shelf-wide sediment distribution? How are kilometer-scale sedimentary features controlled by climate? What controls rapid sedimentation events (landslides, mud volcanoes, and other mass-wasting phenomena)?

MARUM has achieved a position at the forefront of science in several areas, including the subseafloor biosphere, processes underlying natural climate variations, the role of microbial processes in shaping biogeochemical cycles, formation and disintegration of gas hydrates, submarine slope stability, and in integrating numerical modeling into Earth-system science. Through its pioneering efforts in establishing a data information system for Earth Sciences (PANGAEA), MARUM has laid the foundation for data-intensive research strategies in Earth sciences.

The Research Center / Cluster of Excellence has also been at the forefront of establishing novel concepts in graduate training at the University of Bremen. These include international recruitment, supervision by a team of 3–4 experienced researchers, a research stay of several months in another lab, a cumulative thesis, and an advanced-course program including soft-skill courses.

During the first phase of the Excellence initiative, the "Bremen International Graduate School for Marine Sciences" (GLOMAR) was established. Based on the long experience in graduate training at the Faculty of Geosciences, the graduate school has successfully provided a comprehensive three-year curriculum for doctoral students. At the same time, the disciplinary scope was expanded to encompass all aspects of marine sciences at the University of Bremen, including social and legal sciences. Major progress has been achieved in educating a new generation of scientists who are specialists in their discipline but have also gained valuable experience in other disciplines. Considering the substantial thematic overlap and the common goals and strategies in doctoral training, we propose to integrate the graduate school GLOMAR into the Research Center / Cluster of Excellence. The integrated graduate school will maintain its broad thematic spectrum, covering all disciplines involved in marine sciences at the University of Bremen. In addition to all PhD students of MARUM, graduate students in marine sciences from all disciplines who are not funded by the Research Center / Cluster of Excellence can apply for membership to the Graduate School.

MARUM has taken a leading role in developing the gender-equality initiatives of the University of Bremen further. It has introduced new Return-to-Science Fellowships and developed a new mentoring program for female early-career scientist (plan m at MARUM / GLOMAR) together with the university.

The Research Center / Cluster of Excellence also provides technologies and infrastructure for marine research. Driven by the scientific demand, MARUM was the first institution in Germany to operate a large remotely operated vehicle (ROV) and other large-scale deep-sea technologies, such as an Autonomous Underwater Vehicle (AUV) and has developed an underwater drill rig (MeBo). Today, MARUM is one of the few research institutions in the world that not only operates a fleet of large deep-water instruments but also develops new deep-sea technologies (e.g. Hybrid-ROV and advanced deep-sea drill rig, MeBo-II). For the development of new equipment and improvements in complex analytical instruments, MARUM cooperates closely with partners from industry. A major development has been the foundation of the institute MarTech-Bremen by MARUM, the Robotics Innovation Center at the University of Bremen and the Institute of Space Systems (part of the Helmholtz Foundation). The goal of the institute is to develop technologies for a sustainable use of the oceans as a source of energy and mineral resources. Through the development and operation of modern underwater instruments the Research Center has established itself as a leading center of marine research technology in Germany, and is a favored partner in international cooperative projects. Moreover, MARUM operates one of the three IODP core repositories in the world.

Science communication at the MARUM comprises a wide variety of activities in the fields of education and outreach. A well-defined target-group concept forms the basis of these activities. It includes frequent media contacts and exhibitions, as well as regular courses for school classes, kindergarten children, and teachers.

A 7 PROPOSAL FOR A UNIVERSITY ALLOWANCE

The University of Bremen is a mid-sized, research-intensive university located in the city-state of Bremen in Northern Germany. Founded in 1971, the University of Bremen has evolved into the major research institution in the northwestern region of Germany. Research at the University of Bremen is strategically organized in six high-profile areas, which unite researchers from several different disciplines and faculties: Marine, polar and climate research; Materials science and production engineering; Minds, media, machines; Social change, social policy, and the State; Health sciences; and Logistics. Open-minded, with direct lines of communication on campus, and with its flat and efficient hierarchies, the University is quick to seize opportunity and react to challenges.

At a Glance: University of Bremen

- Twelve Faculties, covering the natural sciences, engineering sciences, social sciences, and humanities, as well as one Research Faculty (MARUM)
- 20,000 students (51 % women) in 44 Bachelor and 57 Master's programs, a strong focus on research-based learning, and a certified system of quality management in teaching
- 320 doctoral degrees awarded each year (annual average 2012 – 2016; 43 % women)
- 270 professors (29 % women) and 2,300 other scientific staff (41 % women)
- 50+ additional professorships in conjunction with non-university research institutions in the region, the majority associated with institutes of the Helmholtz Association, Max Planck Society, Leibniz Association, and Fraunhofer Society
- Currently 7 DFG-funded Collaborative Research Centers (2 of these with another lead university) and 6 DFG-funded Research Training Groups
- Total of 6 DFG Gottfried Wilhelm Leibniz Prizes and 17 ERC grants awarded to researchers at the University of Bremen
- One third of the total University budget (325 Million Euros per year) is third-party funding, half of that granted by the DFG

The development of the six high-profile areas is one of the University Leadership's top priorities, building on the strong support provided by the federal State of Bremen. Marine sciences stands out internationally as the most visible research field of the University. To take this development to a new strategic level, the University has established its first and only Research Faculty MARUM. The governance structure of the Research Faculty gives it more autonomy than the traditional faculties of the University and allows for marine sciences to thrive at the University and in close collaboration with its partners.

The strong research orientation of the University benefits from a large number of non-university research institutes in its immediate neighborhood: This close proximity opens up possibilities for intensive cooperation on research projects, and there are currently about 50 joint professorships with the non-university institutions. In 2016, the U Bremen Research Alliance was established between the university and the non-university partners. The Alliance has created a platform for the strategic coordination of research agendas and the joint use of infrastructure. It also promotes international visibility and recruitment. Knowledge transfer is enticing a growing number of enterprises to locate within the technology park area, which encircles the campus and comprises some 400 businesses with 4,500 employees. Since its establishment, the University of Bremen has purposefully pursued a policy of creating close links between its teaching and research activities. A good example is seen in its approach to studying in projects ("Bremen Model"), which fosters elements of independent, research-based learning oriented toward societal issues.

In 2017, the University developed its Strategy 2018–2028. It was put forward by the University Leadership and covers all the facets of university performance – from teaching and research, through academic career paths and personal development, up to digitalisation. It builds upon the University's **Institutional Strategy "Ambitious and Agile"** that has been funded through the Excellence Initiative since 2012, pursuing its vision of being a leading European research university and an inspiring place of education and learning. Core elements of the Strategy are highly relevant to the application for the Cluster of Excellence:

- The University will promote international cooperation by stimulating international exchange between Bremen scientists and leading institutions worldwide, creating stable international collaborative alliances and increasing the proportion of international scholars.
- The University will establish new career paths. On the University's initiative, a new staffing category was adopted into the *Landeshochschulgesetz* (the state law governing universities): In addition to professorships, stable career paths for independent senior scientists have been created. At the same time, the University is expanding its Bremen Early Career Researcher Development (BYRD) to include offers for both doctoral and postdoctoral researchers. This University-wide center benefits from the experience of the two graduate schools established through the framework of the Excellence Initiative, i.e., GLOMAR in marine sciences and BIGSSS in social sciences.
- The University will continue its long-standing and successful efforts to increase the number of women in academia. 29 percent of professorships at the University are held by women and the University has been distinguished three times in succession for its strategy for implementing the DFG's *Research-Oriented Standards on Gender Equality*. In accordance with its diversity and gender equality policy, the University is continuing to increase the proportion of female scientists at all career levels. At 40 percent, the ratio of female PIs in the proposed Cluster of Excellence is setting a new standard within the University.

- The University is currently implementing its research-data management strategy. The underlying guidelines build on the successful data management by PANGAEA. The University's future research-data management will follow the FAIR principle (findable, accessible, interoperable, re-usable), and will be in line with the strategies of a national research-data infrastructure and EU guidelines.
- The University of Bremen will bundle its technology transfer and extensive collaborations with schools, cultural institutions and civil society under the guiding principle of public engagement. In this context, the University's science-communication strategy has been realigned.

At a glance: U Bremen Excellence Chairs

- Visiting professorships for 4+ years
- Flexible funds for a Bremen-based research group, travel and/or part-time salary up to a total of 180 k€ annually per Chair
- Eight Chairs to start in 2019/2020 from the university allowance
- Three additional Chairs included in the Cluster of Excellence proposal

The University Leadership has deemed international collaboration a major strategic goal. Consequently, four of the main objectives contained in the Strategy 2018–2028 are:

- to stimulate international exchange between Bremen researchers and leading institutions worldwide
- to create stable international collaborative alliances
- to increase the proportion of international academics
- to make the appointments policy for recruiting outstanding individuals more flexible

With the **university allowance**, the University Leadership is specifically addressing this set of objectives: It is creating new bridgeheads for collaborations with outstanding research universities in the respective disciplines around the world. For this purpose, it is establishing **U Bremen Excellence Chairs** – binding, long-term visiting professorships for top international researchers to build their own research groups in Bremen. In addition to promoting collaboration with internationally renowned scholars, it will serve to increase scientific expertise at the University of Bremen. In its cluster proposal, MARUM already defined three concrete U Bremen Excellence Chairs. The exclusive use of the university allowance for U Bremen Excellence Chairs was agreed by the university leadership and is endorsed by both the deans of the departments and the Academic Senate.

Chair-holders will be internationally distinguished scholars from abroad who will build their own research groups at the University of Bremen. By so doing, they will expand their research opportunities and will be able to cooperate directly with partners from the University of Bremen. Each of the U Bremen Excellence Chairs will be established initially for a period of four years. If the collaboration is deemed successful by the University Leadership the appointment can be extended until the end of the university allowance funding. In Bremen, the chair-holders and their groups will be supported by the areas with which they cooperate as well as the U Bremen Research Alliance's Welcome Center. Moreover, every chair-holder will be paired with a member of the university leadership team. A coordination point will organize the selection processes and leadership decisions, support the chair-holders and their groups on the spot and be responsible for implementing and monitoring the measure.

U Bremen Excellence Chairs will be outstanding international scientists who will systematically strengthen the University's research profile. They will be selected based on their highly complementary expertise, with respect to the goals of the high-profile areas or in emerging fields with demonstrably high potential. Chairs will be nominated either by one of the six high-profile areas or by a group of at least three professors. The application must document the candidate's scientific reputation, describe collaboration to date, and explain the cooperation planned in Bremen. In addition, details should be given on the size and composition of the group, the frequency and duration of the candidate's presence in Bremen as well as the administrative and organisational support to be provided by the University of Bremen. The final decision on the appointment will be made by the University Leadership and will take strategic as well as equal opportunity and diversity criteria into consideration.

Each Chair will become a member of the University with the associated rights, and will be eligible to supervise doctoral candidates at the University of Bremen. Chairs and their Bremen-based groups will be allocated their own premises and will have access to all relevant infrastructures, including those at non-university research institutions.

Each Chair will receive up to 180 k€ annually. About two-thirds of this funding is foreseen for scientific personnel at the University of Bremen. The remainder of the funding is discretionary. It could, for example, cover a part-time salary or travel expenses. Holders of a U Bremen Excellence Chair will be free to recruit their own group members. A Chair's typical research group will consist of a post-doctoral researcher and a PhD researcher. Responsibility for the personnel will reside with the Chair. The Chair holders themselves will typically undertake several extended research stays in Bremen each year.

The university allowance will be used to establish at least eight U Bremen Excellence Chairs. In addition, three Excellence Chairs will be established with funds from the Cluster of Excellence. The respective chair-holders have already been designated (from the University of Utrecht, California Institute of Technology and the University of Copenhagen). The screening for the first four of the University-wide appointments is under way and will be completed by the time the decision on the Cluster of Excellence is taken. The remaining Excellence Chairs will be filled one year later (2020).

The proposed decision-making process for awarding the Excellence Chairs is in accordance with existing governance. The federal State of Bremen supports the strategic focus of the U Bremen Excellence Chairs and has agreed to augment the university allowance by 50 % of the annual funding (500 k€ per year).

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