Patricia Miloslavich <patricia.miloslavich@scor-int.org>

SCOR Proposal, resubmission

1 message

Fehrenbacher, Jennifer S <jennifer.fehrenbacher@oregonstate.edu> Fri, May 12, 2023 at 7:45 PM

To: "secretariat@scor-int.org" <secretariat@scor-int.org>
Cc: "Fehrenbacher, Jennifer S" <jennifer.fehrenbacher@oregonstate.edu>, Catherine Davis <cdavis24@ncsu.edu>, Clare Bird <clare.bird2@stir.ac.uk>, "Hoogakker, Babette" <B.Hoogakker@hw.ac.uk>, "jorge.cardich.s" <jorge.cardich.s@upch.pe>, Abby Ren <abbyren@ntu.edu.tw>, Raphael Morard <rmorard@marum.de>, "christine.barras@univ-angers.fr" <christine.barras@univ-angers.fr>, Haruka TAKAGI <htakagi@chiba-u.jp>, "Glock, Nicolaas" <nicolaas.glock@uni-hamburg.de>

Dear Patricia,

We are writing to resubmit our 2022 SCOR WG proposal. Our SCOR WG aims to provide a robust synthesis of research methods to improve our understanding of the biology and ecology of planktic **f**oraminifera living **i**n deeper and more **e**xtreme and **r**apidly **c**hanging **e**nvironments ('fierce' species) such as oxygen minimum zones, the ice-ocean interface, high-latitude, and those that live beyond the mixed layer. By focusing on foraminifera from understudied habitats, our team will close a critical research gap and extend foraminifera utility in the fossil record beyond the ocean's sunlit mixed layer.

Although our proposal submitted last year was not recommended for funding, we received very helpful feedback from the SCOR members and have taken the feedback into account in our revisions. Nearly 60% of the national committees and affiliated programs ranked our proposal as 'must fund' to 'may fund'. Reviewers found our SCOR WG proposal topic to be timely because foraminifera are a key component of pelagic environments, and they play a role in the Earth's carbon cycle. Furthermore, because foraminifera are calcifiers, it is imperative to understand how climate change will impact these vital marine species.

There were questions about whether the topic, as presented, represented an advance in oceanographic understanding. In our revised proposal we argue that FIERCE activities will address key research gaps in all oceanographic research fields that use foraminifera. Our planned SOPs will catalyze future work of understanding carbon cycling and climate reconstructions

Other comments included that the proposal did not make clear the need for the development of SOPs for the fierce species nor how the SOPs would be integrated into the study of the non-fierce species. Reviewers noted that we should more clearly describe where open access SOPs and training materials would be stored and accessible. Furthermore, we did not clearly describe mechanisms for funding our proposed meetings and the planned workshops. And finally, it was suggested that although members of our WG are experts on foraminifera, it wasn't clear if we had experience studying the environments that affect foraminifera.

1. In this regard, we have modified the proposal significantly to address the following:The proposal goals are more clearly defined
2. We have made clear in our revised proposal that the SOPs will include handling of foraminifera from both traditional and extreme environments
3. The proposal contains a detailed plan for sharing training materials, which will be stored and disseminated (via GitHub) and will be citable via a DOI (using Zenodo, a general-purpose open repository developed under the European OpenAIRE program and operated by CERN).
4. Although most of the members conduct research on foraminifera, many are also experts in (paleo)+oceanography, and/or extreme environments. We have made an effort to more fully address member expertise. For example, Jorge Cardich (full member) and Dimitri Gutiérrez (associate member) are leading experts in modern oxygen minimum zones, while Catherine Davis (full member), Nicolaas Glock (full member) and Babette Hoogakker (full member) work to reconstruct paleo-oxygen minimum zones. Other members, including Mohammed Ezat (associate member) and Julie Meiland (associate member) have worked extensively in high-latitude environments.

Our updated proposal for consideration for a SCOR working group in the 2023 round is attached. Please let us know if you have any questions.

Warm regards,
Jennifer Fehrenbacher and Abby Ren, on behalf of the FIERCE team.

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Note: My work schedule may be different than your work schedule. Please do not feel obligated to respond out of your normal working hours.

Do you know about the indigenous people of the land you are on right now? If not, check out https://native-land.ca/. Corvallis Oregon stands on the traditional homelands of the Mary's River or Ampinefu Band of Kalapuya, whose ancestors have resided here since Time Immemorial. Following the Willamette Valley Treaty of 1855, the Kalapuya people were forcibly removed to reservations in Western Oregon. Today, descendants of these people are part of the Confederated Tribes of Grand Ronde Community of Oregon and the Confederated Tribes of the Siletz Indians.

2 attachments

FIERCE_SCOR_WPG_2023_FInal.docx
196K

SCOR_Appendix.docx
24K

Foraminifera in Deeper, Extreme, and Rapidly Changing Environments

Summary/Abstract Information contained in foraminifera shells is essential for understanding Earth's past climate system. Most foraminiferal proxies (indicators of, for example, temperature, productivity, or seawater chemistry) and calibration efforts have focused on tropical-subtropical planktic species that live primarily in the sunlit ocean. There are limited foraminiferal proxies from species that occupy deeper habitats (below the sunlit mixed layer to ~1000m) and more 'extreme' environments currently experiencing rapid climate change (i.e., oxygen minimum zones, the ice-ocean interface, high-latitudes). The lack of proxies in deeper and extreme environments limits our ability to reconstruct past conditions and hampers future climate change prediction efforts in these regions. The multi-disciplinary FIERCE WG will test and fine-tune state-of-the-art research methods for studying FIERCE species at a workshop in Peru and with WG members in the Norwegian Arctic. A robust synthesis of research methods will be developed into best practice 'standard operating procedures' (SOPs) for studying FIERCE species, to be published in an open-access, online platform. The SOPs will be broadly applicable to all planktic species and many benthic foraminifera, which expands the outcomes of this project beyond FIERCE species. Our focus on foraminifera from understudied habitats will improve our understanding of the biology and ecology of planktic foraminifera living in these environments, closing a critical research gap, and vastly expanding the utility of fossil foraminifera beyond the ocean's sunlit mixed layer. Given the interdisciplinary and international nature of our vision, a SCOR working group is the best and most practical choice to achieve the proposed goals.

Scientific Background and Rationale

As major carbonate producers in the open ocean (Schiebel, 2002; Schiebel and Movellan, 2012), the production, export, dissolution, and burial of foraminiferal shells provides important feedbacks to the global carbon cycle (Grigoratou et al., 2021; Ridgwell and Zeebe, 2005). Planktic foraminifera shells have an extensive fossil record and are invaluable archives for climate proxies. The past several decades have seen a revolution in our understandings of living planktic foraminifera that vastly improve our use of climate archives. These efforts have primarily focused on a subset of shallow-living, mostly warm water species. Building on this research and rapid advances across multiple fields of ocean sciences, we are now well-positioned to turn to **F**oraminifera species living **I**n Deeper, **E**xtreme, and **R**apidly **C**hanging **E**nvironments (FIERCE) to ask **how diverse is planktic foraminiferal biology, ecology, and geochemistry?**

Proxies are fundamental for extending marine records beyond the bounds of direct observation and for understanding long-term oceanographic and environmental changes driven by climate change. Information about the upper ocean environments is recorded in the trace element and isotopic geochemistry of planktic foraminifera fossil shell/test (see Kucera et al., 2007; Katz et al., 2010). For shell geochemistry to function as a reliable proxy, well-defined relationships, or 'calibrations', between calcification environment and shell chemistry must be established, taking into account biological and ecological influences, such as calcification depth (Reynolds et al., 2018), microhabitat (Fehrenbacher et al., 2018), biomineralization processes, life cycle, diet, symbiotic associations, and photosynthesis and respiration influence on shell geochemistry (Hönisch et al. 2003; Eggins et al. 2004). Biological or ecological offsets can often be accounted for using species-specific calibrations, (e.g., Bemis et al., 2002) but this has generally focused on shallow (above pycnocline) tropical-subtropical species (Tierney et al., 2020; Gray and Evans, 2019), and not 'FIERCE' species. These environments include depths as deep as planktic foraminifera occur (~1000 m), Arctic/Antarctic regions, the sea-ice interface, and oxygen depleted environments such as economically important Eastern Boundary Currents (e.g., US West Coast, Mexico, Peru, South Africa). Consequently, foraminiferal proxy calibrations for these environments lag well behind those for more stable regions and critically limit our understanding of the past conditions in these at-risk habitats and hinders a more holistic understanding of ocean processes, past, present, and future. Reconstructing past changes, to underpin future projections for more 'extreme' environments has never been more needed. Critically, assessing the diversity of life modes and geochemistry within living foraminifera may serve as a guide to understanding how modern research can (or cannot) be mapped onto extinct species.

Planktic foraminifera with shallow (above pycnocline) depth habitats are well-studied. Our knowledge about shallow tropical-subtropical planktic foraminifera is evolving (Bird et al., 2017; 2018; Dong et al., 2022; Takagi et al., 2020) as new techniques have led to more in-depth understandings of diet, (previously identified by TEM/laboratory observations; see Schiebel and Hemleben, 2017), bacterial interactions, parasitism (Greco et al., 2021), and host/algal symbionts interactions (Bird, et al., 2017; 2018; Gast and Caron, 1996; Takagi et al., 2019; LeKieffre et al., 2018). Yet for FIERCE species, which may be symbiont-barren or bearing, little is known about their preferred diet and host/symbiont interactions. Microbial interactions and predation remain poorly understood in all planktic foraminifera species. This lack of understanding makes foraminiferal ecology difficult to model. Thus, foraminiferal turn-over and community shifts in the fossil record can be interpreted only in terms of environmental rather than ecological forcing, limiting and potentially skewing interpretations. A thorough understanding of all planktic foraminifera species ecology and physiology, including FIERCE species, is required to accurately model foraminiferal response to climate (Roy et al. 2015; Grigatorou et al. 2021).

A broader understanding of FIERCE species ecology and an expansion of modern proxy calibrations for FIERCE species is desperately needed as contemporary global change disproportionately impacts extreme and rapidly changing environments such as oxygen

minimum zones (OMZ), the ice-ocean interface, and high-latitude regions which are warming at the most rapid rate on the planet (Serreze et al., 2009). OMZs are expanding (Breitburg et al., 2018; Keeling et al., 2010; Stramma et al., 2010; Schmidtko et al., 2017), oceans are becoming more acidic (Feely et al., 2009), sea ice is melting, and salinity is decreasing (Parkinson, 2019; Jones et al., 2020; Meier et al., 2021). FIERCE species provide records of these biologically distinct environments (Hull et al., 2011; Lu et al., 2016; Hoogakker et al., 2018; Greco et al., 2021; Davis et al., 2021; Winkelbauer et al., 2021). Significant attention has been given to studying the metabolic adaptations of benthic foraminifera in extreme environments (Risgaard-Petersen et al., 2006; Woehle et al., 2018; Orsi et al., 2020; Gomaa et al., 2021), but little is known about the biology and ecology of planktic FIERCE species.

Advances in ecology, geochemistry, genetics, modeling, and across the fields of biological and chemical oceanography make many of these key questions of FIERCE species' ecology and biology imminently answerable. By doing so, we will improve our ability to understand and reconstruct past environments that have undergone rapid climate change and our ability to predict future climate change outcomes, ultimately, connecting the past, present, and future of our oceans. Accomplishing this goal requires a major transdisciplinary international effort and an "un-siloing" of relevant methodologies from both within and outside of fields traditionally associated with foraminiferal research. By assembling a broad community base, explicitly codifying, and openly disseminating relevant information, we will vastly improve our understanding of FIERCE species and build bridges between our understanding of past and future climate states.

As foraminiferologists continue to expand their scope into 'extreme' planktic environments (e.g., Davis et al., 2023; Hoogakker et al., 2022), the assessment, articulation, and dissemination of the current state of knowledge, as well as the development of community standards, becomes increasingly important. Our WG will produce a state-of-the-art synthesis of the ecology, biology, and geochemistry of planktic foraminifera from FIERCE environments, including an assessment of additional knowledge gaps. We will provide training opportunities for interdisciplinary early career scientists through a workshop of the Peruvian Margin and participation in cruises in the Arctic, featuring a developed route towards best practices and community standards, and, crucially, a forward-reaching plan to integrate foraminiferology with other marine sciences. A key workshop outcome will be the identification of pressing research questions needed to expand the use of FIERCE planktic species as oceanographic proxies. We will lower barriers to entry for early career and cross-disciplinary research by standardizing methods for research done across systems (model species, geography, and timescales) and make a crucial step towards knowledge transfer and sustainable capacity building during a training workshop and with the development of the SOPs. Moreover, developing a framework for cultivation, field collection, and preparation of living and fossil foraminifera from non-standard habitats will allow foraminiferal research to be more broadly integrated with efforts aimed at other zooplankton groups, and pelagic ecology more generally. Once general protocols and best-practice methodologies for extreme environments are developed, they can be expanded to other

environments and ultimately guide long-term international projects that extend these protocols into a global sustainable ocean observation program. A SCOR WG supports our ambitious goals to bring together international and interdisciplinary scientists to develop SOPs designed to expand the utility of FIERCE species in modern and paleoclimate research. The SOPs and training materials (see ToRs, below) will be disseminated to the broader community via a partnership with GeoTRACES and via GitHub (citable using Zenodo). Members will share these links in presentations and at conferences, taking advantage of the diverse and international nature of our membership to widely distribute materials.

Terms of Reference

1. **Assess the current state of knowledge and identify critical gaps** (i.e., life history, genetics, ecology, biogeochemistry, preservation) in our understanding of living and fossil FIERCE planktic foraminifera species. This assessment will draw from the varied expertise of FIERCE WG members and be published as a review in an open-access journal (i.e., Biogeosciences or Frontiers in).
2. **Create, validate, and publish an open-access portfolio of best practices** for the culturing, field-collection, and fossil preparation of FIERCE foraminifera species. These best-practices include developing and testing a set of standard operating procedures (SOPs), detailed in the deliverables and made available in collaboration with GEOTRACES and the Ocean Best Practices System (OBPS).
3. **Develop open-access training resources** for cross-disciplinary, early career and other scientists working with FIERCE foraminifera species. Training resources will be grounded in and serve as a complement to written best practices documents. Resources will include video walk-throughs of field and laboratory procedures, slide decks, and recorded workshop sessions, aimed at researchers, students, and technicians.
4. **Develop a strategic plan for long-term international research and collaboration** in planktic foraminiferal research, planned with input from a broad group of marine scientists, to integrate foraminiferal research with research in chemical and biological oceanography and marine ecology. This effort would culminate with a proposal for international long-term foraminifera observation and research. The addition of foraminifera observations supports the ‘plankton diversity and distribution’ Essential Ocean Variables of the Global Ocean Observation System (GOOS).

Working plan

WG members will develop and lead disciplinary groups (including biogeography, ecology, culturing, shell geochemistry, molecular biology) convened quarterly online and annually in person, in conjunction with international conferences, detailed below. Year one will focus on authoring a review of existing practices and knowledge gaps (ToR1). This review forms

the foundation for the SOPs, developed in year two, and the WG workshop at the start of year three. While SOPs are needed for all foraminiferal research, protocols will focus on foraminifera from deeper, 'extreme' and understudied environments include methods for culturing non-spinose and asymbiotic species, protocols for collecting modern samples from deep (beyond the mixed layer to ~1000m) environments, and modified approaches for cleaning fragile shells.

To achieve ToR2 and parts of ToR3, FIERCE will hold a training workshop in Peru, and will provide training opportunities in the Arctic (see Capacity Building). The workshop will connect a growing center of foraminiferal research, the Biogeosciences Laboratory of the Universidad Peruana Cayetano Heredia, with a broader international community. The facilities in Lima and Piura allow easy access to collect live and fossil foraminifera from diverse environments, including the Peruvian OMZ. During the two-week workshop FIERCE will test and iterate upon best practice protocols under development (ToR2), provide on-site training for workshop participants, and generate training resources (ToR3). This will include methods for live collection and culture, preservation of material for ecological, genetic, and geochemical analysis, and collection and preparation of fossil material for the same. Furthermore, FIERCE will provide opportunities for early career researchers to join Arctic/Nordic (R/V Helmer Hanssen and R/V Kronprins Haakon) cruises to enable training in foraminifera ecology and culturing in extreme Arctic environments (cruise time in-kind contribution from members' home institution $20,000). ECRs will be invited to submit an application for participation, with priority given to recent graduates (<5 years post-grad), graduate students, and those from underrepresented communities. During year two, we will prepare tutorial videos and slideshows for SOPs that cannot be carried out on-site (e.g., SOPs for stable isotope and trace element analyses, electron and fluorescent microscopy imaging).

The SOPs developed from the workshops and off-site will be made available for training and public comment by submission to OBPS (ToR3). The review paper (ToR1) and subsequent SOP testing during the workshop and Arctic cruises will feed into online teaching resources (ToR2) and an online best practice manual (ToR2&3). Uniting transdisciplinary specialists through our international consortium and the creation of best practice methods protocols as well as identification of contemporary knowledge gaps will provide ample ideas to support the development of an international long-term research proposal(s) across years two to three (ToR4).

Timeline:

Year 1: If recommended for funding, we will immediately assemble disciplinary subgroups leads and plan our review paper (ToR1). Subgroups will also begin to identify and outline best practice protocols within their disciplines. Subgroup-meetings will be scheduled online every third month. We will also apply for funding to further support the organization and execution of the workshop (ship time, facility fees, accommodations) and travel (ECR Arctic cruises & Peru workshop). Potential funding agencies include (but not limited to) AGU, ASLO, GSA, EGU, the Micropalaeontological Society, Cushman Foundation, Twitter for Good, DFG, NERC, Pages, NSF, NSF Taiwan, Lyell seed fund, JSPS, Chiba University.

The first FIERCE WG meeting will occur at the 2024 Ocean Sciences Meeting (New Orleans, USA) or at the 2024 International Conference on Marine Biology and Biodiversity in (Corfu, Greece). In conjunction with this meeting, we will convene a 1-day transdisciplinary symposium, run by WG members, other plankton specialists, and interested conference attendees. The goal will be to discuss planktic foraminifera best practice protocols with leading scientists from adjacent research fields and facilitate cross-disciplinary exchange with other relevant disciplines. By initiating this discussion at Ocean Sciences, we anticipate to convene a diverse group of marine scientists and connect early career scientists with an interdisciplinary community of marine scientists.

Year 2: The second WG meeting will be held at either the Goldschmidt Meeting in 2025 (European location in 2025) or at another location (TBD) such as the next ECCWO meeting (the Effects of Climate Change on the World's Oceans). In parallel, subgroups will complete their disciplinary sections of the review article within the first 6 months, followed by another online full workgroup meeting during which combined versions of the review article and the best practice protocols will be discussed. The review article will be finalized and submitted (ToR1). Tutorial videos and slideshows for the best practice protocols will be created (ToR2) before the end of year 2.

Year 3: We will host a workshop in Piura and Lima, Peru (ToR2). The facilities at Piura provide a location to test protocols in a near-shore (shelf) environment less impacted by the OMZ, while the OMZ is extremely oxygen depleted close to Lima. The workshop will be split into two sessions, with the first focused on methods specific to living planktic foraminifera in Piura where we expect higher foraminifera abundances (WG member Cardich, personal communication). The second session would be held at the larger Lima facility, IMARPE, and will focus on both live and fossil collection methods involving foraminifera from low-oxygen environments.

The third WG meeting will be held in conjunction with the Peru workshops, where we will finalize best practices and training resources. Videos and slide decks from the training sessions will be edited and uploaded with the best practice portfolio in collaboration with GEOTRACES (ToR2&3). Participants and organizers can provide feedback after all resources are uploaded. We will also finalize the research proposal for a long-term project to sustain our SOPs and create the basis for a global ocean observation program in close collaboration with GOOS (ToR4). Funding agencies that will be targeted for our research proposal(s) include the European Research Council (synergy grants), the National Science Foundation (USA), the Natural Environmental Research Council (UK), and Research Council of Norway (Norway).

Deliverables

1. A **review paper** (ToR1) of the current state of knowledge of planktic FIERCE foraminifera species will be published in an open-access peer-reviewed journal. The paper will

synthesize information about depth habitat, life cycle, genotypes, environment, preservation, and geochemistry, specifically targeting species from understudied habitats. Critical knowledge gaps will be identified with a list of key research areas required to bridge these gaps. Knowledge gaps will encompass uncertainties about extrapolation from shallow-dwellers, metabolism, adaptation to extreme environments, and symbioses and ecological interactions.

2. **Open access training resources** will include slide decks, filmed demonstrations of "**Standard Operating Procedures**" (SOPs) (see ToR2&3; Deliverable 3), and teaching resources for best-practices and protocols. Handling of foraminifera from both traditional and 'extreme' environments will be covered. The current absence of such materials and the commitment of all WG members to apply these standardized protocols in their laboratory groups will facilitate widespread adoption of SOPs. The learning modules we develop will be accessible online, and widely advertised at conferences.
3. **Best practices for research** with cultured, field-collected, and fossil foraminifera will be detailed in comprehensive SOPs (ToR2&3); including instructions and photographs of methods for collecting live and dead plankton specimens from plankton tows, how to culture foraminifera, best practices for long-term preservation of plankton tow collected specimens and sample preparation for analysis (e.g., geochemistry, genetics or microscopy).
4. **Preparation of a research proposal for an international long-term project** that extends the best practice sampling strategies and state-of-the-art methodologies into a global sustainable ocean observation program. (ToR4).

Capacity Building

The FIERCE working group aims to establish sustainable capacity building. One of the key limitations identified to moving the field of foraminiferal research forward is a disconnect between basic questions about the ecology, biology, and geochemistry of FIERCE species, and those with the toolkits to answer these questions. This disconnect may stem from the history of this field as one frequently rooted in geology (most extant planktic foraminifera were identified first as fossil shells), despite the salience of modern biological and oceanographic questions. Without fostering interdisciplinarity and codifying protocols for research that explicitly draw upon advances in the fields of both biology and geochemistry, answering questions about FIERCE foraminifera may remain out of reach. One rather straightforward example is that little is known about the lifecycle of deep dwelling planktic foraminifera - how long they live or what conditions may favor growth or reproduction. While geochemical methods may be readily transferable from better studied species, what environment or what timescale the geochemistry of deep-dwellers represents is unclear. To answer these questions will require tools from genetics, microbial ecology, and culture to be combined. Thus, during the first FIERCE WG

meeting we will selectively target (inter- to transdisciplinary) scientists focusing on other organism groups (e.g., other plankton specialists, micro- and molecular biologists) to join the creation and validation of the SOPs (ToR2). By building capacity for diverse researchers to have open access to these tools, we anticipate this type and more complex questions may be more easily addressed.

In other cases, tools may be available but misunderstood or unstandardized. For example, the use of ethanol, though widely used as a preservative in marine biological applications, may alter the isotopic composition of foraminifera biomass (Enge et al., 2018); the effect of fixatives on foraminiferal shell isotopic and geochemical composition is poorly constrained. This is a critical consideration when attempting to make biological to geochemical connections in foraminifera. Similarly, while fluorescent calcein dye can be used to label laboratory-grown calcite, extended exposure may also alter the carbonate chemistry of the culture water, introducing a potential complication for foraminifera calcification (WG member Davis personal communication). While this information is informally "known" within subfields, explicit codification is necessary to build capacity for broader collaboration. Codifying this type of knowledge within SOPs would not only pave the way for greater collaboration and prevent wasted research effort, but can standardize approaches in ways that make disparate collection and research efforts more compatible, such as has been done to great effect in GEOTRACES (see Cutter et al., 2017) or FOBIMO (foraminifera used for biomonitoring; see Schönfeld et al., 2012) programs.

We not only aim to build capacity by bringing in state-of-the-art skills and methodology to foraminiferal research but also to capacity build globally and generationally. We aim to codify standard practices within the field of foraminiferology and bring in tools from adjacent fields (e.g., genetics, geochemistry). While these tools have been increasingly used to answer questions in benthic foraminifera, they are underutilized in planktic foraminifera. Our full and associate member lists include people with expertise in both FIERCE species as well as those experienced in applying interdisciplinary techniques to benthic and planktic foraminifera, and other marine protists. The SOPs developed during this FIERCE project will also benefit researchers studying other plankton organisms (e.g., pteropods, copepods) and, more broadly, many marine research areas using the same analytical techniques that will be covered by our set of "SOPs" (e.g., stable isotope analysis of other marine calcifiers).

In addition, we plan to prepare a research proposal for an international long-term project that extends these best practice sampling strategies and state-of-the-art methodologies into a global sustainable ocean observation program.

These aims are highlighted in ToR3 and ToR4 and expanded on here. Specifically, the FIERCE aims for capacity building include:

1. **Training early career scientists** in a range of techniques during our Peru workshop and Arctic cruise. Currently, state-of-the-art methodologies are infrequently applied to planktic foraminifera, and this workshop will bring together researchers from wider

disciplines to demonstrate the utility of new methods. These include for example the preparation and fixation of samples for molecular techniques, and the pre-cleaning used for trace element analyses for past environmental reconstructions including calcification temperatures. Slide decks and video tutorials will be archived on Zenodo, where they will be assigned a DOI and be openly accessible. From this early career scientists will receive access to a much larger toolkit of analytical approaches relatively early in their careers.

2. **Providing resources to foster interdisciplinarity** by providing openly available best practices for working with cultured, field collected, and fossil foraminifera. Improving and codifying best practices with input from multiple fields will increase the accessibility of foraminiferal work to other disciplines and allow foraminiferologists to integrate into modern oceanographic and biological collaborations with greater ease. This will be key in broadening the networks of earth career scientists, especially.
3. **Developing relationships between foraminiferologists and scientists in other disciplines**, including plankton ecology, microbiology, ecological and biogeochemical modeling to collaborate and co-supervise students to bring original cutting edge techniques into the field of foraminiferal studies.
4. **Identifying gaps in current knowledge** of FIERCE species, many of which will require interdisciplinary & international partnerships and new approaches to fill. Those will be summarized in the planned overview (review-) paper. The goal will be to establish a roadmap of key questions for early career researchers with the right tools (such as those provided by the proposed workshop and associated materials) to tackle.
5. **Transferring knowledge about state-of-the-art methodologies to host facility** during the workshop in Peru: "hands-on" sessions and sustainability of these applications by capacity building at the host facility.
6. **Preparing a proposal for a sustainable global ocean observation program** that implements the developed best practice strategies. Our goal is to provide a blueprint for collecting foraminifera globally and expanding their utility in modern ocean research and in the paleorecord using internationally established protocols that guarantee results can be compared across studies and through time. Especially as capacity for utilization of 'big data' grows, the establishment of such a program to generate universally comparable datasets will provide timely resources for current and future researchers in the field.

As capacity building efforts specifically target ECRs, as well as groups otherwise generally underrepresented in foraminiferology (e.g., scientists from emerging economies) providing funding for workshop participation is critical. In order to do this, we intend to solicit funds from the following programs to support travel and attendance of 12-20 ECRs, pending funding sources. If this proposal is funded via SCOR we will solicit funds from the following potential sources:

1. The US National Science Foundation will fund training for US and international workshop participants via supplementary awards to US PIs (WG members Davis and Fehrenbacher will explore this option).
2. NERC has funding opportunities for training ECRs via UKRI proposals.
3. The company of Biologists can provide up to £6000 for meeting grants (https://www.biologists.com/grants/meeting-grants)
4. British Council Researcher Links workshop grants provide financial support for workshops for early career researchers. Leading or established researchers can apply to be workshop coordinators and propose a theme for a workshop. It must be a joint application, with one coordinator based at a UK institution and one based at an institution in a partner country. Applicants can be of any nationality. https://www.britishcouncil.org/education/he-science/researcher-links
5. EMBO - Excellence in the life sciences can provide limited workshop funds if the workshops are held in certain countries, including several from which WF members reside (Including France, Germany, Taiwan, and the UK. EMBO also partners with the company of biologists. https://www.embo.org/funding/funding-for-conferences-and-training/workshops/eligibility
6. DFG (German Research Foundation) - Workshops for Early Career Investigators: Travel and accommodation costs for the organisers, plus up to 20 participants in the workshop for early career investigators and external researchers. Also covers miscellaneous costs involved in holding workshops and potential colloquia, plus up to 10,000 euros in coordination costs. https://www.dfg.de/en/research_funding/programmes/individual/workshops_early_career_investigators/index.html
7. TMS (The micropaleontological society) - TMS Educational Trust Awards: Non-specified support of post-graduate training in micropalaeontology https://www.tmsoc.org/tms-educational-trust-awards/

Working Group composition.

FIERCE WG brings together state-of-the-art skills, including proxy development (species community, geochemical and morphometric analysis), molecular taxonomy, cell imaging, metabolic analysis, as well as oceanographic field sampling, culturing, and experimental works, that will be fundamentals to achieve our ToRs. Full members are foraminifera researchers with diverse backgrounds and expertise from paleoceanography, genetics, protistology, and physiology, addressing a wide spectrum of research. The Associate members provide important input from the complementary fields covering biological oceanography, biodiversity modeling, functional modeling, and evolutionary biology. Our Full and Associate members represent 11 different nations/regions, including 2 emerging/developing nations (Peru and Brazil). Half of our members are early career researchers, and they will be supported by experienced senior scientists including 2 Associate members who led SCOR WG138 (Darling, Tyszka), ensuring the success of organizing the WG.

Full Members (no more than 10, please identify chair(s))

Name	**Gender**	**Place of work**	**Expertise relevant to proposal**
1 Jennifer Fehrenbacher (Chair)	F	Oregon State University (USA)	Foraminifera geochemistry, proxy method development and (paleo)+oceanography, including high-latitude and deep dwelling species.
2 Abby Ren (Chair)	F	National Taiwan University (TAIWAN)	Geochemistry and (paleo)+oceanography; Nitrogen isotopes in calcifiers, paleo-productivity, live culturing
3 Babette Hoogakker	F	Heriot-Watt University (UK)	Foraminifera geochemistry, proxy development, (paleo)-oceanography, seawater oxygen reconstructions
4 Catherine Davis (early career)	F	North Carolina State University (USA)	Foraminiferal geochemistry, (paleo)+oceanography, live culture, foraminiferal ecology in low oxygen and low pH environments
5 Clare Bird (early career)	F	University of Stirling (UK)	Marine molecular microbiologist, foraminiferal genotyping and single-cell microbiome metabarcoding
6 Nicolaas Glock	M	University of Hamburg (GERMANY)	Foraminifera, biogeochemistry and nutrient budgets in low oxygen environments, metabolic rates, proxy development and (paleo)+oceanography
7 Christine Barras	F	LPG Angers (FRANCE)	Benthic foram culture, FOBIMO member (standardized protocol), foraminifera geochemistry, proxy development (oxygen, carbonate chemistry)
8 Jorge Cardich (early career)	M	Universidad Peruana Cayetano Heredia, Lima (PERU)	Benthic foraminifera ecology in sediments in association with OMZs and coastal environments from Peru.

9 Haruka Takagi (early career)	F	Chiba University (JAPAN)	planktic foraminifera ecology, symbiosis, photophysiology, global warming effects on foraminifera, symbiotic networks among microplankton
10 Raphael Morard	M	MARUM (GERMANY)	Genetic and morphological diversity in foraminifera evolution of microplankton. Integration of genetic diversity in paleoceanography

Associate Member (no more than 10)

Name	**Gender**	**Place of work**	**Expertise relevant to proposal**
1 Kate Darling	F	University of Edinburgh/University of Stirling (UK)	Genetic diversity and biogeography of Foraminifera. Global evolutionary patterns of planktonic foraminifera
2 Julie Meilland (early career)	F	Marum (GERMANY)	Plankton sampling, planktonic foraminifera population dynamics and related C fluxes, high-latitude species culture
3 Tristan Biard	M	Université du Littoral Côte d'Opale (FRANCE)	In situ imaging & biogeochemical fluxes of Rhizaria (sensu lato)
4 Moriaki Yasuhara	M	The University of Hong Kong (HONG KONG)	Global biodiversity analyses
5 Hidetaka Nomaki	M	JAMSTEC (JAPAN)	(Benthic) culture, deep-sea sampling, biology of foram, analytical techniques (stable and radio isotopes, TEM, X-ray CT, NanoSIMS)
6 Mohamed M. Ezat (early career)	M	UiT the Arctic University of Norway (NORWAY)	Foraminifera geochemistry, proxy development and Arctic/high-latitude paleoceanography

7 Mattia Greco (early career)	M	IO PAN (POLAND)	Evolutionary biology, plankton ecology, bio-informatics, and phylogenetic analyses
8 Jaroslaw Tyszka	M	ING PAN (POLAND)	Modeling (eVolutus), fluorescent labeling and imaging
9 Douglas Villela de Oliveira Lessa (early career)	M	Federal Fluminense University (Niterói, Brazil) (BRAZIL)	Quaternary planktonic foraminifera taxonomy, (paleo)ecology, paleoceanography, statistics for simulating foram species distributions, transfer functions, stable isotopes and Mg/Ca proxies
10 Dimitri Gutiérrez	M	IMARPE (PERU)	Biological oceanography and paleoceanography. Director of research in oceanography and climate change at IMARPE

Working Group contributions

Jennifer Fehrenbacher has extensive experience culturing living planktic foraminifera and analyzing the isotopic and trace element geochemistry of modern and fossil shells. Her recent research focuses on understanding the geochemistry and ecology of deeper dwelling and higher latitude species in eastern boundary upwelling systems.

Abby Ren researches the interaction between biology and the environmental conditions through the course of Earth history. She pioneers the work on developing planktonic foraminifera shell-bound nitrogen isotopes as a paleoceanographic tool to reconstruct past history of the marine nitrogen cycle and has extensive experiences working with foraminifera culturing, isotopic analyses on fossil and modern samples.

Babette Hoogakker is an expert in the development and application of proxy methods to reconstruct past seawater oxygen concentrations, using foraminifera isotopes and trace metals. She has extensive experience in the reconstruction of past ocean circulation and biogeochemical cycles in connection to climate change.

Catherine Davis uses tools from the individual shell (isotopic, trace element, and morphological analyses) to community (assemblage) level, with recent research focusing on how planktic foraminifera respond to and record low-oxygen and low-pH environments. She has experience working with living, recent, and fossil foraminifera and is broadly interested in building bridges between modern- and paleo- oceanography.

Clare Bird pioneers the use of molecular tools to understand foraminiferal metabolism, microbial interactions and adaptability to climate change. She has over ten years' experience in molecular microbiology and enjoys working at the interface between biology and (palae)oceanography.

Nicolaas Glock works at the interface between biogeochemistry, paleoceanography and micropaleontology and focuses on biogeochemical cycling in oxygen depleted marine environments. He studies metabolic and physiological adaptations of foraminifera to extreme environments, quantifies the role of foraminifera in marine nutrient cycling and uses foraminifera to reconstruct past nutrient cycling and redox conditions in oxygen depleted environments.

Christine Barras is specialist of benthic foraminiferal culturing in stable controlled conditions for the calibration of geochemical proxies to reconstruct oxygen conditions or carbonate chemistry of seawater in the past. She is also interested in the ecology of benthic foraminiferal species and the development of biotic indices for ecosystem quality evaluation.

Jorge Cardich studies the ecology of benthic foraminifera and other meiofaunal groups in relation to biogeochemical gradients of organic-rich and oxygen-poor marine environments, and has promoted the studies of foraminiferal propagules from sediments of coastal environments from Peru. He has experience in the reconstruction of oxygenation in the past using microfossils and geochemical proxies.

Haruka Takagi is broadly interested in modern planktic foraminifera species ecology and its interaction to the environment through geological time. Her current research focuses on understanding photosymbiosis in planktic foraminifera using stable isotope analysis, chlorophyll fluorescence, culture experiments and molecular biological techniques.

Raphael Morard works on genetics and morphological diversity of foraminifera. He is interested in the evolution of microplankton and integration of genetic diversity in paleoceanography.

Relationship to other international programs and SCOR Working groups:

The FIERCE working group will build upon and develop relationships with various international programs and existing SCOR working groups. For the development and publication of the SOPs we will work with GEOTRACES and OBPS. GEOTRACES (sponsored by SCOR) represents a well-established international research program that aims to improve the understanding of oceanic trace elements and isotopic biogeochemical cycles. It is an ideal partner to host globally accessible protocols designed to implement improved utility of foraminifera whose shells are recorders of the physico-chemical conditions of the ocean. We furthermore plan to base our SOPs on the GEOTRACES SOPs as well as the "Guide to Best Practices for Oceanic CO_2 Measurements", another SCOR sponsored effort. With GOOS we plan to define an observing

system for planktic foraminifera by integrating them into the phytoplankton and zooplankton biomass and diversity Essential Ocean Variables.

FIERCE benefits from outputs of the past SCOR WG138 "Modern Planktic Foraminifera and Ocean Changes," which focused on understanding tropical-subtropical species. The community has benefited from capacity building efforts and workshops hosted by WG138.

Beyond these direct connections, FIERCE science relates to several other SCOR WGs. MixONET is an active SCOR group with overlapping interests to those of FIERCE, in a desire to develop/improve biological oceanographic research methods to better apply to mixotrophs (foraminifera are non-constitutive mixoplankton); member Bird recently attended the MixITIN conference organized by MixONET. Additionally, there are common interests with MetaZooGene and EBUS. FIERCE will also be of interest to PAGES, especially the 2k-network (https://pastglobalchanges.org/science/wg/2k-network/intro) where our SOPs can inform calibration methods, and our focus on training for ECRs could be particularly relevant. FIERCE could also be of interest to mikrotax (https://www.mikrotax.org/pforams/), with increasing standardization in collecting both modern and fossil material bolstering taxonomic efforts. FIERCE workshops, outputs and progress will also be promoted through the Foraminifera Specialist Group of the Micropaleontological Society (member Hoogakker chair), and the Cushman Foundation. New links have also been developed with Protistology UK, a subgroup of the Microbiology Society, which is a multidisciplinary group utilizing and sharing diverse cutting edge molecular, culturing and biological methods to investigate diverse protists. These links will foster the development of new protocols for foraminifera.

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Appendix - Full Member Publications

Clare Bird

Bird, C., LeKieffre, C., Jauffrais, T., Meibom, A., Geslin, E., Filipsson, H.L., Maire, O., Russell, A.D. and Fehrenbacher, J.S. (2020) Heterotrophic foraminifera capable of inorganic nitrogen assimilation. *Frontiers in Microbiology*, 11:604979. https://doi.org/10.3389/fmicb.2020.604979

Bird, C., Schweizer, M., Roberts, A., Austin, W.E.N., Knudsen, K.L., Evans, K.M., Filipsson, H.L., Sayer, M.D.J., Geslin, E. and Darling, K.F. (2020). The genetic diversity, morphology, biogeography and taxonomic designations of *Ammonia* (Foraminifera) in the Northeast Atlantic. *Marine Micropaleontology*, 155:101726 https://doi.org/10.1016/j.marmicro.2019.02.001

Salonen, I.S., Chronopoulou, P-M., **Bird, C**., Reichart, G-J and Koho, K.A. (2019). Enrichment of intracellular sulphur cycle-associated bacteria in intertidal benthic foraminifera revealed by 16S and aprA gene analysis. *Scientific Reports*, 9:11692. https://doi.org/10.1038/s41598-019-48166-5

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Jorge Cardich

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Catherine Davis

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Jennifer Fehrenbacher

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Nicolaas Glock

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Raphael Morard

Cordier, T., Angeles, I.B., Henry, N., Lejzerowicz, F., Berney, C., **Morard, R**., Brandt, A., Cambon-Bonavita, M.-A., Guidi, L., Lombard, F., Arbizu, P.M., Massana, R., Orejas, C., Poulain, J., Smith, C.R., Wincker, P., Arnaud-Haond, S., Gooday, A.J., de Vargas, C., Pawlowski, J. (2022) Patterns of eukaryotic diversity from the surface to the deep-ocean sediment. *Sci. Adv.,* 8, 26–28. doi:10.1126/sciadv.abj9309

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