Science Action Plan (SAP) of the DOME Programme

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Deep Ocean Microbiomes and Ecosystems (DOME)

Part 1: Why DOME?

1. Introduction

The World Ocean is one global, interconnected body of saltwater made up of the world's five oceanic basins – Atlantic, Pacific, Indian, Arctic, and Southern Oceans. The global ocean comprises an immense biosphere that covers 71% of the Earth's surface. The planet's most habitable space is in the ocean, and about 80% of the livable volume is in the deep ocean, below water depths of 1,000 m. The deep ocean encompasses key biogeographic provinces, including the abyssal plains, hydrothermal vents, cold seeps, seamounts, submarine canyons, trenches, mud volcanoes, etc. in the deep-water column and the seabed sediment. As the oldest and largest biome on Earth, the deep ocean contains a trove of microbial diversity with unique physiology, metabolism, and genetic resources that provide ecosystem services of enormous values to the mankind. The deep-ocean microorganisms, and the communities they form, drive global biogeochemical cycles, including those that regulate the Earth's climate. The ocean is truly the final wild commons and the deep ocean is the last terra incognita of the Earth. We should support the ocean ability to deliver ecosystem goods and services and remain a cornerstone of the global life support system into the future.

Climate change has taken place in geological past that led to ocean anoxic events (OAEs) and mass extinctions on Earth. For the first time in Earth's history however, climate change is being driven by human forcing and proceeding at a pace that may outstrip evolutionary change. Climate change today is affecting the marine environment, inflicting ever-increasing pressures on marine microbiomes and ecosystems. The resulting cumulative impact of human activities has substantially eroded the ocean ecosystems, and often leads to ocean ecosystem degradation or even collapse. Among the nine proposed planetary boundaries which represent the limits within which humans can safely inhabit the Earth, five have now been breached due to human activities: climate change, biosphere integrity loss, land-system change, plastic and chemical pollution, and altered biogeochemical cycles (Figure 1). It is supposed that we are now firmly entrenched within the sixth mass extinction event with loss of biodiversity being most prominent.

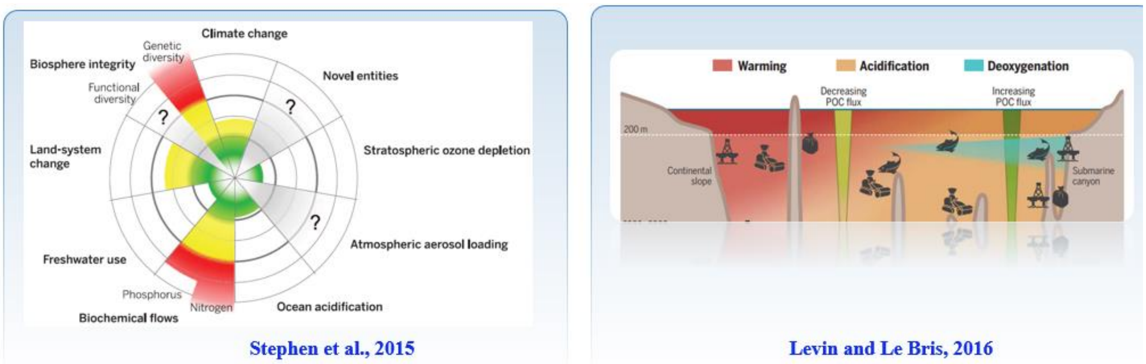

Figure 1. The planetary boundaries and impacts of climate change on the oceans (Steffen et al., 2015; Levin and Le Bris, 2016).

The health and services of the ocean are inherently linked to microorganisms residing in the ocean. Ocean microorganisms exist in highly organized and interactive communities that are versatile and complex. They account for more than 98% of ocean biomass and possess as much variability as the environments they inhabit. Microbiome is a term referring to the communities of microbes and their combined genetic material in a particular environment (that is, their taxonomic and genomic content). The ocean microbiome includes bacteria, archaea, viruses, and single-celled eukaryotes. Although our understanding of fundamental concepts in marine microbiomes has increased, deep-ocean microbiome research, particularly in the context of ecosystem processes and functions, is still in its infancy. A number of critical issues in research and major knowledge gaps must be addressed to fully understand the deep ocean microbiomes and their ecosystem functions. First, it is estimated that the ocean microbiome is consisted of about four gigatons of carbon with the total species richness of a few million taxa. Yet only a small fraction of marine microbial diversity has been characterized to date. In particularly, we know very little about the deep ocean microbiomes. The current estimate of bacterial and archaeal abundance is 10^{29} cells in the ocean water column and more in the seafloor sediment, therefore, the deep ocean ecosystems could hold the greatest number of cells and diversity of microbial life. Furthermore, most climate change impacts in the deep ocean will remain unknown unless our research effort is directed to its vulnerable ecosystems. Additionally, microorganisms in the deep ocean and especially in seafloor sediment tend to grow slowly and their metabolic rate is much lower comparing to their surface ocean counterparts, which renders the deep ocean ecosystems particularly vulnerable.

Second, current estimates suggest that there are 50 million prokaryote genes and 100 million micro-eukaryote genes in the shallow ocean, as described by Tara Oceans. However, no genetic data series is available for the deep ocean, and the deep ocean microbiomes remain to be uncovered. Third, our understanding of ocean microbiomes must go beyond merely identifying its members, but at the same time determining the member’s habitats, functions, and the processes they control in the ocean. Forth, previous works were typically restricted to one single ecosystem or within a given ecosystem and not cross ecosystem boundaries, exchange and transfer of energy, matter, and information, the so-called cross boundary effects on ecosystems, were not studied. Fifth, the deep ocean microbiomes are large in scale and complexity and must include those in the water column and in the sediment as well. The seafloor sediment is considered as the largest carbon store on our planet and therefore, has great implications to climate change and ocean ecosystem functions and evolution. Concurrent studies are needed to determine the flow of matter, energy and information between the different ecosystems and between those in the water column and in the sediment. Finally, understanding of deep-ocean microbiomes and ecosystems must be pursued under the microbiome-ecosystem-people framework, whereby microbiomes and their associated ecosystems are considered as a synergistic functional unit (microbiome-ecology) and their impact to humans and vice versa must be determined and assessed (Figure 2).

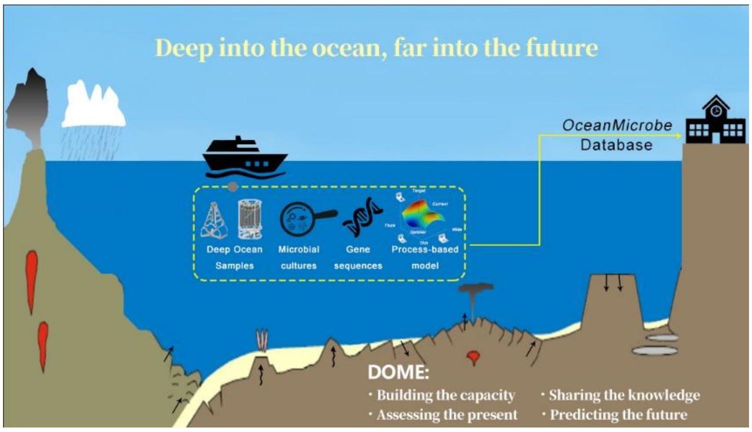

Figure 2. The DOME programme.

Technology advances in the past decades have enabled scientists to explore the last frontier, the deep ocean. The new discoveries are seminal and also alarming. The deep ocean microbiomes are diverse, metabolically, phylogenetically, and functionally. Yet the deep ocean habitats and microbial communities are showing clear signs of natural and anthropogenic impacts. The protection, conservation and sustainable use of habitats, ecosystems and biodiversity of the deep ocean have been the focal point of international concerns. The ocean is changing faster than ever. It is a victim of climate change (i.e., ocean warming, acidification, and deoxygenation). But it can also be a big part of the solution. Therefore, the deep ocean is of crucial importance for life on Earth, and we have to stop the irreversible damages before it is too late.

We adopt the PMO concept— People, Microbe, and Ocean—that is, the interactions and connections between people, microbes, and the ocean, aiming to generate the knowledge on how ecosystem services provided by deep ocean microbiomes impact the societies (i.e., provisional, cultural, supporting and regulatory services). First and foremost, DOME will determine microbial diversity of the deep ocean, going beyond simply identifying the taxonomic members of the deep-ocean microbiomes, but assessing the "Deep Ocean Genome", that is, all the genes and the information they encode. Further, DOME will utilize an ecosystem-level biology approach, combining the study of molecules, cells, populations and communities to assess their ecosystem impacts and multidirectional connections between them. This is needed to bridge the gaps between molecular-level mechanisms, ecosystem processes and global ocean functions. Thus, DOME will generate the critical knowledge and information on the understanding, valuation, and conservation of deep ocean microbial diversity and bioresources and provide fundamental basis for the new treaty on marine biodiversity and sustainable use (the BBNJ Agreement) and other international policy instruments (e.g., the Sustainable Development Goals (SDGs), the Paris Agreement, etc.). Furthermore, DOME differs than other Decade programmes, e.g., Challenger 150, Marine Life 2030, TOWER, OBON, Digital DEPTH, etc., which either focus on a certain part of the deep ocean, not all oceans or all depths, or specific habitats (e.g., seamounts, hydrothermal vents, etc.), or excluding the sediment biosphere, or studying primarily animals in the deep ocean. Rather, DOME will address critical questions (see Part 2 below) that, if tackled and answered, will make considerable contributions to the needed knowledge and information about the deep ocean microbiomes and ecosystems to achieve the Decade of Ocean Challenges, specifically, Ocean Decade Challenge #5: to enhance understanding of the ocean-climate nexus and generate knowledge and solutions to mitigate, adapt and build resilience to the effects of climate change across all geographies and at all scales, and improve services including predictions for the ocean, climate and weather.

Our vision: **Deep into the Ocean, Far into the Future!**

2. Recent scientific and technological developments and findings in Shanghai Ocean University

The Shanghai Engineering Research Center of Hadal Science and Technology (HAST) in Shanghai Ocean University was founded in 2013. HAST has made significant progress in hadal science and technologies, manifested in project funding, developing world-class full-ocean-depth (FOD) pressure-retaining (PR) sampling devices and technologies, and making significant scientific findings.

(1) Project funding

In the past seven years, Dr. Fang led HAST with significant research funding, including one project funded by MOST for 18.53 million RMB, two projects funded by the National Natural Science Foundation of China (NSFC) for 5 million RMB, one project funded by MOST and MOE (Ministry of Education) for 5 million RMB, one project funded by the Department of Education of the Shanghai Municipal Government for 25 million RMB, and one project funded by the Lin-Gang Special Area of Shanghai for 89 million RMB. The total research funding awarded to Dr. Fang was 142 million RMB in seven years (2017-2023). Seven sets of FOD PR sampling and measurement devices were developed in executing the 18.5-M MOST project (2018-2021).

(2) FOD sampling and measuring devices and technologies

During execution of these projects, new sampling and measurement devices and technologies were developed, including seven different pressure-retaining sampling, sample-transferring, and measurement devices, all for FOD. These devices allow us to collect seawater, animals (fish, etc.), sediment, biofilm, in-situ filtration of particle-attached and free-living microbes (by using two different pore-sizes of filters (3 and 0.2 μm), and measure microbial ectoenzyme activities under in-situ temperature and pressure (Figure 3). We also assembled the world's first Hadal Trench Movable Laboratory (HTML), a platform for sampling in all ocean areas at all depths, including the hadal trenches. HTML includes a 3200-tonne mothership *Songhang*, 6 FOD Landers (Gen I&II), 7 sets of PR samplers and measurement devices, two Seabird 911 Plus CTD sampling devices, and several sediment corers. SHOU scientists have extensive sea-going experience and have conducted over 11 deep ocean cruises in the past decade.

(3) Significant scientific findings

(a) Trench sediment microbes have acquired unique metabolic traits

We performed metagenomic and transcriptomic analysis of sediment from the Mariana Trench and found that trench microbes (mainly *Chloroflexi*) possess unique metabolic capabilities, including degrading persistent organic pollutants (POPs) via hydrolytic or oxidative pathways, like polycyclic aromatic hydrocarbons, sulfur and halogenated hydrocarbons, and PCBs, and synthesizing energy storage compounds (e.g., trehalose) following a "feast and famine" metabolic strategy. The 62 assembled metagenomic genomes (MAGs) represent one novel order, one novel family, four novel genera, and six novel species. These findings highlight microbial metabolic adaptation to the extreme trench environment and their role in deep ocean carbon, sulfur and halogen cycles (Figure 4; Liu et al., 2022).

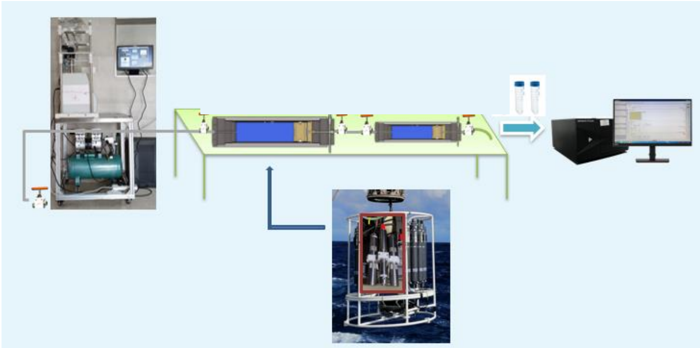

Figure 3. A device for measuring microbial ectoenzyme activities under in-situ temperature and pressure conditions.

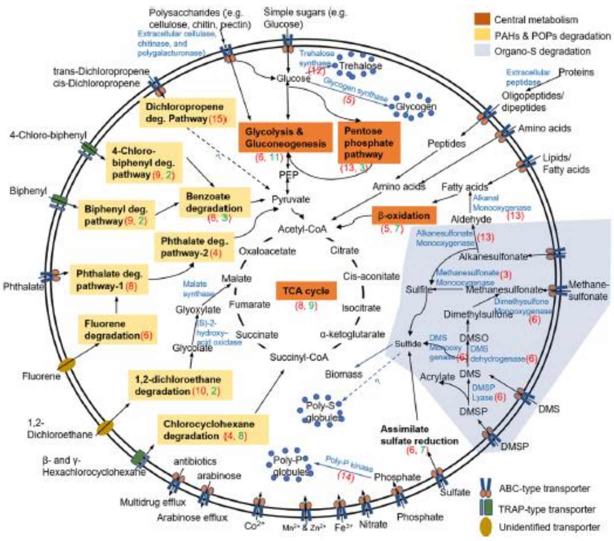

Figure 4. Metabolic potentials of the *Chloroflexi* MAGs (Liu et al., 2022).

(b) **The unique biochemical and biogeochemical capabilities of piezotolerant fungi in hadal trenches**

Piezotolerant trench fungi exhibited growth pressure-dependent biosynthetic capabilities (Figure 5). The production of secondary metabolites was affected by high hydrostatic pressure (HHP), improving the potential of discovering novel natural products from hadal fungi. Antibacterial assay revealed the potential of discovering novel natural products. These results suggest that growth pressure plays an important role in the production of secondary metabolites of these hadal fungi in the Mariana Trench.

Our metagenomic analysis of the Challenger Deep sediment showed that the sediment biosphere comprised six phyla, i.e., Zoopagomycota, Mucoromycota, Ascomycota, Basidiomycota, Chytridiomycota, and Blastocladiomycota, which can be further classified into twenty-seven classes (Fig. 6).

The hadal fungi possessed the complete pathways for assimilatory sulfate reduction, dissimilatory sulfate reduction, and sulfide oxidation (Fig. 6). They were also found to contain partial pathway for the SOX system, but were incomplete for oxidation of thiosulfate. These findings suggest that hadal sediment fungi, like hadal bacteria, could take part in sedimentary sulfur and carbon cycles.

We detected 15 major viral families in the Challenger Deep sediment (Figure 7; Chen et al., 2021), with dsDNA viruses being most abundant. Members of 131 bacteria and archaea classes were associated with 20 viral families, forming many one-to-many relationships between viruses and host, and vice versa. The most frequent hosts were Firmicutes and Bacterioidetes, followed by Euryarchaeota. Furthermore, viruses modulate the activities of the hosts upon infection through auxiliary metabolic genes (AMGs). We identified 40 putative AMGs from the Challenger Deep sediment viruses, having roles in carbon, sulfur, and nitrogen metabolism (Figure 7).

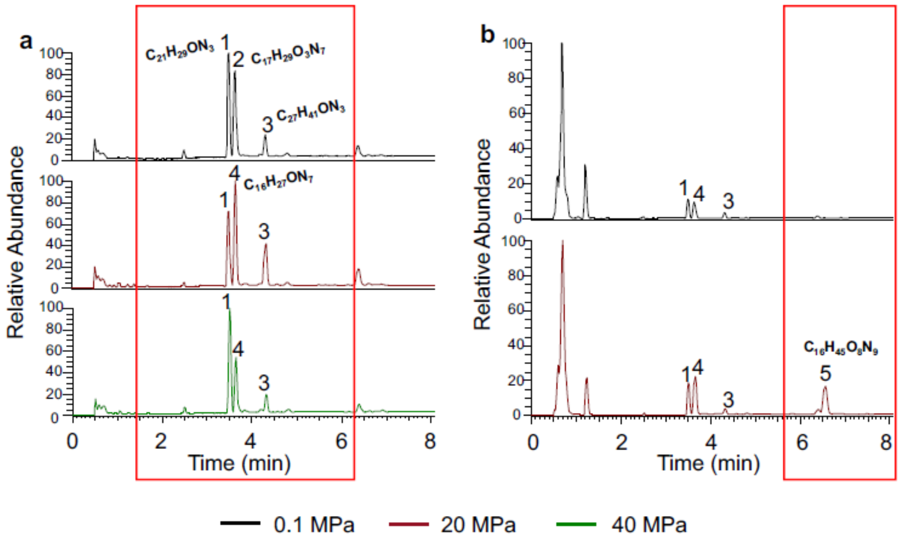

Figure 5. Trench derived fungi exhibited biosynthesis of metabolites under three different hydrostatic pressures. (a) TIC peak of *Cladosporium* sp. CIEL 2; (b) TIC peak of *Stemphylium vesicarium* CIEL 5 (Peng et al., 2021).

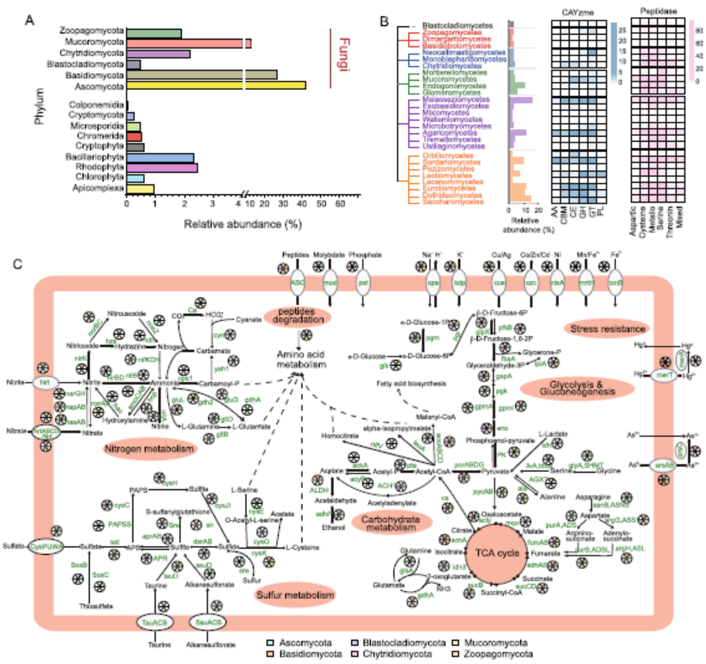

Figure 6. Composition of microeukaryotic community, and metabolic functions of the dominant fungal groups in the Challenger Deep sediment biosphere.

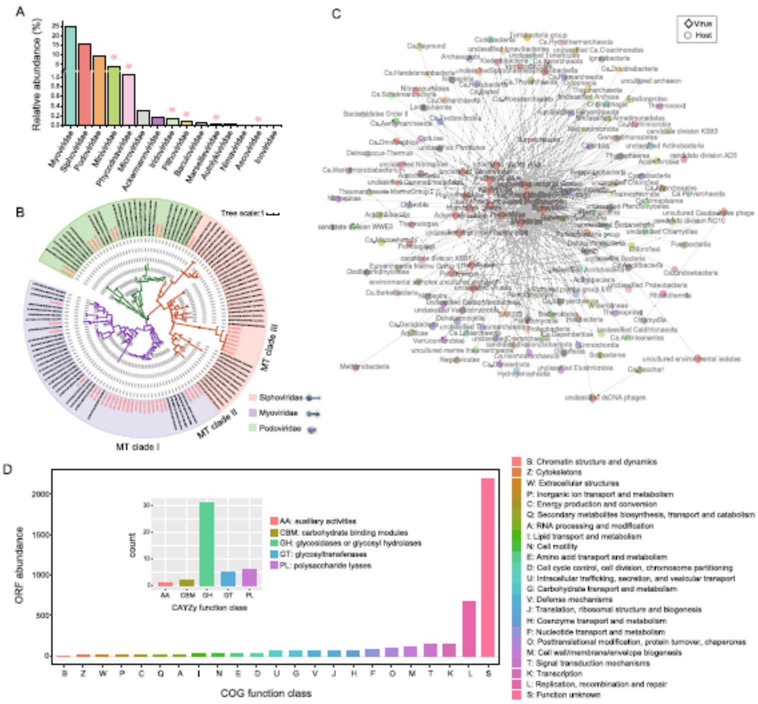

Figure 7. Diversity of metavirome, virus-host association, and viral genome annotation in the Challenger Deep sediment biosphere (Chen et al., 2021).

(c) Hadal trenches as a sink for global black carbon

We determined the concentration and distribution of black carbon in six hadal trench sediment around the globe (Figure 8). We found that black carbon constituted 10% of trench total organic carbon, with its primary source from terrestrial C3 plants and fossil fuels (Figure 9). We estimate a black carbon burial rate of 1.0 ± 0.5 Tg yr^{-1} in the hadal zone, which is seven-fold higher than the global ocean average per unit area. We propose that the hadal zone is an important, but overlooked, sink of black carbon in the ocean (Zhang et al., 2022).

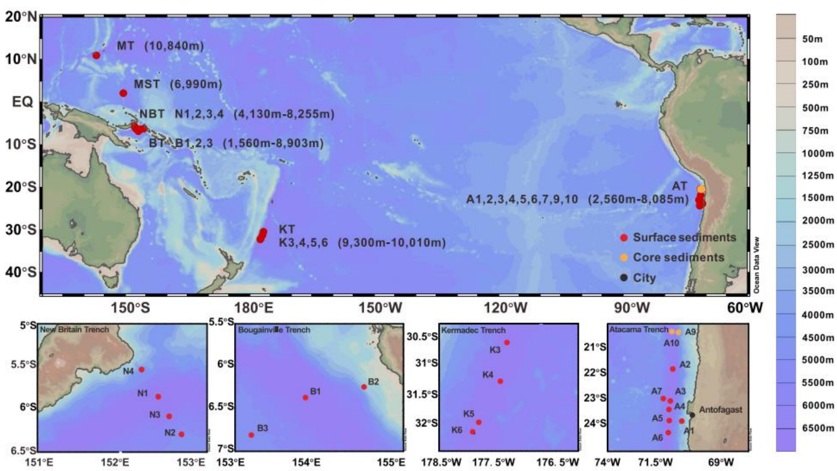

Figure 8. The distribution and concentration of black carbon were studies in six hadal trenches around the world (Zhang et al., 2022).

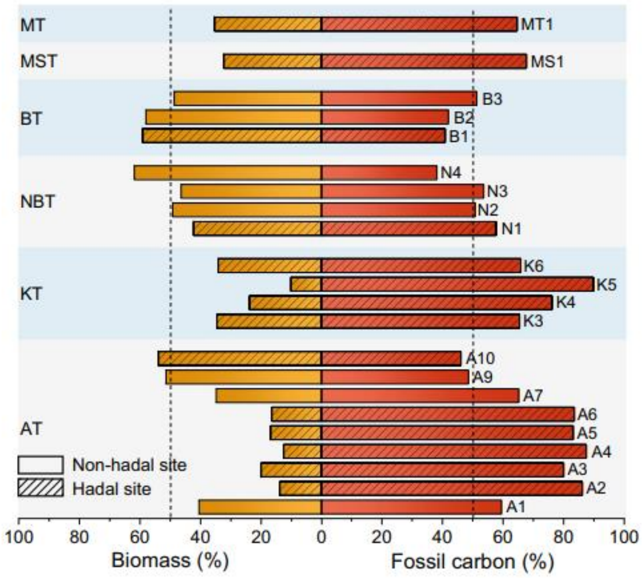

Figure 9. Radioactive carbon isotopic composition ($\Delta^{14}C$)-based estimate for proportion (%) of fossil carbon and biomass burning to the Black carbon pool in surface sediments from six trench regions (Zhang et al., 2022).

(d) Microbial dichotomy, changes in physiology, metabolism and association network interactions with hydrostatic pressure

One of the long-standing questions in marine microbial ecology is how community composition, physiology, metabolism, and microbial interactions are shaped by environmental factors, e.g., hydrostatic pressure (HP; depth). Bacterial communities are usually separated into free-living (FLM) or particle-attached (PAM) microbes via size-filtration, the so-called microbial dichotomy, although there are dynamic exchanges between the two communities.

In a laboratory simulation of particle sinking with increasing depth (HP), we found that microbial diversity and species richness of the PAM and FLM communities decreased significantly with increasing HP and decreasing temperature. Ecological network analysis showed that increasing HP and decreasing temperature enhanced microbial network interactions and resulted in higher vulnerability to networks of the PAM communities and more resilience of those of the FLM communities. Most interestingly, the PAM communities occupied most of the module hubs of the networks, whereas the FLM communities mainly served as connectors of the modules (Figure 10). Furthermore, transcriptomic analysis indicates that the PAM communities were more active at low pressure, while the FLM communities were functionally more important at higher pressure (Figure 11). These findings suggest that the different microbiomes with distinct physiology, metabolism and ecological functions in the different pelagic zones and likely, in the seafloor sediment biosphere.

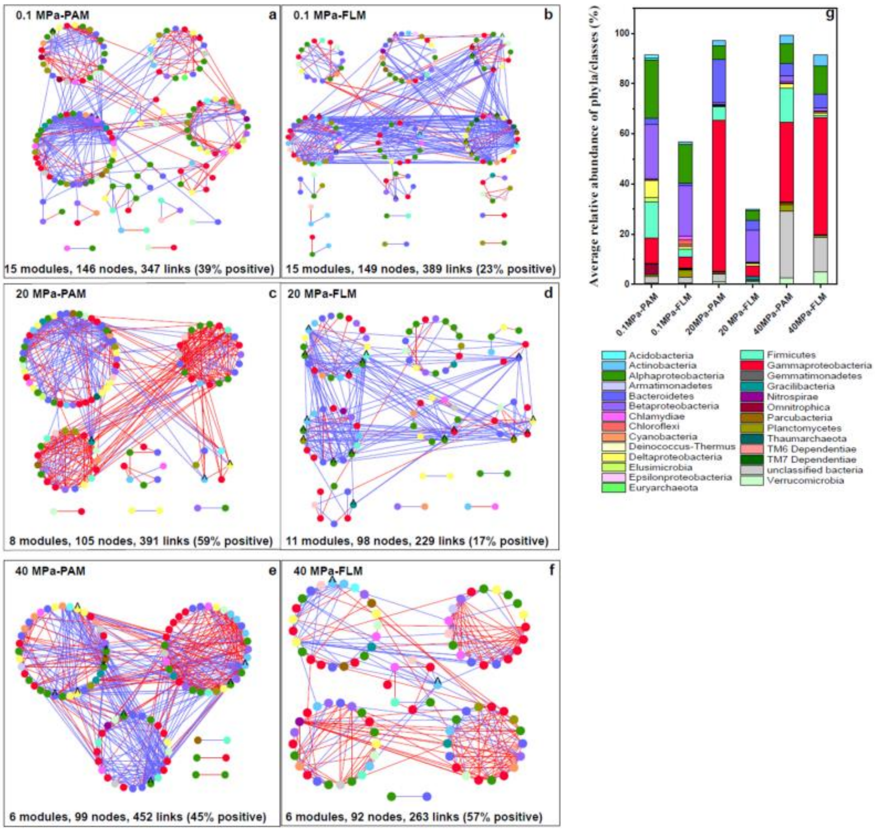

Figure 10. Network analysis of the particle-attached (PAM) and free-living microbial (FLM) communities during POM sinking at 0.1, 20, and 40 MPa (Liu et al., 2022).

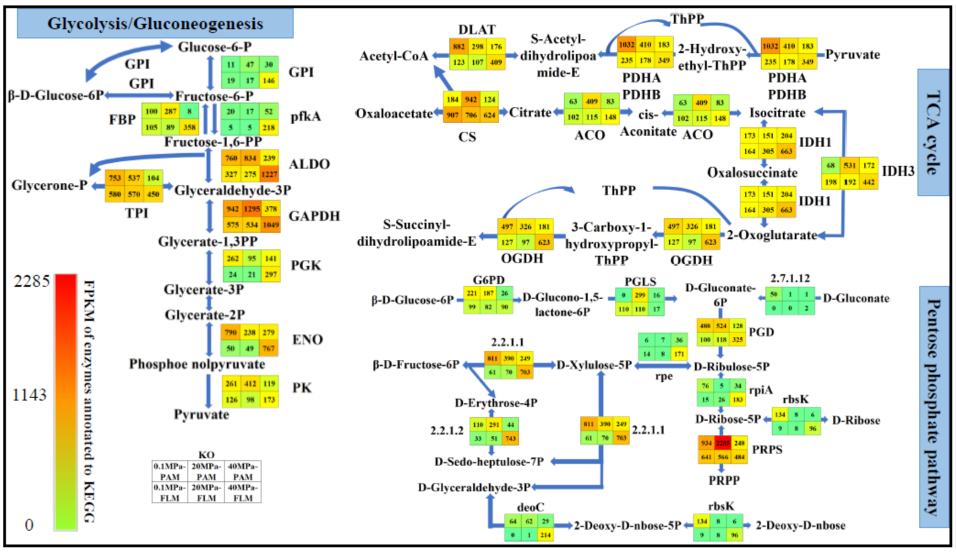

Figure 11. The differential expression of genes in three different metabolic pathways by PAM and FLM at different hydrostatic pressures (Liu et al., 2020).

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Part 2: What will we do?

2.1 Objectives

The Ocean Decade roadmap specifically calls for sustained and systematic ocean observations all ocean basins and all depths, to enable characterization of essential ocean variables and investigate natural and human-induced changes. In addition, the recently reached Agreement under the United Nations Convention on the Law of the Sea on the Conservation and Sustainable Use of Marine Biological Diversity of Areas beyond National Jurisdiction recognizes "the need to address, in a coherent and cooperative manner, biological diversity loss and degradation of ecosystems of the ocean, due, in particular, to climate change impacts on marine ecosystems, …" and also "the need for the comprehensive global regime under the Convention to better address the conservation and sustainable use of marine biological diversity of areas beyond national jurisdiction." However, only a very small proportion of the deep ocean, less than 0.01% by remote instruments, has been investigated, and biological and physical data of the deep ocean is scarce. Furthermore, marine sediment constitutes one of the largest habitats on Earth, and host abundant microbial cells roughly equal to the total number of prokaryotic microbes in the ocean and in soil. The DOME programme will build an integrated international network of research platforms to determine microbial diversity and ecosystem processes, functions and evolution, for science-informed, ecosystem-based management and sustainable use of the deep.

Objective 1: to reveal the taxonomic and genetic diversity, the core functionality and transformative power of the deep ocean microbiomes across scales and time. Microorganisms have seldom been included in ecosystem management plans and policy. This objective will change the current status of insufficient scientific knowledge on deep ocean microbiomes. DOME will increase our understanding of deep ocean microbes and their role in maintaining ecosystem health and resilience, and provide scientific guidance to meet the challenges of the 21st century in management of deep ocean ecosystems in the face of global climate change.

2.2 Key content (knowledge gaps): taxonomic and genetic diversity, core functionality and transformative power of the deep ocean microbes

The marine microbiome is the invisible majority of the ocean. Like the microbiomes that are inside our intestine and surrounding us, the proper functioning of the ocean microbiomes depends on the diversity and abundance of its microbial communities. It is estimated that the total number of prokaryotic genes identified in the ocean is similar to that of human intestine. However, the proportion of genes with unknown functions compared to that with known functions in ocean prokaryotes is more than 5 times higher than in the human intestinal microbiome, implicating the great functionality of the ocean microbes. Recent studies showed that there is a clear relationship between the ocean's health status and the state of its microbiome. The threats we are currently facing, including climate change, can affect the marine microbiomes.

The deep ocean accounts for 80% of the ocean volume and is the largest living space on Earth. Previous studies showed that the deep ocean microbes exhibited great diversity, unique physiological features, and metabolic capabilities. However, we have only investigated a very small proportion of the deep ocean, and biological and physical data of the deep ocean is scarce. There is a pressing need to advance the field toward across-scale and time-range characterization of deep ocean microbiomes, particularly in the context of ecosystem processes and functions. The majority of deep ocean microorganisms remain uncharacterized. We identify the following priority research areas for deep ocean microbiomes with multiple approaches to advance the field.

- Identify microorganisms and uncover their novelty, diversity and distributions in the water column and the seafloor sediment in different geographies, including special habitats of the ocean, e.g., the gyres, seamounts, trenches, mud volcanoes, cold seeps, hydrothermal vents, submarine canyons, the polar regions, etc.;
- Determine different components of deep ocean microbiomes based on size fractionation, including virus-enriched (<0.2 μm), free-living (0.2-3.0 μm), particle-attached prokaryotes (>3.0-5.0 μm), and single-celled eukaryotes (>5.0 μm);
- Determine the global patterns of the functional and taxonomic architecture of the deep ocean microbiomes, including those across regions and the depth stratification patterns in the pelagic water column, and the stratifying factors and environmental drivers;
- The continuum of meta-omics approach, from genomics and functional genomics to transcriptomics, proteomics and metabolomics will be utilized to conduct the global "omics" assessment of deep ocean microbiomes and explore the genetic, metabolic, functional, and structural diversity and strategies of deep ocean microorganisms;
- Develop a holistic view and understanding of the deep ocean microbiomes. DOME will determine the full extent of the taxonomic, functional, and structural diversity of the deep ocean microbiomes, to explore the evolution, ecology, and physiology of deep ocean prokaryotes (bacteria, archaea), viruses, and single-celled eukaryotes;
- Produce digital catalogs and atlases of microorganisms and metagenomes to assist research at the ecosystem scale and future bioprospecting efforts and help predict the genetic resources and ecosystem services potentially delivered by diverse and fully functioning deep ocean ecosystems in the changing world;
- Quantify biotic (e.g., taxonomic, genetic and functional diversity) and abiotic (i.e., environmental factors) variables for a mechanistic understanding of the deep ocean microbiome.
- Develop health indexes of the ocean microbiome to then build ecosystem health index, ocean health index, and genome-enabled, process-based ecosystem models to reveal and predict the state and evolution of deep ocean microbiomes and ecosystems;
- Draw up an open-access inventory of the marine microbiomes to facilitate access to all data, including those from Areas Beyond National Jurisdiction (ABNJ);
- Promote the "ocean culture" and stewardship and the essential role of the marine microbiome in the science and civil communities;
- Accelerate capacity building and establish research infrastructure and funding programs to ensure that ocean microbiome and ecosystem research benefits societies around the world, especially for those of the SIDs, LDCs, and LLDCs.
- Develop affordable instruments and protocols that can be used to generate comprehensive, reliable and long-term data on deep ocean microbiomes and ecosystems.

In addition, seafloor sediment constitutes one of the largest habitats on Earth, and host abundant microbial cells, roughly equal to the total number of prokaryotic microbes in the ocean and in soil. Recent studies showed that marine sediments harbor abundant bacterial cells as well as bacterial endospores. Our studies showed niche separation in the water column and distinct microbial communities between bottom seawater and sediment in the deep ocean. Other published work revealed close interactions between microbial communities in the water column and those in the sediment below. Therefore, it is imperative to concurrently study microbiomes in the seafloor sediment biosphere.

Objective 2: Determine the composition, organization, and architecture of deep ocean ecosystems, explore the biogeochemical basis of deep ocean ecosystem evolution, functions and services, and establish scientific and standardized and unified ocean observation approaches for assessing their state and inform sustainable management policies (i.e., ecosystem-based management).

The deep ocean is a diverse environment that ranges from deep seafloor (abyssal plains) to the rich oases that are present at seeps, vents, seamounts, trenches, and mud volcanoes, etc. Most of the deep-ocean seafloor is covered with fine-grained sediments, composed of biogenic, terrigenous, volcanogenic and authigenic particles. Therefore, the deep ocean provides a huge area of water columns, solid surfaces and heterogeneous pore spaces, as well as a highly variable geochemical, geophysical and biological environmental conditions, forming diversified deep-sea ecosystems. However, current investigations primarily focused on a few types of "hot spot" habitats, such as seeps, vents, trenches etc., leaving the majority of the deep ocean ecosystems largely unknown.

The oceanic ecosystems as a whole are experiencing substantial pressures from climate and human activities and likely reach tipping points in the function and in the services they provide to the humankind. The health and resilience of oceanic ecosystems can mitigate these stressors but it depends on their status, e.g., diversity and distribution, isolation vs. connectivity, spatial and temporal stability, functioning, etc. Our understanding of which, especially for those in the deep ocean is particularly important as the deep ocean is intimately connected to the surface ocean and represents 80% of the whole ocean volume. The fundamental problems in understanding the deep ocean ecosystems (DOEs) and addressing climate-ocean interactions and consequences include, no systematic transdisciplinary studies of the DOEs and their components (microbiomes, as described above), strong imbalance in studies between the global North and South and between ocean basins, and those that focus on the DOEs in the water column and ignoring DOEs of the sediment. DOME is set to build a robust global network to tackle geographic disparities in infrastructure, scientific research, technologies, accessing data and services, to produce knowledge-based measures to address the climate and biodiversity crises of the deep ocean. DOME will tackle the following priorities to deliver knowledge that is critical for ocean governance and sustainable management of the global deep ocean ecosystems in the face of unprecedented global change.

We identify the following priority research areas for deep ocean microbiomes with multiple approaches to advance the field.

- Conduct a comprehensive survey and mapping of the deep ocean ecosystems and determine the global extent and inventory of DOEs. As deep ocean ecological patterns and processes occur across a wide range of scales, we will map geomorphology, ecology, and microbiology over broad scales and time range to understand the state and resilience of each ecosystem, and the carrying capacity of the deep ocean ecosystems to sustain climate change.

- Determine the composition and functional structure of each deep ocean ecosystem;
- Determine the drivers and the tipping points of deep ocean ecosystem change, using molecular microbiological, geochemical, and palaeoceanographic proxies.
- Establish systematic and standardized classification schemes of deep ocean ecosystems and standardized monitoring and assessment protocols and rubrics.
- Examine microbial and ecosystem responses to natural and anthropogenic stressors, and determine the impact of multiple stressors on ecosystem evolution, functions and services.
- Conduct valuation of deep ocean ecosystems in climate mitigation and its inclusion in governance and management plans and policies
- Determine the significant role of the pelagic and benthic fungi in driving deep ocean biogeochemical cycles. Our recent isolation of piezotolerant fungi and metagenomic analysis of the sediment biosphere of the Mariana Trench implicate the important role of fungi in driving deep ocean biogeochemistry.
- A deep ocean genome-enable, process-based ecosystem model will be constructed based on interacting organisms, processes, and environmental factors to account for interactions, feedback loops and dependencies between ecosystem components, so as to predict future deep ocean ecosystem state and inform science-based decision-making for managing the ocean at the ecosystem level.

Objects 3: The past and the present holds the key to the future, an interdisciplinary study of the Most Impacted Ocean Regions (MIORs) by climate change – the Oxygen Minimum Zones

The ocean as a whole is an interconnected system between the surface and the depth vertically and between different biogeographic provinces horizontally. DOME will conduct interdisciplinary studies on selected most impacted ocean regions (MIORs) by climate change, such as the oxygen minimum zones (OMZs), using transdisciplinary approaches.

Our notion: the past and the present holds the key to the future, and the present can be a harbinger of the future. We will study the oceanography, biogeochemistry, microbiology, ecology, and evolution of the pelagic ecosystems, and the ecological and biogeochemical signatures preserved in the sediment of the MIORs. The knowledge and information gathered in these studies will provide new insight and perspectives on evolution of the oceans in facing of climate change, and develop climate analogs to understand the evolution trends and responses of modern oceans to climate forcings.

There have been multiple ocean anoxic events (OAEs) in the geological past, particularly during the Cretaceous. Today’s ocean is becoming warmer, more acidic and deoxygenated. Many water masses have recorded a marked expansion of the oxygen minimum zones (OMZs) in all oceans over the past decades, resembling exactly the model originally invoked for the genesis of the Cretaceous OAEs. As oxygen concentrations decrease, the number of habitats available to aerobically respiring organisms in pelagic and benthic ecosystems declines, resulting in changes in microbiology and biogeochemistry of these ecosystems.

Oceanic oxygen minimum zones (OMZs) are defined as low dissolved oxygen (DO) zones in the ocean, with DO either < 20 μmol/kg (OMZ20) or 60 μmol/kg (OMZ60), typically occurring in the mid-water depths (200-1,000 m). OMZs are developed by a combination of three factors, increasing in ocean temperature, increased thermal stratification, and respiration of consumers in the water column. Recent studies show that from 1960 to 2019, OMZ60 areas cover 15-32% of global ocean (Zhou et al., 2022). Assuming the trend continues as in the 1960-2019 period, OMZ60 would cover the entire the North Pacific by 2038, Bay of Bengal by 2048, equatorial Atlantic by 2051, equatorial Pacific by 2058, and Arabian Sea by 2084, singling a significant global ocean problem.

There are significant differences in microbiology, biogeochemistry, ecology and oceanography between the OMZ and the surrounding area of the sea. It seems that the expansion of OMZs in the ocean can lead to more severe consequences like development of ocean anoxic events, if other major factors come into play, such as an abrupt increase in atmospheric CO_2 due to volcanogenic activities. At the simplest level, OMZs occurred in the water column will result in sedimentary records of a concatenation of changes in sedimentology, geochemistry and microbiology, which may induce changes in the atmosphere (like removing CO_2) and restore climatic equilibrium. Therefore, a comparative study of microbial ecology and biogeochemistry of the ecosystems in the water column and the seafloor sediment would greatly increase our understanding and critical insight of the causal mechanisms of ocean deoxygenation and predict the long-term Earth systems response to climate change. Studying the microbiology, ecology and biogeochemistry of OMZs in modern ocean, particularly their imprints in sediment archives may hold the key to forecasting climate change and rapid transition of OMZs to global OAEs.

DOME will select OMZ as model systems, like those in the northeast subarctic Pacific (NESAP) and the equatorial Pacific, to conduct interdisciplinary studies on the connection and interaction of the pelagic and sedimentary ecosystems. Specifically, DOME will conduct the following studies

(1) Determine fundamental oceanographic conditions within and around the OMZ, including primary production, sea temperature, DO concentration, areal extent and depth of the OMZ;
(2) Determine OMZ microbiota, taxonomy, physiology, and metabolism;
(3) Reveal Biogeochemical processes and microbial energetics in OMZs;
(4) Reveal the interconnecting carbon, nitrogen and sulfur cycles and microbial energetics, and the released greenhouse gases (CO_2, N_2O, etc.) in OMZs;
(5) Determine geochemical signatures (stable carbon and oxygen isotope ratios, microbial biomarkers and the derived proxies) indicating environmental conditions; inorganic geochemical proxies for redox conditions, in the sediment;
(6) Construct co-occurrence networks—to determine the interactions between microbes in the OMZs and between microbes in the water column and those in the sediment under the OMZs.
(7) Build genome-enabled, geochemical process-based models to assess the potential impacts of OMZ expansion in the modern ocean marine resources and global climate trends.

Part 3: How to do?

3.1 Framework

The DOME programme is poised to pioneer the advancement and utilization of novel and evolving technologies. It aims to revolutionize the process from intact sampling techniques to real-time, on-site observations and measurements. Through the integration of diverse disciplines, DOME seeks to chart and comprehend the shifts in microbiological and ecological seascapes within the depths of our oceans. This comprehensive endeavor involves temporal and spatial monitoring to delineate the dynamic changes occurring in these uncharted realms, including the transfer of energy, matter, and information between ecosystems. One of the core objectives of DOME is to foster international collaboration among participating nations, their esteemed marine research institutions, and various stakeholders. By providing a robust framework for cooperation, it aims to unite global efforts toward increase our understanding and preserving the delicate balance of deep-sea microbiomes and ecosystems.

To achieve this, DOME is dedicated to establishing a systematic approach, fortified infrastructure and cutting-edge tools. These foundational elements are crucial in cultivating international capacities that seamlessly amalgamate the exploration and safeguarding of deep-sea ecosystems. This integration caters to the exigencies of swift observations and evaluations, driving innovation in marine science and technology. Furthermore, DOME aspires to stimulate partnerships by leveraging resources and research infrastructure. This collaborative ethos fosters an environment conducive to the advancement of scientific discovery, promoting sustainable practices, and propelling the exploration of the unknown facets of our oceans. In essence, the DOME programme stands as a beacon for pioneering deep ocean microbiome and ecosystem research and innovation. It embodies a commitment to unraveling the emergent properties, function, and evolution of the deep ocean microbiomes and ecosystems while concurrently nurturing a global network dedicated to preserving these invaluable ecosystems.

The DOME initiatives are tailored to expand public involvement in multifaceted domains, encompassing ocean literacy, education, governance, policy, and management. Its core mission is to foster broader societal engagement, ensuring inclusivity and accessibility. To realize its social objectives, DOME embraces a collaborative ethos, welcoming a diverse array of stakeholders intrigued by or gaining from deep ocean microbiome research. This inclusive approach aims not only to elevate awareness and understanding but also to cultivate active participation and support from a spectrum of interested and impacted entities. By uniting various perspectives and interests, DOME endeavors to create a collective momentum toward comprehensive exploration and preservation of the deep ocean microbiomes and ecosystems.

3.1.1 Approval of the DOME initiative/programme

To realize its objectives and social impact, DOME will rely on an array of initiatives spearheaded and executed by stakeholders. These efforts, spanning international, regional, and national programs, will involve active collaboration among governments, United Nations agencies, research institutions, and individual scientists. Together, these entities will engage in robust cooperation, leveraging novel technologies across intact sampling, in-situ observation, and measurements. Their collective aim is to craft a comprehensive global ocean sample-data system, *OceanMicrobe*, uniting expertise and resources to unravel the mysteries of the deep ocean realm.

3.1.2 Implementation and cooperation of DOME

The international alliance forged by DOME will be fortified by enhancing collaborations and interactions with prominent international entities. By engaging with NGOs and existing global initiatives, DOME aims to jointly drive scientific research and technological advancements in areas of common concerns. This concerted effort seeks to establish and refine an innovative cooperation mechanism, fostering mutually beneficial and symbiotic partnerships.

DOME envisions a series of regular symposia as a cornerstone of its implementation strategy. These gatherings will serve as pivotal platforms to deliberate various initiatives, exchange accumulated knowledge, assess progress, and identify potential synergies and collaborative avenues. The intent is to facilitate inclusive discussions and foster a culture of shared insights and experiences among all stakeholders.

Moreover, the DOME initiative remains inclusive and accessible to all potential partners keenly interested in the exploration of deep ocean microbiomes and ecosystems. This open invitation encourages a diverse spectrum of collaborators to join forces in the collective endeavor towards comprehensive exploration, conservation, and understanding of the deep ocean realms.

3.1.3 Cooperation with stakeholders

The DOME initiative plans to develop a global ocean sample-data system called *OceanMicrobe*, which is a unified big data platform integrating molecular biology data with geological, physical, and geochemical datasets. *OceanMicrobe* will enable us to link multiple project works, studying deep ocean biodiversity as well as microbiologically driven and mediated biogeochemical processes. The DOME initiative will change the way we study, understand, and manage deep ocean microbiomes and ecosystems and their responses to various pressures like pollution, habitat loss, and climate change. It involves conducting in-situ observations and sampling, establishing and enhancing standardized data and sample handling protocols, and conducting state-of-the-art meta-omics analyses (Figure 12). The resulting outcomes will provide a comprehensive description of typical deep-sea microbial and ecological environment characteristics for ocean stakeholders, including government agencies, non-profit organizations, corporations, scholars, educators, and citizens.

DOME aims to orchestrate comprehensive international joint expeditions, rallying scientists, engineers, decision-makers, funders, and enthusiasts in the global marine community to actively engage in uncovering deep ocean microbial resources and ecosystems. By collaboratively crafting scientific research agendas, collectively partaking in marine expeditions, and collaboratively generating scientific findings, it endeavors to forge strong connections between the exploration, investigation, and safeguarding of characteristic deep ocean microbiomes and ecosystems. This concerted effort seeks to foster a shared understanding and commitment among diverse stakeholders towards the discovery, preservation, and sustainable management of these unique and critical marine ecosystems. Through unified efforts and shared contributions, DOME endeavors to establish a framework that integrates expertise and resources, driving impactful advancements in the understanding and conservation of deep ocean ecosystems worldwide.

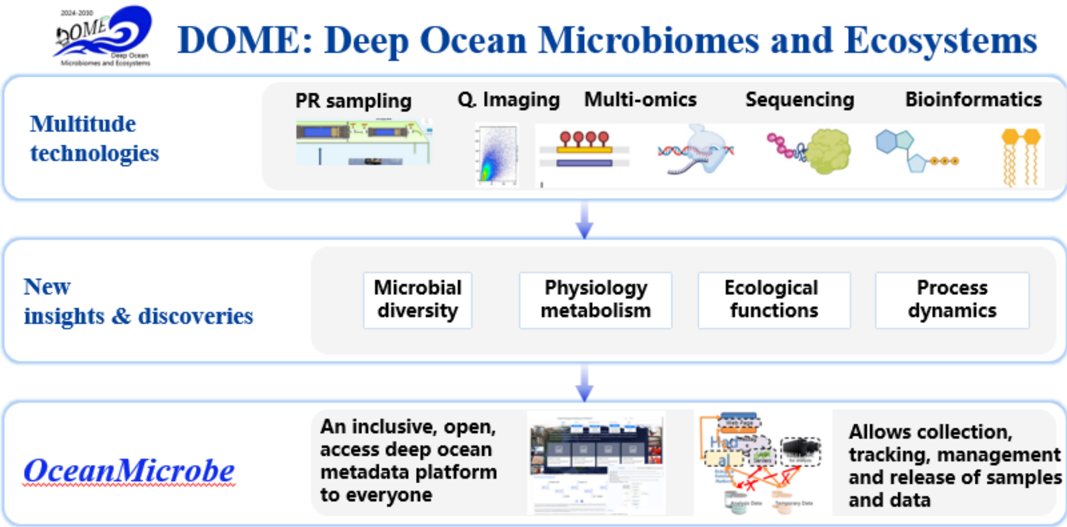

Figure 12. DOME, a Decade programme designed to characterize deep ocean microbial diversity and ecological processes in response to climate change.

3.1.4 Data and information management

The data and information generated by the DOME programme will serve as the cornerstone for achieving its objectives and societal outcomes. Establishing an inclusive, open, high-quality, high-resolution, and continuously recorded deep ocean metadata platform is pivotal. This platform will encompass research data, data analysis, and interpretations for simulating the dynamic succession of wide-ranging deep ocean microbiomes and ecosystems. It aims to track and forecast ecosystem evolution and future changes in biodiversity and ecosystem dynamics. Additionally, this platform will also include a deep ocean sample management module. This module will facilitate the timely collection, full-lifecycle tracking, management, and immediate release of specimen sample information data. It will provide international open access to online queries, shared utilization, and services for specimen sample data.

DOME will establish a portal website to introduce the international dynamics, expert courses, journal reports, videos & audios and other relevant information of typical deep-ocean ecosystems, and give full play to the social benefits of public data through a comprehensive information release mechanism. It will also use social media to actively advertise research on deep ocean microbiomes and ecosystems in a timely manner to improve science education and publicity efficiency.

3.1.5 Capacity building

DOME will carry out training and seminar activities. It will collaborate with IOC and other partners to organize international training courses, providing professional training opportunities in deep ocean microbial diversity and ecosystem research, conservation to personnel concerned in developing countries and various stakeholders. The training courses will also enhance equitable participation in deep ocean governance of SIDS, LDCs and LLDCs. Scientific seminars and symposia will be held regularly to exchange research findings and new ideas. Scholarships and exchange opportunities will also be provided to participating parties.

DOME will establish robust partnerships between local knowledge holders and scientists in project design, knowledge gathering, synthesis, management, and decision-making. These practices aim to foster greater engagement and close collaboration with local individuals and organizations. It seeks to inspire the younger generation and communities to recognize the value of ocean science research and collaboration, ultimately involving them in collective efforts towards achieving ocean sustainability and the Decade's SDGs.

3.2 Coordination

To fulfill DOME's objectives and social impact, regional and international coordination and collaboration is pivotal. The program must effectively engage government agencies, NGOs, corporations, educators, and citizens. This collective effort ensures seamless collaboration, optimizing resources for deep ocean ecosystem exploration and conservation. By aligning diverse stakeholders, DOME aims to create a comprehensive framework for sustainable ocean development, management and governance. This inclusive approach maximizes expertise and perspectives, driving impactful strategies for the preservation of our ocean depths.

DOME will establish a international steering committee (ISC) to provide coordination and operational guidance on issues such as the identification of key experts related to typical deep ocean microbiomes and ecosystems, formulation of research questions, selection of technical routes, and allocation of resources. The ISC also jointly design the coordination and implementation framework of the programme. The ISC is composed of representatives from countries/institutions closely associated with DOME (key partners) and high-level experts from the research teams. The ISC will carry out work in accordance with the terms of functions in annex III.

The DOME Management Office will be set up as the daily management body. It will be operated by the sponsor and is responsible for the overall coordination and management of DOME and administrative support.

In the forthcoming decade and beyond, DOME's research objectives will proliferate, necessitating swift adaptability to evolving needs in ocean science and management. To ensure agility, each project involved must annually furnish reports on their progress, outputs, and outcomes to the programme. Concurrently, the Steering Committee will conduct periodic evaluations of all initiatives, refining the scientific implementation roadmap as needed. This dynamic process aims to enhance responsiveness to emerging trends, needs, and advancements. Additionally, the program will continually augment its mechanism for updates, ensuring a robust structure capable of swiftly accommodating changes and ensuring alignment with evolving research landscapes and societal demands.

Part 4: What can we obtain from DOME?

DOME will build an integrated international network of research platforms, using observational, experimental, modeling, and technological approaches to determine deep ocean microbial taxonomic, genetic and functional diversity, ecosystem processes, and ocean's carrying capacity to sustain climate change. Overall, DOME will accelerate the generation and transfer of knowledge and education to all stakeholders for a richer and more holistic understanding of the deep ocean microbiomes and ecosystems needed for sustainable management of the ocean, and unlocking ocean-based solutions to climate change (Figure 13).

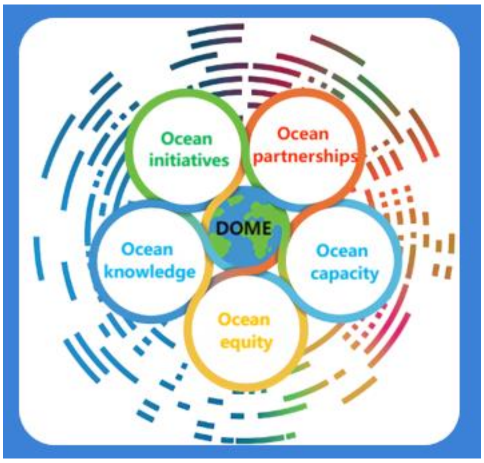

Figure 13. The DOME outcomes.

(1) Knowledge of deep ocean microbial diversity and genetic resources will be revealed and expanded. Novel microbes and their gene sequences will be revealed, cataloged and deposited in *OceanMicrobe*. The role of deep ocean microbiomes in the changes in ocean ecosystems with climate change, and the associated changes in ecosystem functions and services will be delineated; Thus, DOME will provide a more extensive and comprehensive coverage of the deep ocean ecosystems in both the water column and the sediment.

(2). The architecture of deep ocean ecosystems will be determined from environmental metadata, meta-omics data, and microbial cultures. Meanwhile, the biochemical/physical data, elemental cycles and process dynamics in deep ocean habitats and ecosystems will also be explored. DOME will be able to determine the spatiotemporal dynamics of the deep ocean microbiomes and ecosystem processes in response to global climate change, and derive cumulative human impact indexes to reveal ecosystem evolution and state, and genome-enabled, process-based models to examine the carrying capacity of deep ocean ecosystems, and guide solutions to mitigate, adapt and build resilience to the effects of climate change across the globe.

3. From different levels (gene, cell, microbiome, ecosystem, etc.), the evolution patterns of typical deep ocean ecosystems in the context of anthropogenic disturbance and global change will be studied, to improve the predictability of deep ocean ecosystems. DOME will disseminate knowledge and build partnerships between scientists, policymakers and civil society to find solutions to the immense challenges facing the ocean;

4. An effective deep ocean sample-data platform— *OceanMicrobe*, will be developed to store and share the produced metadata, gene sequences, sample information, and support global deep ocean development and management. *OceanMicrobe* will be the first such

database allowing equal, open access to all data, knowledge, and technologies for everyone everywhere.

5. Capacity building is a key outcome of DOME, and includes developing human resources, building infrastructures, sharing technologies and skills, exchanging knowledge, and finding and sharing sustained resources. A wealth of knowledge on deep ocean microbial resources and ecosystems will be generated and promoted to all stakeholders so as to train young professionals involved in deep ocean scientific research and governance and to facilitate equitable participation of SIDS, LDCs and LLDCs in deep ocean conservation and utilization.

Annex I: Endorsement Criteria for DOME Initiatives

(1) Accelerate the generation of knowledge about the global deep ocean microbiomes and ecosystems, including those in the water column and sediments, and contribute to fulfilling the Ocean Decade SDGs.

(2) Contribute to the achievement of DOME high-level objectives, including: (i). conduct long-term observation and research on the global deep-ocean microbiomes and ecosystems; (ii). integrate multisource data to create a comprehensive sample-data platform *OceanMicrobe*; (iii). reveal the diversity, core functions and transformative power of the deep ocean microbes; (iv). determine the architecture, organization, geochemical and geophysical characteristics of deep ocean ecosystems, and microbial-mediated life processes; (v). reveal multi-scale variability, stability, and resilience of deep ocean ecosystems to address the current knowledge gaps for assessing the impacts of climate change and other human activities on deep ocean microbiomes and ecosystems.

(3) Endeavors to “co-design and co-deliver” programs and initiatives with relevant stakeholders to facilitate the uptake and spread of DOME science and knowledge for societal needs.

(4) Provide a feasible implementation plan, including a list of partners, time line and expected outcomes.

(5) Avoid duplication of applications, that is, the proposed project should be clearly different from other Decade Actions, and represent a class of difficult problems that need to be solved but have not yet been reflected in the endorsed actions.

(6) Ensure the data and resulting knowledge are shared and deposited as per the DOME data and information management plan.

(7) Conduct capacity building activities among woman scientists, young scientists, especially those from SIDS, LDCs and LLDCs.

Annex II: Proposed initiatives during the DOME Feasibility Study

There are XX (XX) actions/activities with a seven-year period, which compose the substances of the DOME. All information is as of January 2024 and subject to change. Principal Investigators (PI) and contributors of the DOME programme are listed in each section.

(1) Microbial biogeography in the South Pacific Gyre.

The major ocean gyres collectively cover most of the area of the open ocean. The South Pacific Gyre (SPG) is the largest of the ocean gyres and an ideal region for exploring the nature of the water column and seafloor sediment microbial communities and ecosystem functions in the low-activity heart of an open-ocean gyre. This project aims to evaluate microbial diversity, distribution, and ecosystem processes and functions in sediment of the South Pacific Gyre. This project will provide rich knowledge and information on how gyre ecosystems, though large in area but less in surface productivity, would exert meaningful impact to global climate change in building its carrying capacity.

PI and contributors: XX. XXX; XX. XXX; XX. XXX

(2) Title of the project

The aim of this project is to xxxxx.

Annex III: Terms of Reference of the DOME International Steering Committee

The Steering Committee (SC) of DOME will provide guidance, oversight and coordination on the development and implementation of DOME, and review and recommend endorsements of new DOME project(s).

1. Functions

- Review and provide inputs to the development of DOME Science Action Plan, as well as relevant strategic documents and guidelines;
- Identify core experts, formulate research questions, and allocate research resources;
- Guide and coordinate among regional sub-committee;
- Review the development progress on DOME, and recommend actionable strategies for engagement and resource mobilization to support the development and implementation of DOME;
- Provide coordination and facilitate collaboration among relevant parties in the developments and implementation of the DOME;
- Review and recommend the endorsement of new DOME project(s);

2. Composition and terms

The ISC will consist of well-known scientists from different disciplines who are willing to participate in DOME. Meanwhile, other stakeholders could also be invited.

The initial term of the ISC members is three years, with possible extension of no more than two terms. There will be one chair or two co-chairs of the ISC, whose term and extension are the same as members. In case of resignation, inactivity or other issues affecting the operation of the ISC, he/she could recommend a successor (prefer to be from the same discipline) who will perform his/her duties for the rest of the term.

3. Meetings

The ISC meets regularly, at least once a year, and authorizes the establishment of different working groups, which may meet at any time as needed for specific work.

4. Secretariat support

The Secretariat, nominated by the lead institute and guided by the ISC, prepares and submits action plans, implementation outlines and annual reports for consideration by the ISC. It should also maintain good communication with UN/IOC to report on the implementation and progress of the programme, and guide the operation of the DSC, SDC, and DEC.

5. Regional sub-committees

Five regional sub-committees for the Pacific, Indian, Atlantic, Arctic and Southern Oceans will be established in the programme. Each regional sub-committee, composed of ISC members, project leaders and other authoritative researchers in the region, is responsible for overseeing and advancing the implementation of projects in the region to ensure that the outputs/outcomes meet the objectives of the DOME programme, and for interacting with regional stakeholders to ensure complementarity and collaboration over the region.

6. Sample and Data Center (SDC)

The DSP, under the guidance of the Secretariat, is responsible for the coordination, management, and sharing of data and samples involved in the programme, as well as the construction of a public website.

7. The DOME Science Center (DSC)

DSC will be responsible for coordinating and supporting project participants in organizing thematic seminars, symposia, and international exchange activities. Every year end DOME will sponsor the “DOME International Ocean Science and Management Symposium” (DIOSMS), a platform for cross-disciplinary dialogue among scientist, stakeholders, decision-makers, and the public, with the aim to advance fundamental understanding of deep ocean ecosystems and the influence of human activities, including climate change.