Australian and New Zealand
IODP Consortium

Ocean Planet:

An ANZIC workshop report focused on future research challenges and opportunities for collaborative international scientific ocean drilling

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Acknowledging: Participants and submissions to the ANZIC Ocean Planet workshop.

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Executive Summary

The ANZIC Ocean Planet Workshop (14-16 April 2019) and focused Working Group sessions represent a multidisciplinary community effort that defines scientific themes and challenges for the next phase of marine research using the capabilities of current and anticipated platforms of the International Ocean Discovery Program (IODP). Attended by 75 mostly early- and mid-career participants from Australia, New Zealand, Japan, and the United States, the workshop featured nine keynote presentations. Working groups identified important themes and challenges that are fundamental to understanding the Earth system. This research relies upon ocean-going research platforms to recover geological, geobiological, and microbiological information preserved in sediment and rock beneath the seafloor and to monitor subseafloor environments through the global ocean.

The workshop program was built around five scientific themes: Biosphere Frontiers, Earth Dynamics, Core to Crust, Global Climate, Natural Hazards, and Ocean Health through Time. Workshop sessions focused on these themes and developed 19 associated scientific challenges. Underpinning these are legacy samples and data, technology, engineering, education, public outreach, big data, and societal impact. Although all challenges are important, the asterisks that follow denote those of particular relevance and interest to ANZIC.

Ocean Health through Time comprises the ocean's response to natural perturbations in biogeochemical cycles*; the lateral and vertical influence of human disturbance on the ocean floor; and the drivers and proxies of evolution, extinction, and recovery of life*.

Global Climate entails coupling between the climate system and the carbon cycle; the drivers, rates, and magnitudes of sea level change in a dynamic world*; the extremes, variations, drivers, and impacts of Earth's hydrologic cycle*; and cryosphere dynamics*.

Biosphere Frontiers addresses the habitable limits for life*; the composition, complexity, diversity, and mobility of subseafloor communities*; the sensitivity of ecosystems to environmental changes; and how the signatures of life are preserved through time and space*.

Earth Dynamics: Core to Crust encompasses the controls on the lifecycle of ocean basins and continents*; how the core and mantle interact with Earth's surface*; the rates, magnitudes, and pathways of physico-chemical transfer among the geosphere, hydrosphere, and biosphere*; and the composition, structure, and dynamics of Earth's upper mantle.

Natural Hazards involves the mechanisms and periodicities of destructive earthquakes*; the impacts of submarine and coastal volcanism; the consequences of submarine slope failures on coastal communities and critical infrastructure*; and the magnitudes, frequencies, and impacts of natural disasters*.

The ANZIC Ocean Planet Workshop will contribute to formulating the next science framework for scientific ocean drilling which in turn will guide the focused planning of specific drilling, logging, and monitoring projects.

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Preface

With about 60% of Australia's and 95% of New Zealand's territory offshore, our two nations' vast oceans are central to the heritage, heart, and economic future of our countries. Despite their importance, much of our ocean territories remains unexplored and poorly understood. A challenge for the 21^{st} century is to manage our oceans sustainably so we can continue to enjoy the economic, environmental, social, and cultural benefits they provide for generations to come. As such, our countries share common marine research needs that recognise the value of international collaborative ocean science including participation in the International Ocean Discovery Program (IODP).

Scientific ocean drilling through the IODP is a continuation of the world's longest running and most successful international geosciences research collaboration. International scientific ocean drilling celebrated its 50th anniversary in 2018. The IODP operates deep-sea drilling platforms to collect continuous core samples of sediments and rocks and borehole data from below the sea floor for dedicated research purposes and for the benefit of society. A carefully developed, rigorous science framework is a key contributor to the outstanding success of the IODP, and the current plan - *Illuminating Earth's Past, Present and Future* - ends in 2023.

Planning for the next science framework post-2023 is happening and includes six planning workshops seeking input from the global science community. As one of IODP's twenty three international partners ANZIC was honored by being invited to host one of the workshops. The workshops both reviewed ongoing needs from the current plan and developed new ideas for the next framework. The outcomes from the six workshops are being used to inform the development and finalization of the next framework.

This report contains the result of the ANZIC workshop – the ANIC Ocean Planet Workshop held in Canberra, ACT, Australia between the 14-16 April 2019. Congratulations and thank you to Kelly Kenney, Larisa Medenis and Leanne Armand who organised what was a very successful workshop. On behalf of the ANZIC Governing Council, thank you to all the participants who contributed to the success of the Workshop. We can be confident our input will be well received by IODP and be reflected in the new framework.

Ian Poiner, Chair, ANZIC Governing Council

The International Ocean Discovery Program (IODP) is the world's largest and most successful geoscience research and training program. Scientific ocean drilling samples geological materials from the deep subsurface, obtains continuous records of past events spanning millions of years of Earth's history, and monitors active geological processes with *in situ* laboratories. Australia has been a member of the IODP (and its predecessors) since 1988 and a consortium leader with New Zealand since 2013. IODP membership is a success story for both Australian and New Zealand researchers and our respective nations.

Australian and New Zealand marine research have proud histories, supported by increased national collaboration and infrastructure, and developing wide leadership across our diverse marine environments spanning the tropics to the Antarctic and across the Indian and Pacific Oceans, and more generally to the singular global ocean and marine environment. Therefore, international marine research activities provide the highly translational knowledge base that underpins our choices to support national and international management and policy changes, understand geological processes that impact Earth's evolution and our lives, and invite resource protection or utilization, all essential for Australia and New Zealand to fulfil and benefit from our blue economy potentials.

Guided by global, community-driven science plans, the scope of the 50-year program has grown to encompass more than geoscience. The IODP now incorporates nascent geobiology and interdisciplinary molecular biology. ANZIC members have always contributed to the development of successive science plans for scientific ocean drilling, which have provided the scientific framework and foci for global marine geoscience research questions that have stimulated expeditions of successive generations of international research teams.

This report contains the ANZIC community's continued enthusiastic engagement with, and input into, the next Strategic Framework for international scientific ocean drilling. The report summarizes community input from the ANZIC Ocean Planet Workshop held in Canberra, ACT, Australia, between the 14-16th April 2019 (Appendix 1), and includes input through community consultation (Appendix 2). The results of the Ocean Planet Workshop were published shortly after the event in EOS (Appendix 3). The report highlights the scientific questions that ANZIC researchers, and in particular early and mid-career researchers, have highlighted as challenges that future geoscience and biogeoscience research from scientific ocean drilling can or should aim to answer.

Into the future, international scientific ocean drilling will contribute to the knowledge concerning ocean health and planetary exploration science. Australian and New Zealand's continued membership will allow us to lead the way in answering fundamental questions about Australasian and Antarctic geological history, context, and future, including climate, faunal, and floral impacts.

This ANZIC Ocean Planet report clearly outlines the future scientific initiatives that Australian and New Zealand researchers have projected our nations' interests, global leadership opportunities, and future international collaborations. It is a voice that will be captured and amplified in the next strategic framework that will guide scientific ocean drilling through to 2050.

Leanne Armand, ANZIC Program Scientist
ANZIC Ocean Planet Workshop Canberra, Australia

Introduction and Context

Scientific ocean drilling provides the only means of accessing valuable samples and data from more than a few tens of meters beneath the seafloor, to conduct experiments in the deep sub-seafloor, and to monitor ongoing processes in deep sub-seafloor environments.

Long range planning has been integral to scientific ocean drilling since 1981. Efforts now underway among the 23-member nations of the current International Ocean Discovery Program (IODP; 2013-2023) are aimed at developing a new science framework for the next phase of international scientific ocean drilling. The ANZIC Ocean Planet Workshop is one of several national (e.g., China, Japan, USA) and consortia (e.g., ANZIC, ECORD: European Consortium for Ocean Research Drilling) workshops held in 2019 that are providing input for formulation of the new science plan that is scheduled to be finalized in 2020. The IODP Forum bears overall responsibility for producing the new science plan.

Scientific ocean drilling was initiated by the USA as the Deep Sea Drilling Project (DSDP; 1968-1983), and DSDP formally included international partners during the International Phase of Ocean Drilling (IPOD; 1975-1983). During DSDP no international long-range planning was conducted. Although Australian and New Zealand scientists joined DSDP expeditions on the DSDP's sole drilling platform, the *Glomar Challenger*, it was not until during the Ocean Drilling Program (ODP; 1985-2003) that Australia formally joined international scientific ocean drilling efforts, in 1988, as part of the Pacific Rim, or PacRim, Consortium consisting of Australia, Canada, Chinese Taipei, and South Korea. As with DSDP, ODP operated a single drilling platform, *JOIDES Resolution*."

Long-range planning for ODP was undertaken at two major international conferences: the Conference on Scientific Ocean Drilling I (COSOD I) in 1981, and the COSOD II in 1987. Using reports from these two conferences, together with input from the ODP science advisory structure and other scientific and technical advice, Joint Oceanographic Institutions Inc (JOI) produced ODP Long Range Plans in 1990 and 1996.

International scientific ocean drilling underwent a step change in 2003, evolving from a single-platform (USA) to the multi-platform (ECORD, Japan, USA) Integrated Ocean Drilling Program (IODP; 2003-2013). Three conferences provided input for the first-ever decadal science plan for scientific ocean drilling, the *IODP Initial Science Plan: Earth, Oceans, and Life*. The Conference on Cooperative Ocean Riser Drilling (CONCORD), held in 1997, formulated new scientific objectives requiring riser drilling on the *Chikyu*, and defined the strategies and technology needed to achieve these goals. The Conference on Multi-Platform Experiments (COMPLEX), convened in 1999, defined globally important scientific objectives through riserless drilling in the oceans on the *JOIDES Resolution*. The Alternate Platforms Conference (APLACON), held in 2001, addressed scientific themes that required technologies on 'Mission Specific Platforms' (MSPs) other than those provided by *Chikyu* and *JOIDES Resolution*. Australia and New Zealand joined IODP as ANZIC in 2008.

Decadal planning for the current incarnation of international scientific ocean drilling, the International Ocean Discovery Program, was undertaken at the IODP New Ventures in Exploring Scientific Targets (INVEST) conference held in 2009. INVEST provided input for the current decadal science plan for scientific ocean drilling: *Illuminating Earth's Past, Present, and Future (The International Ocean Discovery Program, 2011)*.

Australia and New Zealand have been both informal and formal members of international scientific ocean drilling efforts for longer than any other nation in the Southern Hemisphere. ANZIC scientists have vast expertise and experience in researching the geology, geobiology, and microbiology of the Earth beneath the Southern Ocean, the Southwest Pacific, and the Indian Ocean, that is half of our ocean planet. Therefore, ANZIC's contributions to the next science framework for international scientific ocean drilling are vital to the future program's success.

This report outlines the five research themes and accompanying 19 challenges formulated at the ANZIC Ocean Planet Workshop in April 2019, addressing first-order questions about the sub-seafloor biosphere, geodynamics, climate, natural hazards, and ocean health (Figure 1). They provide a blueprint for future research objectives that will enable us to advance our critical knowledge to help address some of today's and tomorrow's most pressing environmental challenges.

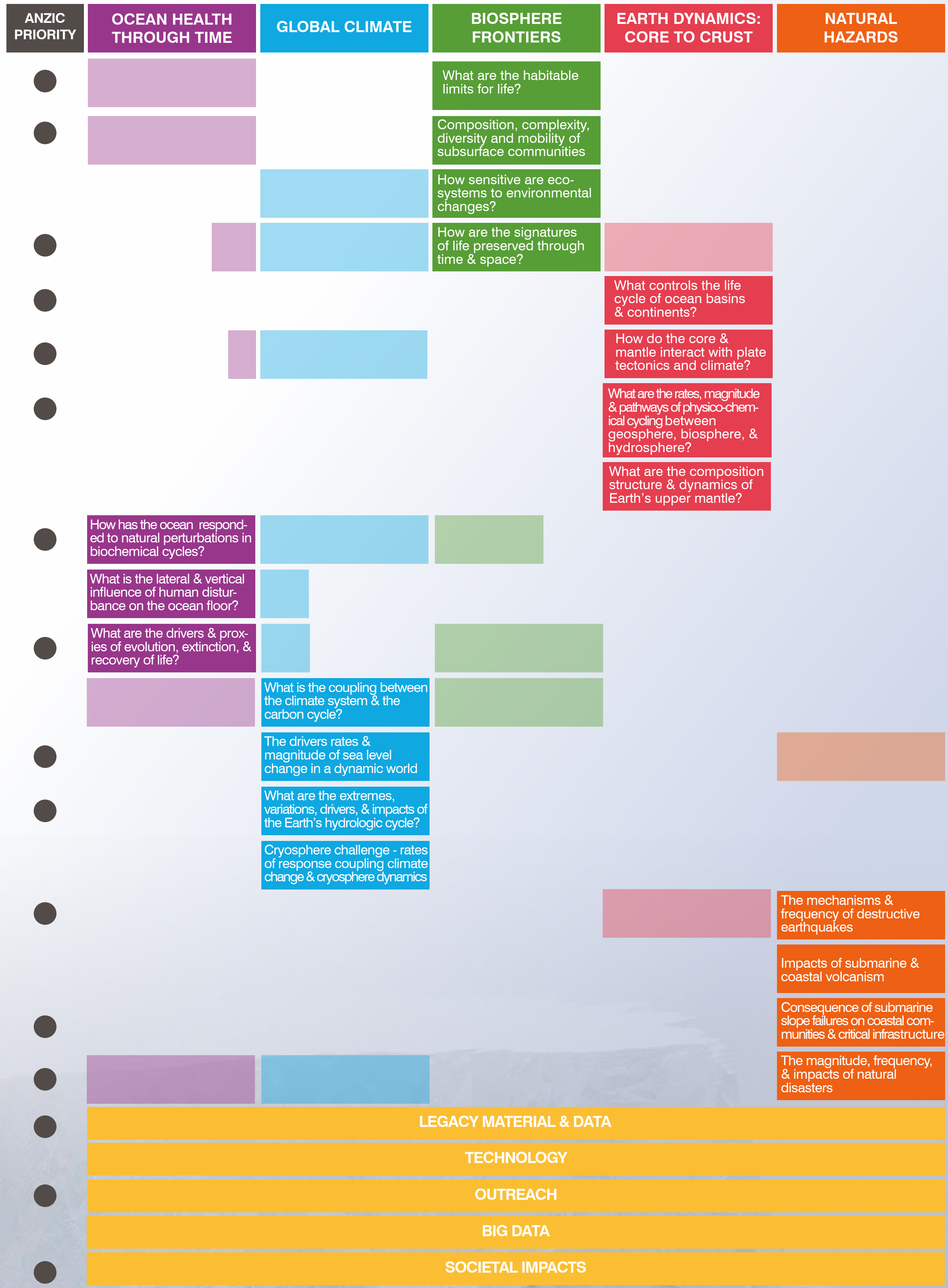


Figure 1. Ocean Planet community-derived interests are championed under the five research themes covered by the workshop, with the 19 major challenges identified by the statements under each theme that are detailed in this workshop report. Proportional cross-relational linkages identified between the themes and specific challenges are shown by additional colored boxes under related theme columns. Participants recognized ANZIC-specific priorities that are shown by black dots. Five broad universal underpinning platforms (yellow bars) support all themes in terms of the delivery of the challenges and should be considered in the development of the next science framework for scientific ocean drilling.

THEME 1: Ocean Health Through Time

The geological record preserved in marine sediments contains evidence about how the oceans have changed through time. In particular, changes in biogeochemical cycles that have driven the abundance, diversity, and recovery of life following mass extinctions are documented in the rock record. This new theme has been developed to explain the interactions between life and the environment over geological timeframes and the response of biological activity to natural perturbations. For the Anthropocene, human-impacted perturbations will also be explored. The objectives of this theme closely align with those of Theme 2 (Global Climate), and the scientific challenges that they address have some overlap. However, whereas Global Climate focuses on the drivers that impact and influence climate change, Ocean Health examines the impact of those climatic changes on life. This understanding of past environments and more recent impacts will provide information about the likely response of the ocean-biosphere system to modern changes in ocean chemistry and Earth's climate.

Challenge 1: How has the ocean responded to natural perturbations in biogeochemical cycles?

The Earth is generally regarded as a closed system for naturally occurring material. Biogeochemical cycles of carbon and other significant elements such as nitrogen, oxygen sulfur, phosphorus, calcium, iron, mercury, selenium, and silica comprise the fluxes of elements between different parts of the Earth, ranging from biotic to abiotic processes, from the atmosphere to terrestrial and oceanic environments. Each cycle involves a large variety of pathways and reservoirs where elements may be stored for varying intervals of time. In particular, sedimentary rocks contain the most detailed records of past life and biogeochemical processes. Reconstructions of these records have the potential to reveal interactions between life and the environment over geological timeframes. Understanding past environments also provides information about the response of the ocean-biosphere system to natural perturbations over Earth's history.

Some of the most pressing questions are:

- What are key biological, chemical, and geological controls of oxygen levels throughout Earth's history?
- What are the biological, chemical, and physical processes that have controlled the partitioning of various elements among the oceans, land, and atmosphere in the geological past?
- How did biological, chemical, and geological processes interact with Earth's climate in the geological past?
- Can we understand the cycles of trace elements in the oceans?

By combining disciplines including organic and isotopic geochemistry, microbial paleogenomics, geology, paleontology, palynology, sedimentology, and the latest modelling tools, we will be able to reconstruct ancient ecosystems and trace the evolution of biogeochemical cycles through time. This multidisciplinary approach will help us to understand the processes that control, for example, oxygen concentrations in the atmosphere and oceans, ocean acidification, the evolution of multicellular life, mass extinctions (Challenge 3), and the formation of valuable minerals and other resources. Further, it is critical to continue to develop new models that allow marine ecosystems and biogeochemistry to be accurately linked to global ocean circulation models. These are used to study the role of ocean circulation and its variability in controlling and modulating global biogeochemical cycles and the interplay between climate and biogeochemical processes.

Challenge 2: What is the lateral and vertical influence of human disturbance on the ocean floor?

We currently live in the Anthropocene, an epoch subject to the dominant influence of humans on climate and the environment (Zalasiewicz et al., 2015). It is now widely accepted that increased global emissions of CO_2 since the industrial revolution have been a critical driver of human-induced climate change. Furthermore, the oceans and the sediments being deposited on the ocean floor are also being impacted by, for example, the production of long-lasting human-made materials. These materials include Persistent Organic Pollutants (POPs), pesticides, biocides, plastics, and pharmaceuticals including antibiotics (Ritter et al., 2007; Bakir et al., 2014), which are resistant to environmental degradation.

In recent years, attention has been focused on the fate of plastics in our waterways from rivers to the continental shelf and into the deep ocean (Thompson et al., 2004; Figure 2). It has been predicted that plastics, particularly microplastics, will be distributed globally – from the atmosphere (bound to particles), through terrestrial systems to the deep ocean floor. Where these (micro)plastics accumulate in sediments, they will be 'fossilized' and will serve as a key stratigraphic marker of the Anthropocene (Zalasiewicz et al., 2016).

Very little is known about the impact of POPs and other contaminants on the chemistry of our oceans and the benthic ecosystem. Questions that arise include:

- What is the rate and extent of vertical migration of man-made pollutants in the sedimentary column?
- What is the impact of pollutants on the subseafloor biosphere?

To fully understand the impact of contaminants in the oceans, we require baseline studies to ensure the rates and magnitudes of change. Such studies should include an array of scientific disciplines, for example, microbiology, genomics, biology, geology, chemistry, organic and inorganic geochemistry (including dating and stable isotopic tools such as clumped isotopic analysis). By identifying chemical proxies and biogeochemical signals for man-made pollutants, and comparing the pre-Anthropocene with modern sediments, we will be able to accurately assess anthropogenic impacts on our planet's health.

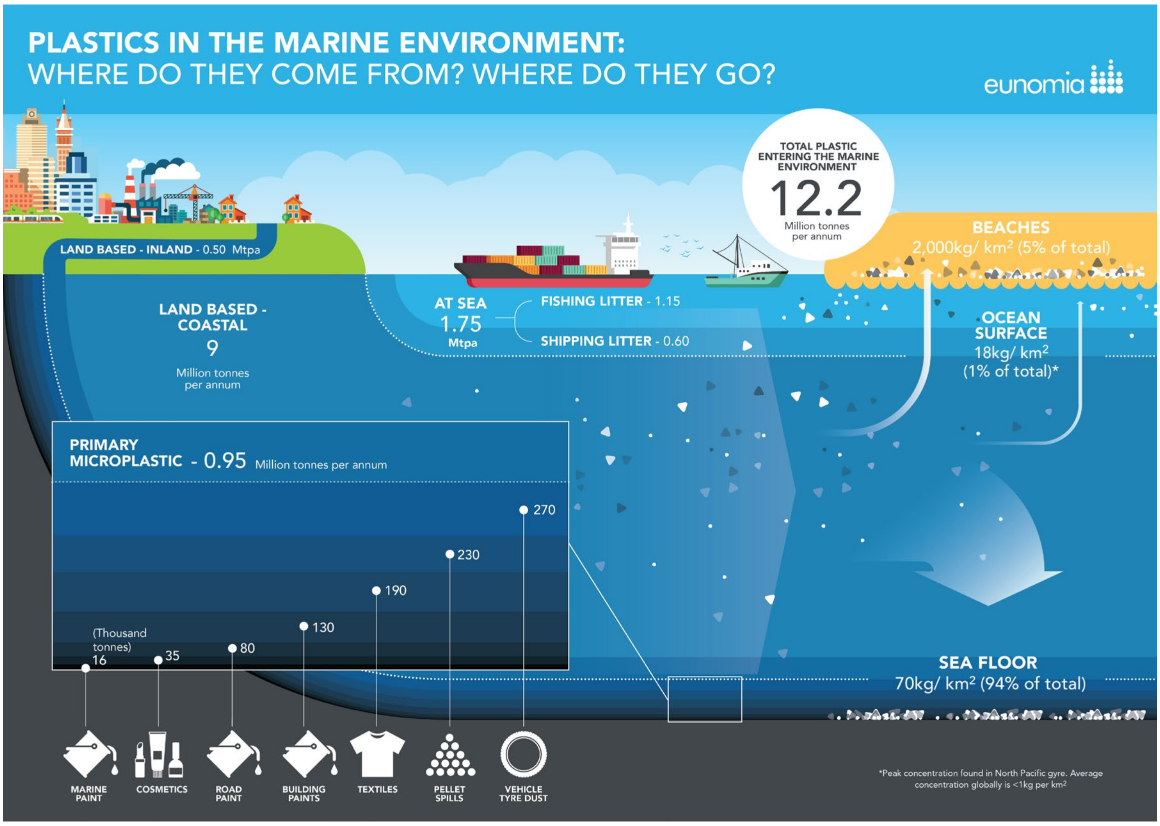


Figure 2: The quantity of plastics in our environment including how much reaches the sea floor. Around 80% of all plastics annually derive from the land, mainly in the form of mismanaged waste (e.g. plastic packaging and drink bottles). The other 20% is from plastics released at sea largely from the fishing industry and shipping. Some 94% of this plastic in the ocean ends up on the sea floor. Accumulation of 70 kg of plastic per square kilometre of sea bed has been estimated. Plastic concentrations are high at some mid-ocean localities with the highest recorded at North Pacific Gyre (https://www.eunomia.co.uk/reports-tools/plastics-in-the-marine-environment/). Illustration courtesy Eunomia Research & Consulting's 2016 public report " Plastics in the Marine Environment".

Challenge 3: What are the drivers and proxies of evolution, extinction and recovery of life?

Earth's history is marked by many mass extinctions of varying magnitude, and diverse drivers, that changed life's trajectory, as depicted in Figure 3. Mass extinctions are defined as a global event or a combination of smaller events (over a relatively short geological time span) when more than 75 % of estimated species on Earth are destroyed (Wiese and Reitner, 2011). Large igneous provinces (LIPs; due to increased magmatic activity associated with the aggregation and segregation of supercontinents) correlate temporally with all but one (end-Ordovician) mass extinction event, suggesting that massive volcanism could be a major contributor, but not necessarily the only cause. For example, the end-Cretaceous extinction correlates temporally with both a LIP (Deccan Traps) and a bolide impact (Chicxulub). Fossil and geochemical evidence tends to suggest that the end-Permian, end-Devonian, end-Cretaceous and end-Triassic events were prolonged periods of biotic stress triggered by a combination of tectonically induced hydrothermal and volcanic processes, leading to eutrophic oceans, global warming, sea level rise, and global anoxia (Figure 3).

The consequences of abrupt global warming, generally associated with most extinction events, are considered to have been mainly harmful to the biosphere (especially the marine ecosystem) in the geologic past. When ecosystems are devastated on a global scale, communities are reorganized and some distressed organisms can eventually recover. All extinctions are followed by recovery, yet research on patterns of biological and ecological recoveries are rather limited. It is assumed that recovery after a major extinction is repressed and prolonged by a succession of extinction pulses, as well as the long-term environmental stress encountered by surviving organisms. Mass extinctions are among the few readily recognisable turning points in the evolution and recovery of life on our planet and they serve as analogues for understanding ecological responses in marine and terrestrial systems (e.g., Twitchett et al., 2001) to probable shifts in environmental change (Hönisch et al., 2012). Current extinction rates (and their predicted trends) due to global warming and related stresses are higher than nearly all those documented over the entire Phanerozoic era (~540 million years), implying that global ecosystems may be approaching a planetary-scale acute 'tipping point' due to anthropogenic activities (Barnosky et al., 2011), as described under Challenge 2.

Low-oxygen, low-nutrient regions also known as "oceanic dead zones" or "oxygen minimum zones" have been increasing since the 1950s. Such conditions along with ocean acidification are highly toxic to marine life. Similar environmental conditions have been recorded across several ancient extinction boundary events, especially from outcrop samples and cores representing the ancient shorelines of supercontinents (e.g., Grice et al., 2005; Jaraula et al., 2013; Kasprak et al., 2015). However, we still lack deep-time cores from extinction boundary events, in particular for the Triassic and older. Deep-time cores will provide high-resolution archives of mass extinction, recovery, and evolution of life (e.g., Lowery et al., 2018). Furthermore, it is now possible to reconstruct the evolution and recovery of life in unprecedented detail with the advent of highly sophisticated techniques, e.g., tandem mass spectrometry tools; compound specific stable isotope technologies (C, H, N, S) of biomarkers/biomolecules, polycyclic aromatic hydrocarbons distributions associated with fire, fungal, algal, or plant sources or even hydrothermal processes (Whiteside and Grice, 2016); inorganic isotope proxies (e.g., clumped isotopes of carbonates); various novel dating tools, including paleontology and palynology approaches and in some cases paleogenomics.

Results of this research challenge will accurately inform the community and policy makers on how the Earth and its ecosystems respond to catastrophic events, the probable analogous contemporary conditions that the human race may be confronted with, and the foundations of mitigation actions. Identification of change impacts on biodiversity and perturbations of ocean circulation, along with global acidification, will have dramatic consequences for the marine ecosystem and the many industries (e.g., fishing) reliant on its sustainability.

In addition, most of the world's population live in coastal regions. Climate change-related risks include more frequent sea level rise, inundation and subsequent flooding. The results stemming from this challenge will further provide fundamental knowledge that will assist local decision makers directly dealing with environmental risks in coastal zones.

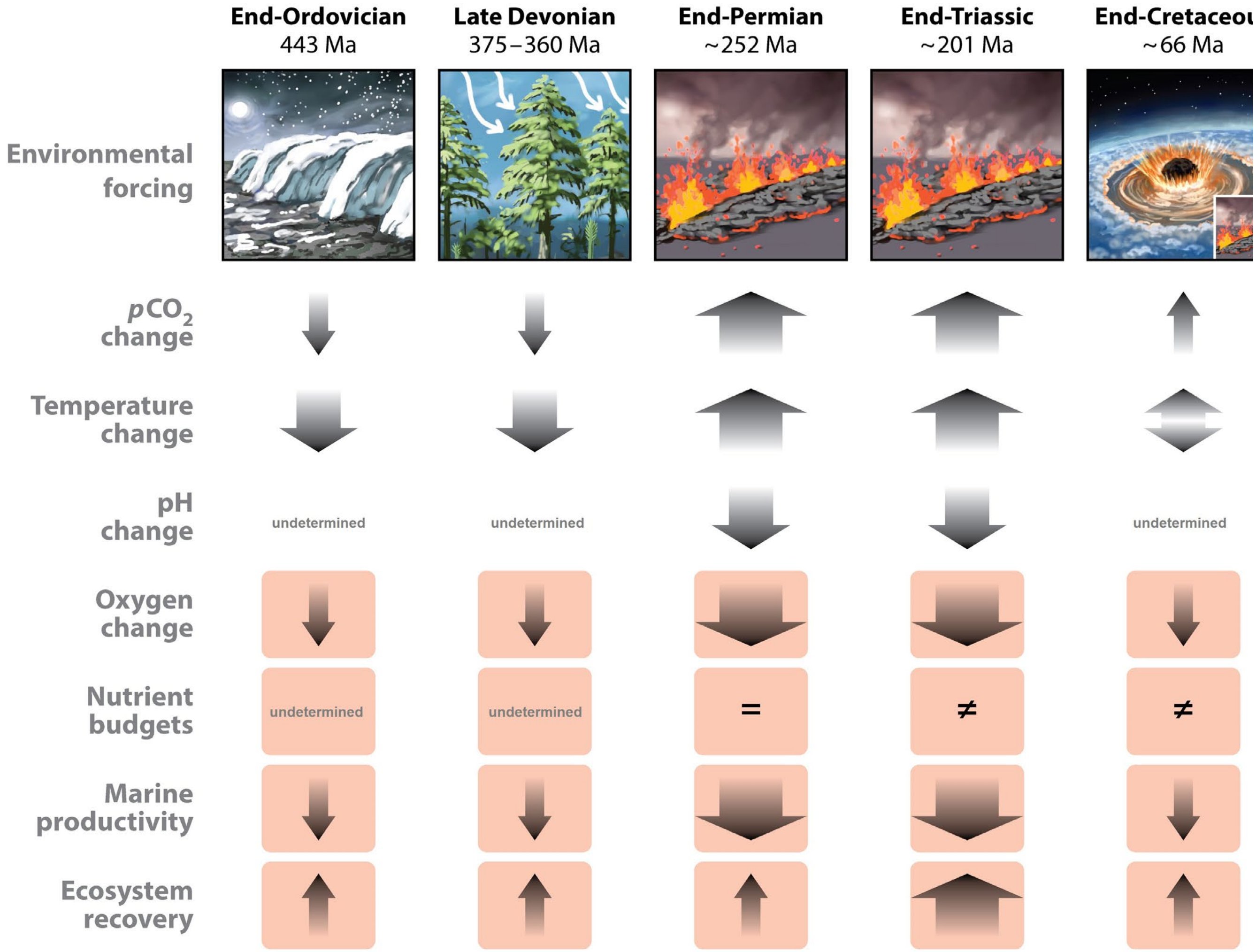


Figure 3: Environmental forces associated with the big five mass extinctions (after Whiteside and Grice, 2016). All mass extinctions events are associated with widespread volcanism, with the exception of the end-Ordovician. The end-Cretaceous extinction was triggered by volcanism related to a meteorite impact. In recent years, palynology and paleontology along with stable isotopes of carbonates, sulfide minerals, individual biomarkers, and organic matter, have helped to provide evidence for various environmental forcings.

ANZIC PRIORITIES

This new theme has particular relevance to the ANZIC consortium, since changes in the marine environment may have significant impact on well-being. Because most of our population live in coastal regions, predictions of sea level variations, plus likely changes in ocean acidification, biodiversity, and ocean circulation, have major implications for population distribution (ocean inundation and flooding) as well as for marine industries such as fishing. Thus, the outputs from this challenge will provide fundamental knowledge that will assist local decision makers directly dealing with environmental risks in coastal zones.

In addition, the oceans surrounding Australia and New Zealand include regions that likely contain sections through mass extinction events (e.g., end-Permian and end-Triassic off western Australia; end-Cretaceous on the Kerguelen Plateau), ocean anoxic events (Great Australian Bight, Kerguelen Plateau, Naturaliste Plateau), and terrestrial climatic variations that occurred during the Cretaceous period on the recently identified Zealandia.

THEME 2: Global Climate

The field of paleoceanography reconstruction largely originated from advances in scientific ocean drilling, which has identified numerous baseline shifts in climate and the oceans through geological time. With the current concern around anthropogenic climate change and our desire to determine the degree of impact, it is critical that we build high resolution models based on geological data that allow us to interrogate and predict key processes and tipping points in our evolving climate (Figure 4). Whilst Theme 1 examines the impact on life and the limits of habitability of a changing Earth, this theme uses the geological record to determine and track the drivers that have caused complex changes in the global climate through time. With increasing complexity of Earth system models that are capable of coupling atmospheric, biological, oceanic, and cryospheric processes, we are now better equipped to develop targeted drilling campaigns to test model-based hypotheses. Such campaigns will also help identify underrepresented or missing processes in models. Consequently, scientific ocean drilling remains a critical component for resolving uncertainties relating to Earth system sensitivity under future climate change.

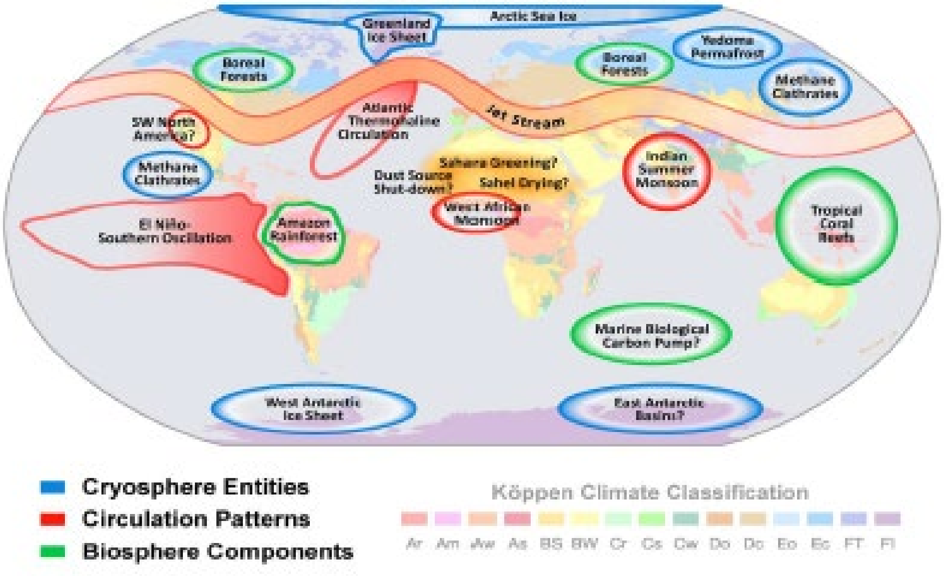


Figure 4: Tipping points in the Earth climate system. Source: Postdam Institute for Climate Impact Research, 2017.

In 2018, atmospheric CO_2 concentrations exceeded 410 ppm, and are predicted to exceed 900 ppm by 2100 (IPCC Relative Concentration Pathway (RCP) scenario RCP8.5). From scientific ocean drilling, we have been able to grasp just how significant these concentrations are, with most proxies indicating it has been at least 3 million years since atmospheric CO_2 concentrations have exceeded 400 ppm, while 900 ppm represents the approximate atmospheric concentrations during the peak of the Cenozoic “greenhouse climates” of the mid Eocene (~50 Ma). The implications of this input of carbon dioxide into the atmosphere for Earth system sensitivity remains unknown, due to the complexities of feedbacks associated with the carbon and hydrological cycles, biochemical processes, and variability in the cryosphere. Scientific ocean drilling has provided a key portal into understanding Earth’s climate history through a global network of seafloor sediment cores. Critically, reconstructions obtained from these geological archives inherently include all feedback processes in the Earth system.

To gain a fuller understanding of Earth system response to perturbations in radiative forcings, we require records that cross gradients: from the pole-to-equator, land-to-sea, and shallow-to-deep-waters. The development of targeted, transect-based drilling campaigns, focused on hypothesis-testing or improved understanding of processes, remains one of the most important tools to understand drivers of atmospheric and ocean circulation, and teleconnections in an evolving climate. Such studies are required at a range of spatial and temporal scales. Where feasible, high-resolution analyses may allow for identification of tipping points in the climate system, although such analyses must be of sufficient resolution to separate non-linear behaviors from the long-term mean climate state.

Drilling approach: An integrated approach, using model-based hypothesis from increasingly complex Earth system models coupled to ice sheets, biological systems, and the carbon cycle, is needed to guide pole-to-equator drilling transects in regions of greatest uncertainty. Such transects must target key paleowater depths to determine ocean circulation and heat redistribution processes through a range of climate boundary conditions. To assess the relevance of these paleo-records for future climate changes, the full suite of processes that could alter ocean structure in the geological past needs to be accounted for (e.g., tectonics and mantle processes versus cryosphere feedbacks).

Within this broad framework, we identify four key Challenges as of particular importance for future scientific ocean drilling research on the theme of Global Climate. All four challenges in this theme overlap significantly, highlighting the interconnected nature of Earth's climate system.

Challenge 4: What is the coupling between the climate system and the carbon cycle?

Understanding the full Earth system response to changing atmospheric composition is a key societal challenge for the future. Warming associated with increased CO_2 in the atmosphere could lead to perturbations of other aspects of the global carbon cycle (CH_4) and to changes in other greenhouse gases (H_2O and N_2O) resulting in large-scale positive or negative warming feedbacks (e.g., thawing of permafrost, disassociation of gas hydrates, changes in ocean ventilation and biological pump; Figure 4). Consequently, understanding the complexity of these carbon cycle feedbacks using records of past climates is an essential tool to estimate the global average increase in temperature per doubling of carbon dioxide (i.e., climate sensitivity).

The role of fast (e.g., changes in sea ice, permafrost, vegetation, biological systems) and slow (e.g., tectonic plate movements) Earth system feedbacks in amplifying or dampening climate sensitivity remains poorly quantified. The natural carbon cycle is governed by changes in the rates of ocean ventilation relating to upwelling, and also in land to sea exchanges of carbon due to changes in vegetation cover and continental weathering. Ocean records capture terrestrial runoff allowing for reconstructions of land-to-sea carbon cycle dynamics.

Identifying unquantified or inadequately quantified carbon reservoirs (e.g., seafloor carbon) that may become more mobile as climate warms is another critical area for investigation. Better understanding of the physical climate system and the sources, sinks, and fluxes of carbon may provide valuable insights into the consequences of mitigating carbon hazards via geoengineering.

This challenge provides direct crossover into the **Ocean Health Through Time** theme by identifying perturbations in biogeochemical cycles, as well as understanding the climate history that may have driven biological turnover in the past. Cross over into the **Earth Dynamics** theme is achieved through a requirement to understand processes related to long-term carbon cycle changes, such as silicate and carbonate weathering, volcanism and subduction, and paleobathymetry (e.g., continental shelf extent).

Challenge 5: What are the drivers, rates, and magnitude of sea level change in a dynamic world?

The rate of modern sea level rise continues to accelerate, with a sea level rise of up to 0.82 m by 2100 projected by the IPCC. However, this excludes a contribution resulting from the collapse of the marine-based sectors of the Antarctic Ice Sheets (AIS), which observations suggest is accelerating, potentially leading to irreversible retreat and a long-term sea level rise over several centuries to millennia. Current models vary significantly in estimates of potential future contributions from the AIS. However, ice sheet models calibrated by paleo-data (obtained from previous drilling, e.g., IODP Expedition 318) suggest an additional 1 m contribution from Antarctic melt is physically plausible, depending on the ice sheet physics employed and treatment of uncertainties associated with paleo-data used to calibrate these models. Projections beyond 2100 also demonstrate a wide spread of values, although most models indicate stabilization of ice sheet retreat and minimal loss under RCP 2.6 (<20 cm), or accelerated retreat of marine-based sectors of the AIS under RCP 8.5, with several meters contribution by 2300. Consequently, determining the rates, and magnitudes of sea level change from past ice sheet retreat remains relevant for calibration of models used to project future sea level rise.

Coral reef records (e.g., IODP Expeditions 310, 325) have revealed sea level rise rates of ~1 m per century occurred through the last glacial termination, but were punctuated by rapid discharge events where rates approached 4 m per century. However, it remains ambiguous which ice sheets contributed to these rapid sea level events, and whether the current ice sheet configuration is susceptible to such retreat. Reducing uncertainties and determining rates and magnitudes of retreat during a range of warmer-than-present climate scenarios remain challenges and should be core foci of future scientific ocean drilling research.

Eustatic sea level changes have a range of drivers, and scientific ocean drilling has the potential to determine these. Relative sea level deviations from eustatic sea level are a critical factor to isolate, and can result from a range of tectonic, mantle dynamics, and sediment loading processes (Figure 5). Deviations from eustatic sea level can also result from Glacial Isostatic Adjustment (GIA) processes, and sea level fingerprinting methods using GIA sea level models can identify possible sources of ice melt. However this requires a portfolio of globally distributed records of sea level change from coral reefs and continental margins, coupled with direct measures of ice extent from the polar regions obtained from geologic drilling.

Deep sea and shallow rift basin records contain oxygen isotopic tracers that provide critical continuous records of changing global ice reservoirs through time. However, these are complicated by temperature signals (which vary between ocean basins) and cannot identify source regions of ice – or the relative contributions of marine-based vs terrestrial-based ice (and therefore calibration to eustatic sea level variance). These valuable proxy records of sea level are still critical to obtaining and refining uncertainties, but require complementing by independent measures of sea level, and direct measures of ice sheet variance in either hemisphere.

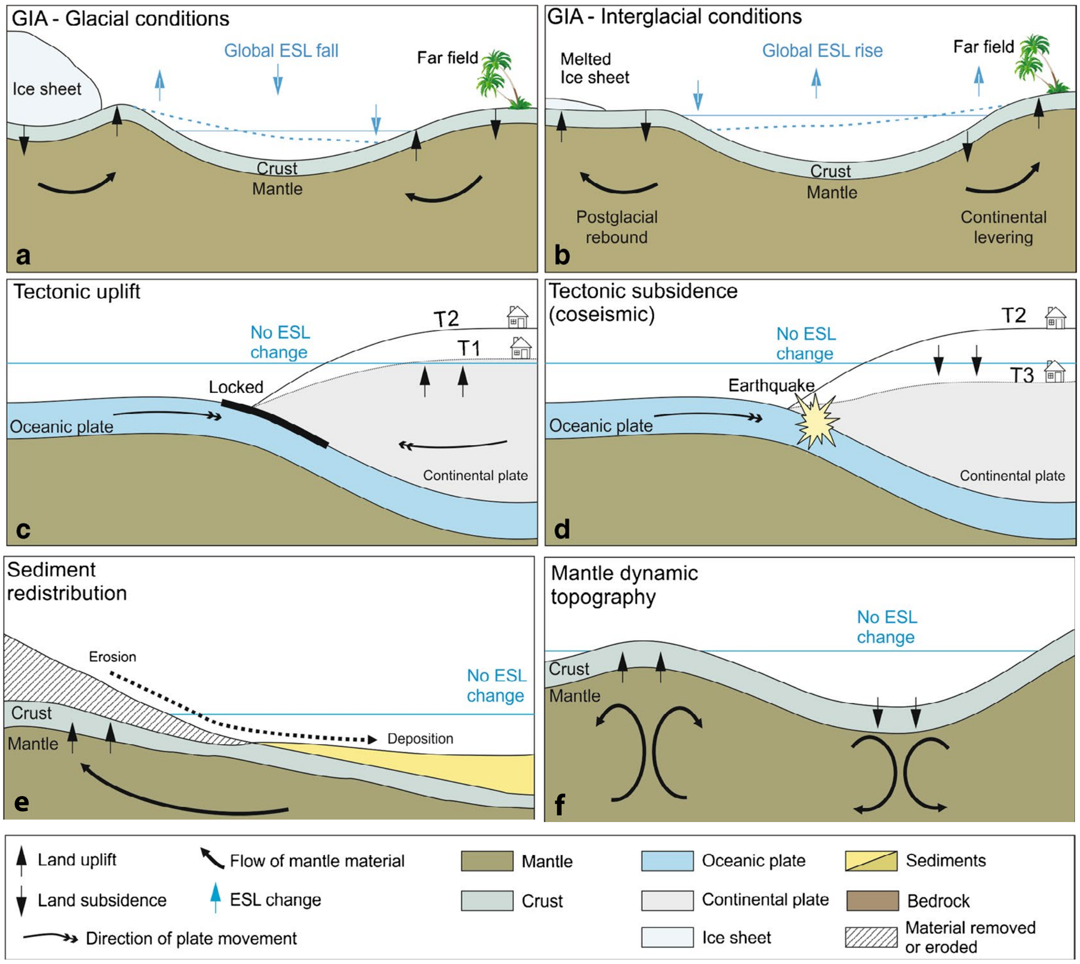


Figure 5: Glacial, tectonic, mantle, and erosional influences on eustatic sea level (ESL) and relative sea levels. After Rovere et al., 2016; Current Climate Change Reports.

A critical factor to determine when attempting to identify forcings for ice sheet and sea level variance is changing paleotopography in the northern hemisphere and Antarctica. Tectonics and high rates of erosion in glacial settings can lead to increasing marine inundation through time, but also can enhance mountain uplift due to isostatic unloading (Figure 5). These feedbacks may be a critical factor in resolving non-linear responses in ice sheet growth and decay to long-term climate and carbon cycle forcings (Figure 6).

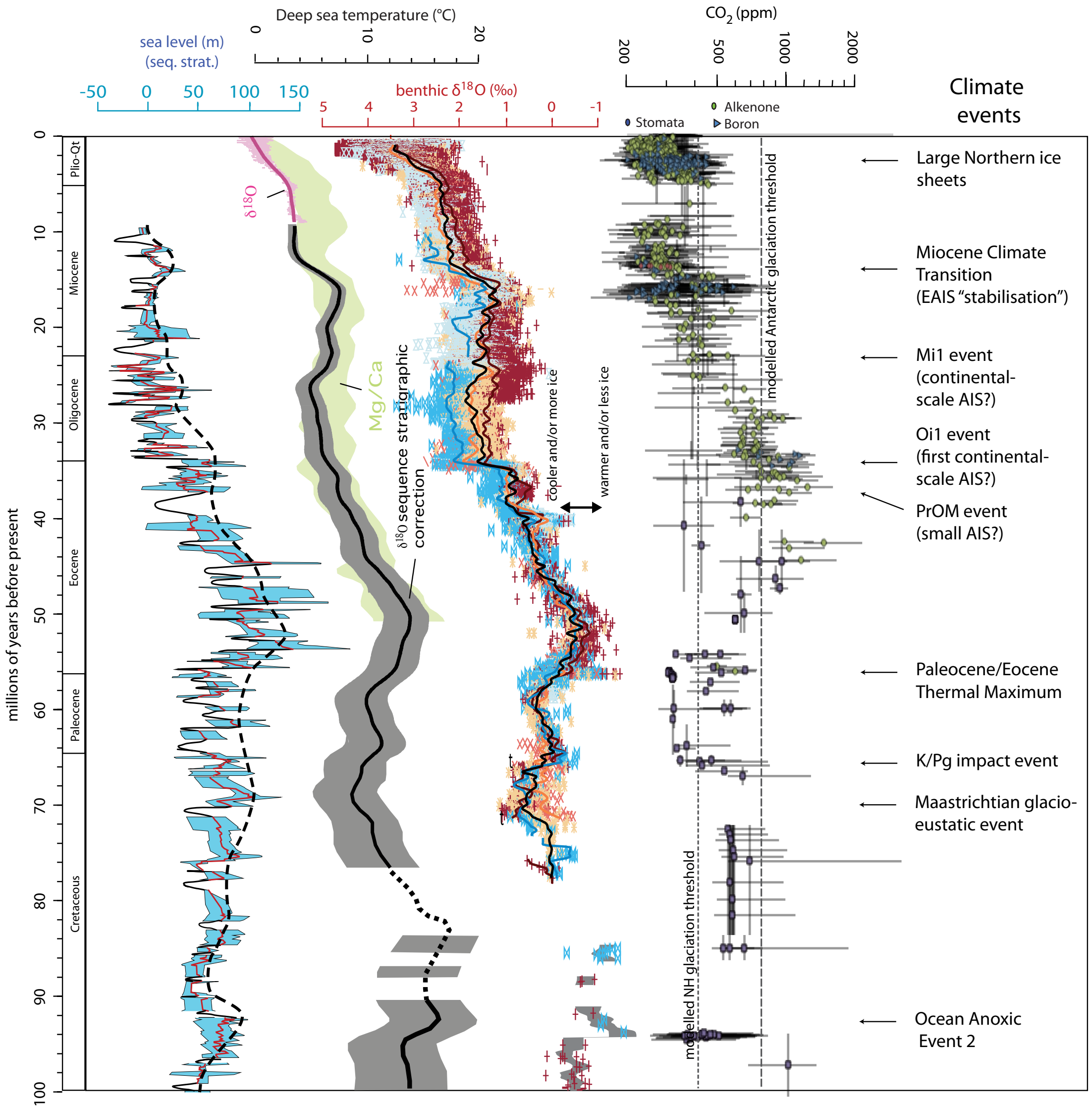


Figure 6: A compilation of far-field sea level records (Kominz et al., 2008), climate proxies (δ¹⁸O; Cramer et al., 2009), and atmospheric CO_2 (Foster et al., 2017), and relevant Cenozoic climate events over the past 100 million years. The Mi1, Oi1, and PrOM events are large transient oxygen isotope excursion inferred to represents steps in Antarctica's glacial history.

Mantle dynamics and regional tectonics further complicate deep-time sea level histories, especially when attempting to reference to modern sea level. Regardless of this, glacial-interglacial scale amplitude changes can still be determined from continental margin drilling, and at high latitudes the area extent of ice volume can be determined to identify past periods of physical ice sheet deposition.

This challenge provides linkage with the biosphere-related themes, including ecosystem changes or shifts of habitats, e.g., continental shelf inundation, changes in sediment supply, coral reef drowning, shifts in hydrological (e.g., groundwater/terrestrial/cryospheric storage) or biogeochemical cycles. Linkages to the carbon cycle challenge are made through physical changes relating to sea level, such as continental shelf inundations resulting in changing carbon sources and sinks, or carbonate reef drowning, and through the intertwined greenhouse gas forcings and feedbacks of climate and sea level. The Earth in Motion themes are also a critical overlap with this challenge, with mantle dynamics, and regional uplift/subsidence in a range of tectonic settings, all introducing uncertainties (Figure 5).

Challenge 6: What are the extremes, variations, drivers, and impacts of the Earth's hydrological cycle?

Changes in the hydrological cycle present severe challenges to sustaining human populations globally; water resources are essential for habitation, irrigation and food supply, and energy. However, shifts in global hydrology also have important hazard implications relating to increases in extreme weather events.

The various reservoirs of freshwater on the planet include the atmosphere, ice sheets, glaciers, sea ice, and surface- and ground-water. The transfer of freshwater into the ocean regulates salinity gradients within the water column and between ocean basins, and is a key factor governing global heat distribution via ocean circulation, global precipitation patterns, and shifts in Arctic and Southern Ocean sea ice. Low-latitude precipitation patterns remain important to determine, given global population centers are concentrated in these regions. It remains critical to continue investigating decadal to millennial climate modes, such as El Niño Southern Oscillation (ENSO), in an evolving climate.

Furthermore, awareness of the importance of mid- to high-latitude processes and teleconnections for global precipitation and weather patterns is increasing. For example, alpine glaciers regulate seasonal release of meltwater that sustains food supply, while ice sheets can govern large-scale atmospheric and precipitation patterns globally (Figure 7). Consequently, enhanced ice sheet melt in coming decades and centuries is anticipated to have significant downstream impacts on the broader global hydrological cycle. Avenues for future investigation include better determination of the high- to low-latitude and land-ocean teleconnections associated with the hydrological cycle.

Other critical aspects of the Earth's hydrological cycle that requires further investigation are the drivers of regional and global aridification events, and the implications of these on vegetation. Examples include the spread of C4 grasses, desertification of Africa and Australia, and changes in boreal forest extent. How aridification influences nutrient delivery or other depositional shifts in offshore systems that may affect offshore biological systems is also an important question.

Sampling of offshore sediments to understand the terrestrial hydrosphere can be achieved by targeting regions of surface runoff from rivers or glacial meltwater, or groundwater reservoirs. Terrestrial groundwater storage on continental shelves and its flow to the ocean are a particularly understudied aspect of the hydrological cycle, especially during large-scale climate and sea level shifts in the past. Sequestration of meteoritic water reserves in continental shelf groundwaters has likely varied greatly in the geological past in response to shifting land precipitation patterns, or to changes in the stratigraphic architecture or geometry of continental shelves resulting from tectonic events or sea level change. This potentially influences a range of processes, including global ocean salinity budgets and circulation, the transfer of carbon and other nutrients from the land to sea, and incursions of brackish water into on-land freshwater groundwater reservoirs. Such changes will also influence a range of surface biological systems as well as the deep biosphere. In a modern context, the influence of pollution (e.g., nitrates, microplastics) in offshore groundwater reservoirs may also be assessed (see Theme 1).

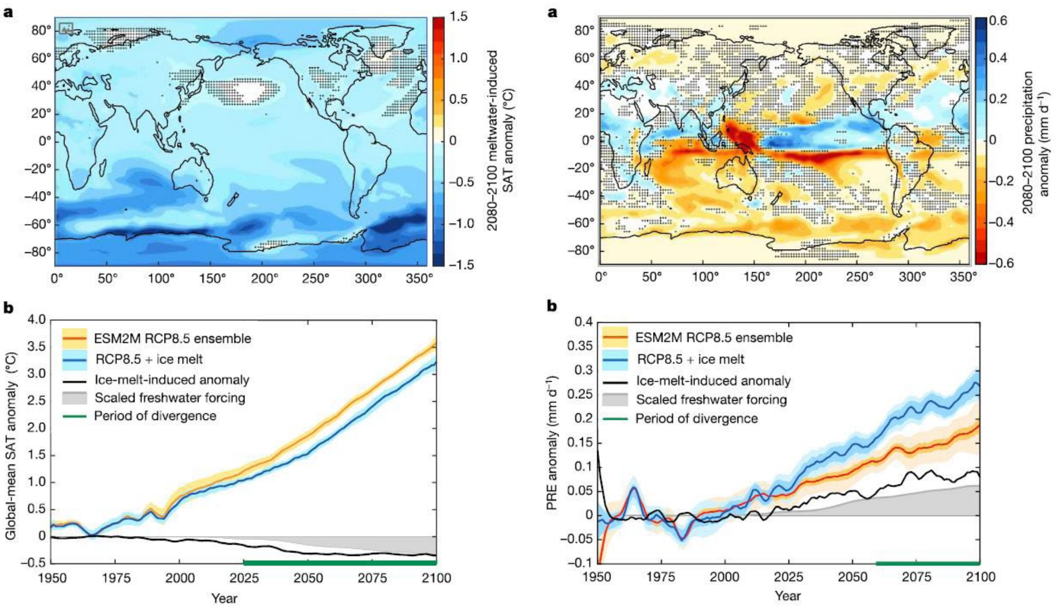


Figure 7: Ice sheet meltwater influences on global precipitation patterns, highlighting high-latitude influences on low precipitation (from Bronselaer et al., 2018.).

Crossover with other themes include solid Earth processes, whereby tectonic influences are a key control on long-term hydrological change. These influences include mountain uplift and alteration of atmospheric jet-streams and circulation, and also tectonic ocean gateway opening/closure that acts to regulate exchange between the major ocean basins. Links to the biosphere can be made through assessment of the modern deep biosphere, as well as evolutionary history from fossils. The influence of hydrological changes on mantle processes can potentially be assessed through subduction zone inputs.

Challenge 7: What are the links between cryosphere dynamics and global circulation patterns in the ocean and atmosphere?

Ocean circulation is the primary mechanism of global heat transport on longer time scales and is driven by a combination of factors, including changes in atmospheric circulation patterns and density gradients in the ocean. In coming decades and centuries it is anticipated that contraction of sea ice and ice sheets in the polar regions of both hemispheres will have widespread implications for global atmospheric and ocean circulation. As the influence of cryosphere processes is anticipated to contract towards the poles, reduced latitudinal thermal gradients will affect wind stress on the ocean surface, while change in freshwater input from melting ice sheet and seasonal sea ice melt will significantly influence density gradients in the ocean that underpin the thermohaline circulation.

Melting of polar ice sheets has driven some of the largest feedbacks in the climate system since ~34 million years ago, and these were once considered slow feedbacks. However, an increased awareness over last decade of dynamic processes for marine-based ice sheets suggest rates of melting that are potentially significantly higher than many Earth system models currently incorporate. Consequently, the drivers and implications of polar amplification in a range of atmospheric boundary conditions require addressing (especially in high Arctic and south of 60°S).

Conversely, climate variations at low latitudes directly influence the atmosphere, ocean, ice sheets, sea ice, and biosphere in polar regions. The poleward migration of wind-driven ocean currents is enhancing heat fluxes to the polar region and is implicated in the accelerated loss of marine-based ice sheets, ice shelves, and sea ice, both today and in the geologic past. High-latitude feedbacks in the Arctic, including reduced albedo associated with sea ice loss, act to amplify Arctic warming relative to the global mean (by a factor of 3) with consequences for Greenland Ice Sheet melting, atmospheric circulation patterns, and meridional overturning circulation. In the southern hemisphere, the Southern Ocean currently absorbs more anthropogenic heat and carbon than oceans in other latitudes due to its large thermal inertia. This heat uptake is currently helping to suppress amplified Antarctic warming. However, paleoclimate data and models indicate that the Southern Ocean's ability to absorb this heat is limited, and show Antarctic polar amplification in response to elevated atmospheric CO_2 levels is of similar scale to that of the Arctic.

Warming and freshening of polar surface waters under scenarios of polar amplification will act to increase stratification associated with sea ice changes and ice sheet meltwater fluxes. Changes in stratification will inhibit surface water exchange with nutrient-rich deep waters, with consequences for heat and gas exchange between the ocean and atmosphere (Figure 8). Antarctic Bottom Water and North Atlantic Deepwater production rates are important controls on the ocean's ability to store heat and carbon. Both of these water masses are fundamentally influenced by processes linked to the cryosphere, whereby density properties of the waters are regulated by sea ice modification processes, freshwater input by ice sheet meltwater, and supercooling processes associated with marine terminating ice sheets and ice shelves.

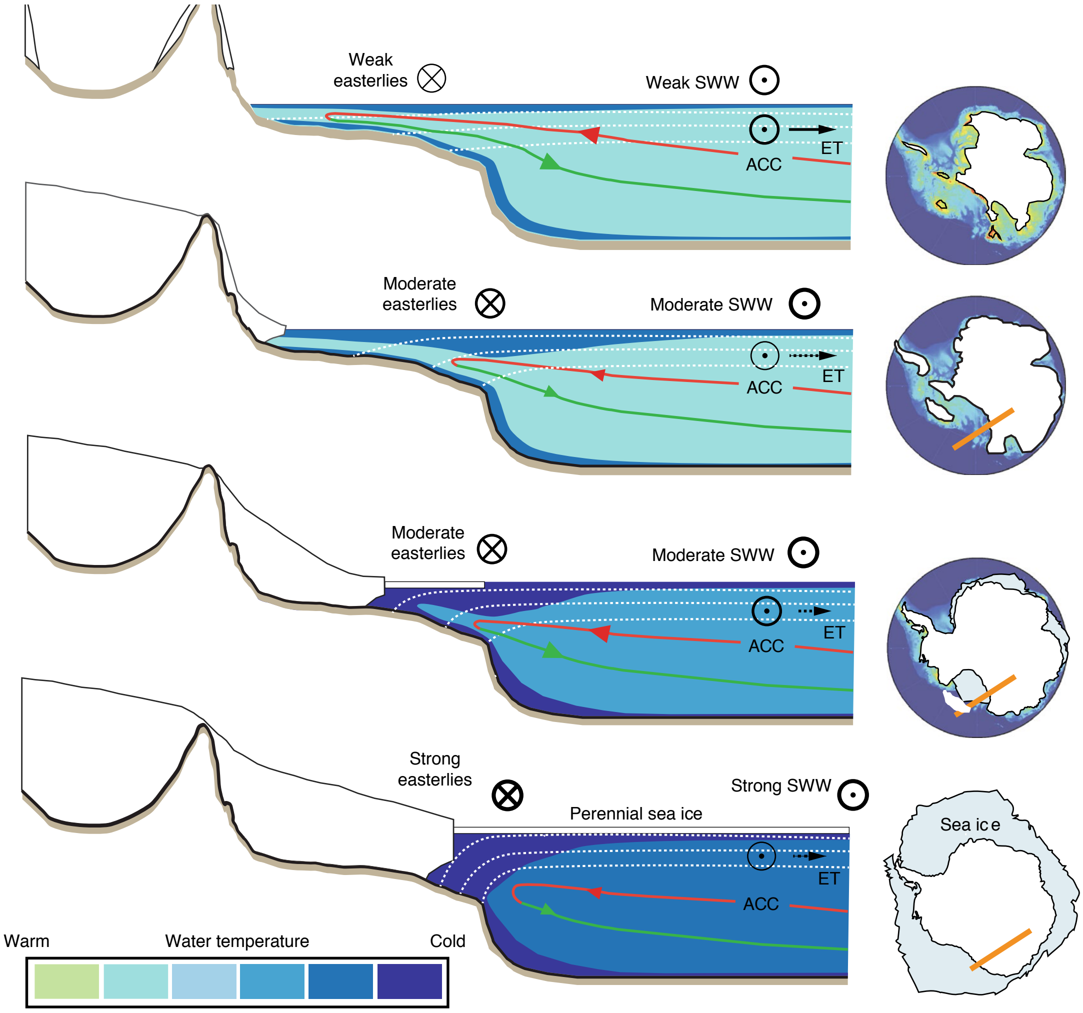


Figure 8: Atmosphere-ocean-ice interactions at the Antarctic margin under various warm (top) to cold (bottom) climate states. Modified from Levy et al., 2019.

SEDIMENT-WATER INTERFACE RECOVERY

Given the imperative for understanding the context of anthropogenic climate change (Figure 9), a strong consensus exists within the community for scientific ocean drilling to collect multicores as a standard operating practice at each drill site, where feasible. This could also be targeted at strategically located sites nearby (e.g., sites with higher accumulation rates than the primary drill site) to understand modern depositional systems and assist in deeper time interpretations. These cores will preserve the sediment-water interface that is commonly lost with piston coring methods, and allow ocean changes to be reconstructed into the present day. These observations of modern boundary conditions will enable a better interpretation of deeper time proxies obtained from drilling deeper into the sediment column. Multicores are quick to obtain, and would be unlikely to significantly reduce operational time for drilling.

Given the global reach of scientific ocean drilling, this opens the possibility to make significant and unique contribution to the understanding of a myriad of global ocean system processes, ranging from changes in the ocean heat content on decadal to centennial scale, to the role of the Southern Hemisphere oceans in driving regional temperature changes. An urgent need is to address the deficit in knowledge of ocean temperature changes across the past few centuries, given the ocean's role as a primary heat reservoir in the global climate system and as an important regulator of global climate on longer time scales. Temperature compilations (Figure 6) are a qualitative indicator of the timing of the onset of industrial-era warming by latitude, and quantifying these changes is an imperative, particularly for the Southern Hemisphere (McGregor et al., 2015; Abram et al., 2016). Records that preserve present-day conditions could further fingerprint ocean basin differences in Anthropocene impacts and changes, such as accumulation of microplastics in ocean sediments (linking with the Ocean Health Theme) and the established microbiology on the seafloor.

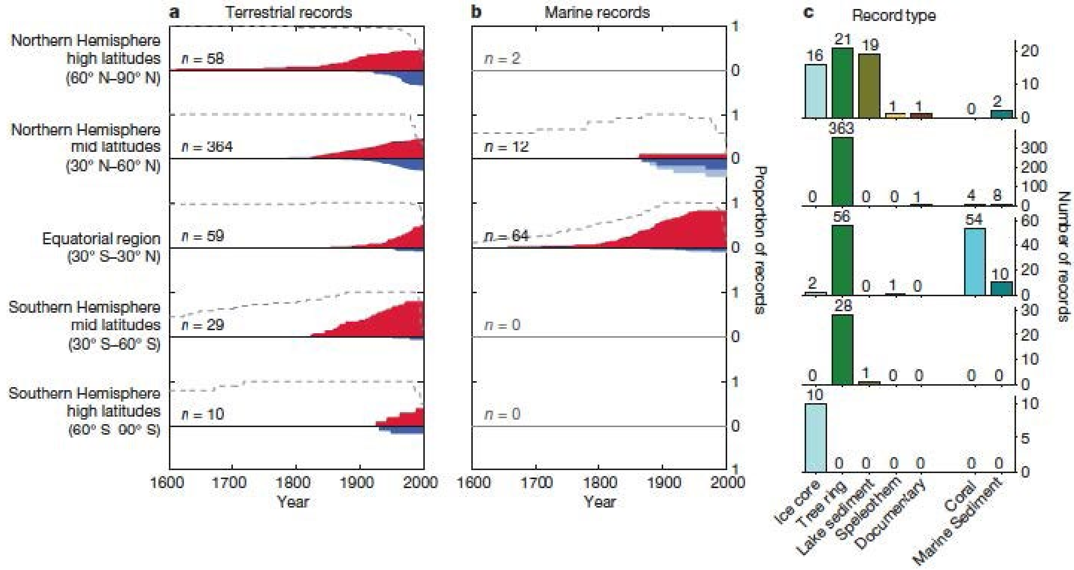


Figure 9: Post 1500 CE temperature trends for terrestrial (a) and ocean (b) proxy records, grouped by latitudinal band (after Abram et al., 2016). Records show latitudinal development of sustained significant warming (red; upward) or cooling (blue; downward) trends. Distributions are a proportion of total records within each latitudinal band (n is the number of total records). Grey values indicate an insufficient number of site-level records (n ≤2) for meaningful comparison. Light shading in b denotes trends at marine sediment core sites with an a priori upwelling regime and may not be representative of latitudinal average climate. Dashed lines show the temporal coverage of site-level records (expressed as a proportion of latitudinal band total, n).(c) The number and type of proxy records available by latitudinal band. The marine compilation is dominated by coral records, with only a small number of sediment core records for mid- and high latitudes. Addressing this deficit is urgently needed, given the ocean's role as a primary heat reservoir and important regulator of global climate on longer time scales. The compilation in a and b is a qualitative indicator of the timing of the onset of industrial-era warming by latitude and quantifying these changes is an imperative, particularly for the Southern Hemisphere (McGregor et al., 2015; Abram et al., 2016).

THEME 3: Biosphere Frontiers

The implementation of strict contamination-control procedures in 2001 for ODP legs and subsequent IODP expeditions enabled confirmation of the existence of a deep microbiome with taxonomically diverse, metabolically active archaea and bacteria (Morono et al., 2011). Over the last decade, significant progress has been made to estimate the diversity, abundance, and complexity of subsurface life. A refined assessment of the total biomass of the deep biosphere has revealed that this significant ecosystem rivals the oceanic microbial biomass in abundance (Kallmeyer et al., 2012; Figure 10). Deep microbial communities have been found to actively drive diagenetic processes in extreme environments with highly limited availability of photosynthetically derived detrital energy source, implying that such ecosystems rely on alternative food sources (Røy et al., 2012). In addition, communities focused along fluid pathways have also been detected in the sub-seafloor oceanic crust (Lever et al., 2013, Tully et al., 2018), opening new opportunities to study the limits of life and the complexity of the deep microbiome. Furthermore, a major study conducted off Japan by Inagaki et al. (2015) reported evidence of microbial communities living at ~40-60°C in sediments and lignite coal beds as deep as 2.5 km below the seafloor. The greatest biomass was detected within the lignite layers in communities that showed close similarities to organotrophic communities in forest soils. This significant discovery highlights the survival of indigenous communities in forest-derived sediments for tens of millions of years after burial. Ongoing drilling programs (e.g., Exp. 370 off Muroto) are seeking to discover the limits of temperature and pressure for life to exist in the subsurface.

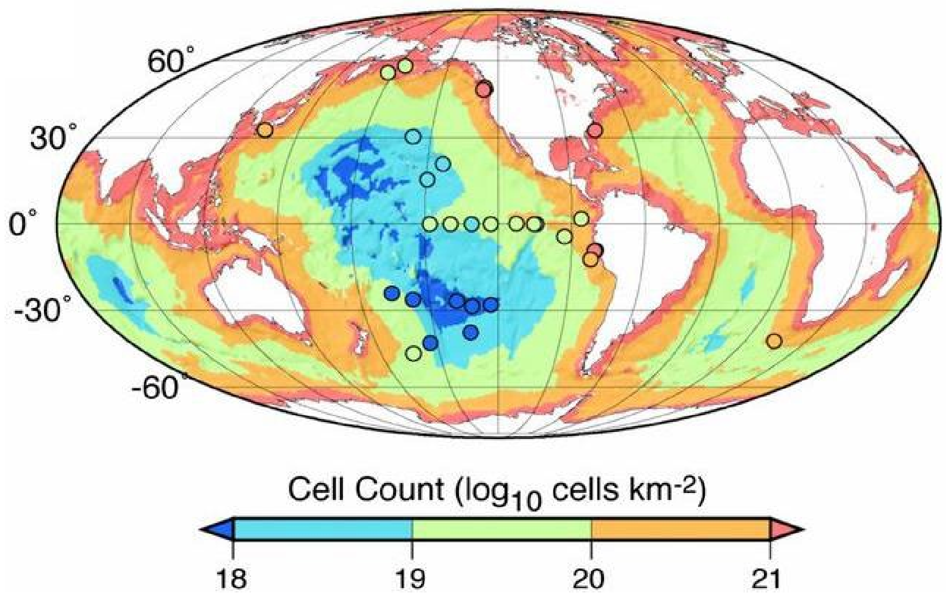


Figure 10: Geographic distribution of sub-seafloor sedimentary cell abundance highlighting the global extent and abundance of the deep biosphere with dots indicating site locations (from Kallmeyer et al., 2012).

While only a limited number of drilling expeditions have been dedicated to the characterisation of the deep biosphere over the last two decades, these expeditions have made major scientific discoveries that have deepened our understanding of the evolution and complexity of life. Such discoveries have been underpinned by the rapid advancement in DNA and RNA sequencing technology. However, a number of outstanding questions remain unanswered and it is likely that most of the deep, hot biosphere is yet to be discovered. New expeditions will therefore play a key role in unravelling the mysteries of this vast and unique ecosystem.

Drilling approach: To maximize our understanding of the deep, hot microbiome, an integrated approach should be used, combining an array of proxies established in microbiology, geochemistry, mineralogy and planetary sciences. It is also necessary to implement future protocols for consistent sampling and analysis of deep biosphere samples in order to promote the development of easily accessible data sets that are comparable between expeditions.

An overarching objective is to build a "deep biosphere 3D atlas" that highlights the abundance and diversity of microbial, archaea, and eukaryotic communities, both laterally and vertically. This will lead to a greater understanding of the regional controls (with implications for paleogeographic interpretation) and the influence of chemical and physical gradients on the biosphere. Additionally, such information will not only provide key insights into the limits of life on Earth, but also provide valuable data that can contribute to the search for life on other planetary bodies. Through a better understanding of the nature and limits of the deep biosphere, we may also discover communities that have potential applications in, for example, pharmaceuticals, food, and energy. We will gain new knowledge of biosphere-geosphere interactions and the influence of the deep microbiome on global biogeochemical cycles. The Biosphere Frontiers theme therefore presents strong synergies with both the Ocean Health Through Time and Global Climate themes.

In order to address the main challenges identified for deep microbiome studies, four key Challenges are presented for future scientific ocean drilling research on the theme of Biosphere Frontiers.

Challenge 8: What are the habitable limits for life?

The biosphere is characterized by a range of extreme subseafloor environments, from high temperature, acutely acidic settings associated with hydrothermal vents, to high pressure subsurface sediments. In these systems, controlling factors for life existence, such as pressure, temperature, pH conditions, nutrient concentrations, mineralogy, salinity, redox conditions, and the availability of electron donors and acceptors as well as key geological parameters, are still not clearly understood (e.g., Cockell et al., 2016; Jones et al., 2018). Scientific ocean drilling therefore provides a unique opportunity to investigate all these factors, explore the continuum from life to non-life, and characterize relationships between the deep and near-surface chemical reservoirs sustaining the sub-surface biome.

In addition, although carbon is regarded as the key element for the building blocks of all known life on Earth, the potential for alternative forms of life based on other elements has been suggested. Silicon, for instance, is the second-most abundant element in the Earth's crust after oxygen and has chemical similarities with carbon. Recent advances in microbiology have considered silicon-based life and Challenge 8 will provide unique insights into this possibility.

Additionally, although several theories and geological settings have been proposed for the origin of life on our planet, this fundamental question presently remains one of the great challenges in biology. In brief, methanogens are regarded as organisms with metabolisms likely to be the most primitive among those identified in extant life (Boyd et al., 2014a). These organisms use an ancient CO_2 fixation pathway which involves several Ni- and Fe-dependent enzymes (Russell and Martin, 2004), and environments where H_2 as well as Ni and Fe-rich minerals are largely available have been shown to effectively sustain methanogenic activity (Boyd et al., 2014b). The most primitive methanogen identified by phylogenetic reconstruction is a hyperthermophilic organism isolated from a deep sea hydrothermal vent and thriving at temperatures up to 122°C (Takai et al., 2008). The primitive nature, ecology, and physiological characteristics of this organism are similar to those expected for a hot, deep primordial biosphere (Figure 11).

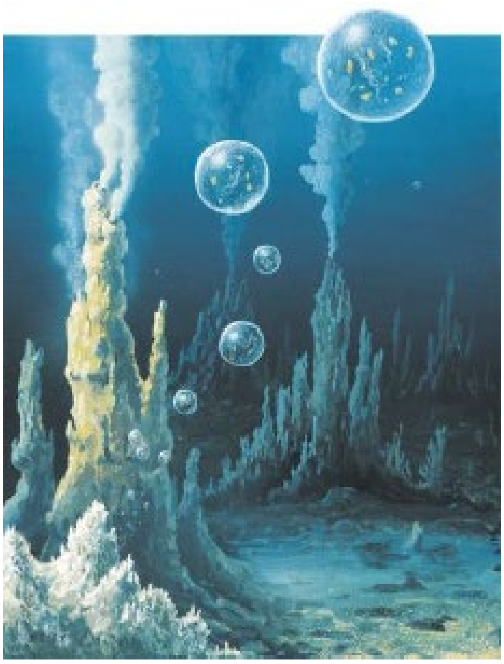


Figure 11: Deep-sea hydrothermal vents may have provided the suitable environmental conditions for the beginning of life (Figure from Deamer, 2014).

Studying the deep biosphere thriving under extreme environmental conditions, such as under constant anoxia, darkness, and high pressure and temperature, and with highly restricted energy sources, this challenge will allow us to provide new insights into primordial life. Our new knowledge may also provide key knowledge about LUCA, the Last Universal Common Ancestor, from which all Earth's organisms derive.

Questions for this challenge include:

- What are the key limits within which carbon-based life can exist?
- Can non-carbon-based life be detected in sub-seafloor environments?
- Can studies of the deep biosphere provide new insights into LUCA and the origins of life?

Challenge 9: Composition, complexity, diversity and mobility of subsurface communities

Understanding the diversity of organisms beneath the seafloor has undergone major advances since the Deep Biosphere was defined as a stand-alone theme in the 2003 IODP Initial Science Plan. Most studies have focused on the identification and characterisation of bacterial and archael communities. The recent revolution in archaeal genomics has been largely driven by the discovery of a variety of archaeal subsurface lineages, providing crucial information about the evolution of all Archaea (Colman et al., 2017). A holistic understanding of the deep biome is now needed to provide a comprehensive analysis of all sub-surface communities.

Bacterial and archaeal communities are common in the subsurface environments, where their distributions appears to be controlled by the lithology and hydrogeochemical history of the region (e.g., Bomberg et al., 2015). Insight into the abundance, diversity, and complexity of these communities have been gained over the past decade (e.g., Colman et al., 2017). However, much less is understood about the third domain of life Eukarya, in particular fungi. Fungal communities have been shown to be active in the continental and deep subseafloor, where they likely have a major role in organic matter degradation in subseafloor environments (Edgcomb et al., 2011; Orsi et al., 2013). In addition, viruses have been identified in deep groundwater (Eydal et al., 2009), and have been suggested as a control on bacterial colonization of the terrestrial deep biosphere after hydraulic fracturing (Daly et al., 2019).

We know little about endemicity of sub-seafloor organisms. Although several studies have reported organisms that appear to be endemic to the deep biosphere (Chivian et al., 2008; Magnabosco et al., 2014), others have demonstrated that deep biosphere species are also present in near-surface environments such as hot springs (Teske, 2006; Lazar et al., 2015). It has been proposed that environmental characteristics including high temperature, low nutrient flux, strongly reducing conditions, and oxidant limitation that can be displayed both in deep sub-surface and near-surface settings select for the same taxa. To fully address this research question, genomes reconstructed from deep microbial populations and near-surface communities will need to be compared to further assess if closely related genotypes thriving in both environments express specific physiological adaptations.

"Quorum sensing", the fascinating ability of bacteria to use a cell-cell communication system involving production of and response to secreted signals, is poorly understood (Figure 12). Quorum sensing appears to play a major role in cooperation and competition among microbial communities and controls interactions within specific species and also between species (Waters and Bassler, 2005). Although a wealth of knowledge has accumulated on the molecular processes, signal characteristics, and behavioral responses related to quorum sensing, few studies have focused on the deep microbiome. To date, it remains unclear to what depth microbial communities organize themselves to optimize the use of limited resources, what strategies they develop, and whether their produced molecular signals vary (laterally and vertically).

Overall, studies on deep biosphere communities consistently suggest a high degree of complexity in these poorly understood ecosystems. Rapid advances in technologies such as novel high-throughput and high-data genomic approaches provide new opportunities to unravel the mysteries of life occurring in the deep Earth. For instance, recently developed techniques can now differentiate dormant and metabolically active populations (Lomstein et al., 2012), and characterize the activity and genomic material for individual microbial cells (Morono et al., 2011; Lloyd et al., 2013). Future advances will allow us to systematically obtain complementary biogeochemical measurements and develop robust models of key microbial processes (e.g., oxygen/iron/manganese/nitrate/sulfate reduction rates and methanogenesis). Finally, to enable in-depth understanding needed to address this challenge, we will need to cultivate the newly discovered microbes to assess their growth rates and adaptation strategies.

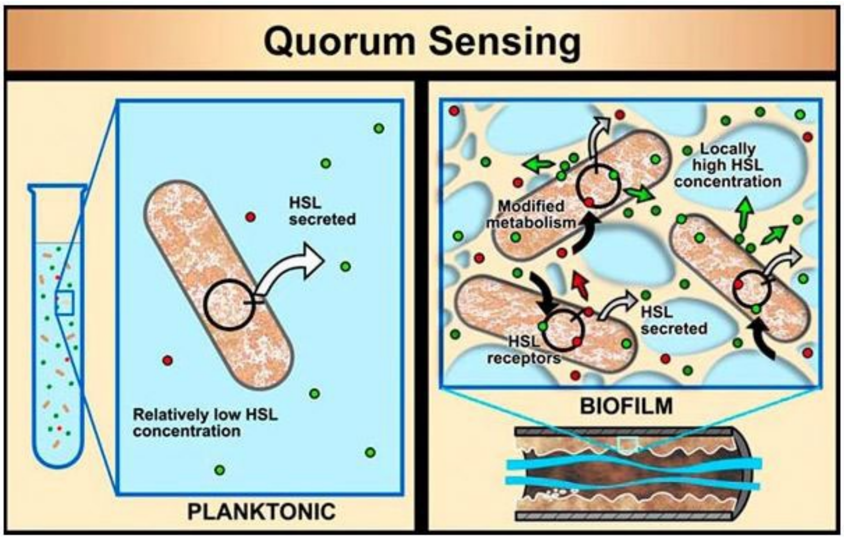


Figure 12: The concept of Quorum Sensing, showing how planktonic cells communicate with each other through the secretion of chemical signals (Image source: P. Dirckx, Center for Biofilm Engineering, Montana State University, Bozeman).

Challenge 10: How sensitive is the deep biosphere to anthropogenic impact?

Climate change is a fundamental driver of global variations in, for example, sea level, surface water temperatures, hypoxia, and acidification (see also Challenge 3). Since most deep communities thrive under stable thermal regimes, it is likely that, warming of just 0.1°C would generate stress and cause major variations in depth or latitudinal distributions of microbial communities, as well as impact species interactions (Levin and Le Bris, 2015). In addition, increased associated stratification of the water column may lead to restricted deep-water ventilation and to a decrease in nutrient fluxes within the deep ocean. Consequently, naturally nutrient-poor environments will be further deprived of organic matter over time, potentially resulting in altered microbial activities (Smith et al., 2008).

Currently, little is known about the sensitivity of the deep biosphere to environmental perturbations. To effectively assess how sensitive these communities might be to anthropogenic environmental impacts, it is critical to 1) understand how past natural variations in environmental conditions impacted the marine biosphere, and 2) conduct baseline studies of the modern biosphere for future comparative studies.

Scientific ocean drilling can reveal how environmental factors such as rapid changes in sedimentation rate, creation of physical barriers restricting water circulation, or chemical fluctuations due to the circulation of hydrothermal fluids through the crust affected sub-seafloor ecosystems in the geological past. Recovering drill core in targeted basins will promote new insights into the synergies between the biosphere and the geosphere over time.

In addition, in order to conduct “long term monitoring” of the deep microbiome, baseline studies will better define the extent, diversity, and complexity of the modern subseafloor communities. Importantly, future studies of the deep microbiome should be consistent in their approach, using comparable technologies and interoperable datasets, in order to effectively allow comparisons over time. Such goals closely align with Challenge 9, and will require implementation of a “3D Atlas of the Deep Biosphere”.

Data from both modern and paleo-environments will allow prediction of ongoing and future impact of Anthropogenic activities on the deep microbiome (Figure 13). Impacts may include intensive terrestrial run-off of nutrients from agriculture leading to permanent euxinic (anoxic and sulfidic) conditions in the bottom waters, intensive maritime traffic causing perturbations on the seafloor (Sardain et al., 2019), accumulation and burial of anthropogenic pollutants (see also Theme 1), mine tailings disposal, oil and gas extraction, and deep-sea mining activities (Ahnert and Borowski, 2000). Spatial planning to restrict direct human disturbance—for example, by creating networks of deep ocean marine protected areas—has been instigated to establish refugia for endangered species and habitats, and reduce cumulative stresses (Levin and Le Bris, 2015). Outputs from this challenge strongly align with this initiative and will contribute directly to planning decisions. Furthermore, this challenge should be addressed concurrently with challenges of Theme 2 (Global Climate), in order to effectively assess the response of the hydrosphere, atmosphere, cryosphere, biosphere, and major biogeochemical cycles to local and global environmental perturbations.

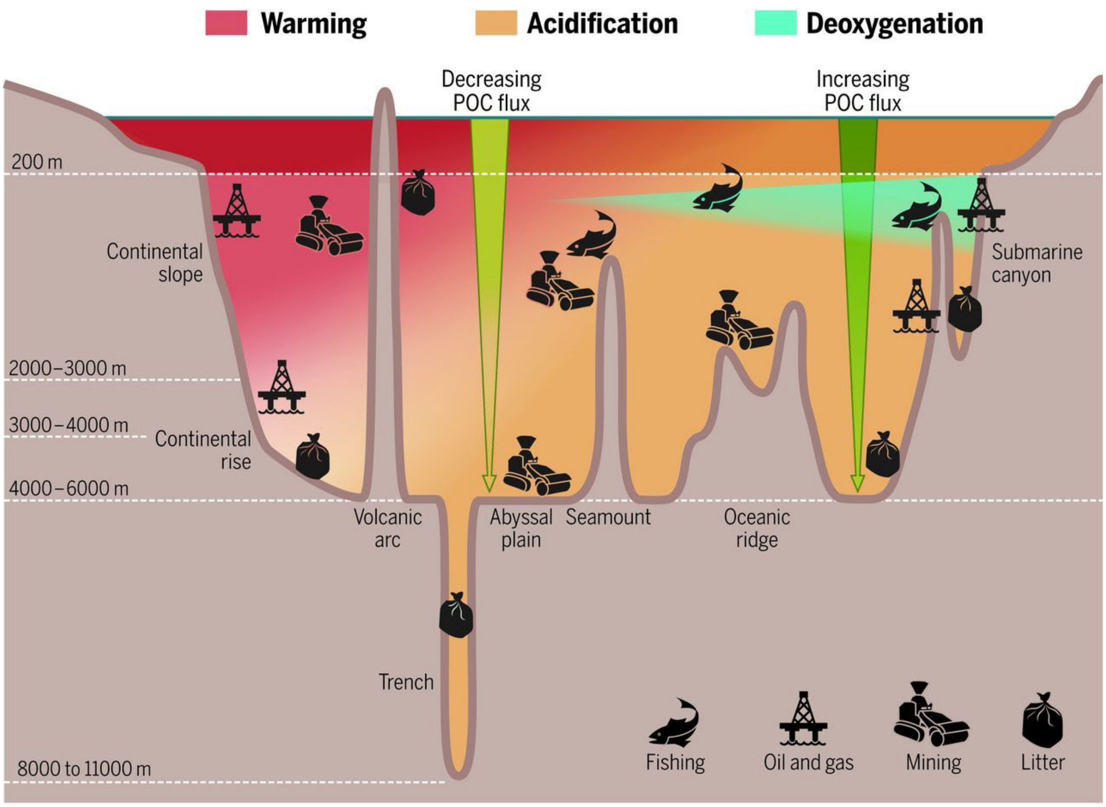


Figure13: Diagram representing current and potential future human exploitation activities and waste disposal with related CO_2-induced changes in the temperature, pH, and oxygenation of the deep ocean, in relation to ocean depth (from Levin and Le Bris, 2015). Although the future impact of anthropogenic activities on the deep biosphere presently remains unknown, a significant, detrimental influence is expected.

Challenge 11: How are the signatures of life preserved through time and space?

The signatures of life, or "biosignatures," have been commonly described as "an object, substance, and/or pattern whose origin specifically requires a biological agent" (Des Marais et al. 2003). Biosignatures can include the following features: cellular and extracellular morphologies, biogenic fabrics in rock and sediments, bio-organic molecular structures, chirality, biogenic minerals, biogenic stable isotope patterns in minerals and organic compounds, specific atmospheric gases, and remotely detectable features on planetary surfaces (Des Marais et al. 2008). Cutting-edge tools for reconstructing, for example, biomarker, palynologic, and paleontologic profiles, stable isotopic compositions, and paleogenomic data sets can all be used to understand the ancient biosphere. Studying the coevolution of life and its surrounding environment is a powerful approach to unraveling species origin, evolution, and extinction, understanding the early Earth, characterizing habitable environments, and contributing to the search for life in the universe. This challenge therefore strongly aligns with Challenge 8.

A significant challenge when studying sediment cores lies in the understanding of the preservation potential, transformation, and migration of organic matter within the sedimentary pile. In particular, deciphering proxies of ancient biosphere versus products of diagenesis and contamination has proven extremely challenging. Studying ocean drill core material offers a unique opportunity to assess the preservation potential of paleoenvironmental archives and markers of ancient life through time and under diverse environmental conditions (e.g., oxic, anoxic, euxinic, ferruginous.)

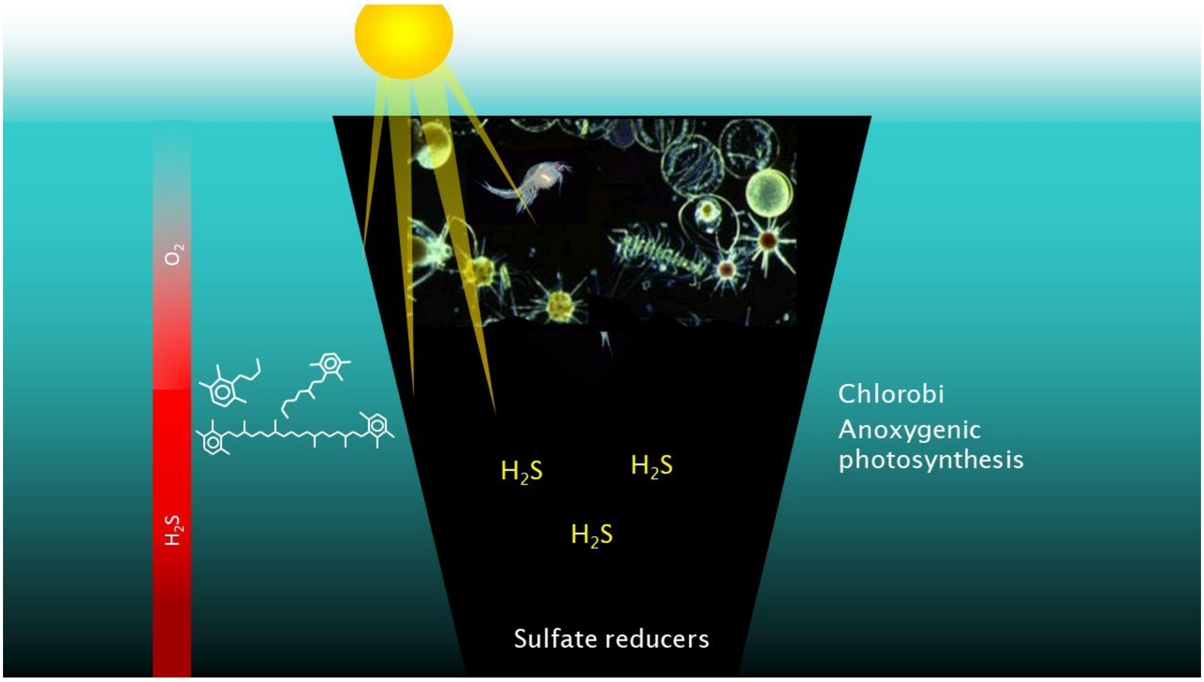


Figure 14: Illustration representing the microbial communities in the Chicxulub crater at the peak ring from expedition 364 (Schaefer et al., 2019). Biomarkers support the rapid transport of microbial mat debris into the crater, followed by cyanobacterial colonisation and periods of photic zone euxinia (PZE) developing in the crater. PZE biomarkers are from green-green and brown-green pigmented Chlorobiaceae and purple pigmented Chromatiaceae. These organisms are anaerobic photoautotrophs utilizing hydrogen sulfide as an electron donor in photosynthesis. They produce specific bacteriochlorophylls and carotenoids to harvest light energy and to fix CO_2. They live at the chemocline in lakes or marine basins where sulfide concentrations are high within the photic zone. Biosignatures deriving from these organisms are therefore particularly useful to reconstruct paleo-environmental conditions associated with biological crises and natural climate perturbations. cal crises and natural climate perturbations.

It allows us to develop a robust understanding of the signatures of fossilized microbial communities (e.g., through the characterization of biolipids or ancient DNA) and gives us tools to distinguish ancient fossilized life forms from contemporary communities (Figure 14). Through this knowledge, we will have established proxies for ancient life and documented evidence for the biosphere's recorded response to major climatic perturbations in the past. We will also be able to build novel proxies to predict the biosphere's response to future environmental changes.

Key questions for this challenge include:

- Can we identify biosignatures that trace the history of biotic evolution?
- What biosignatures or evidence of subsurface ecosystems can resist the test of time?
- What environmental conditions promote the preservation of biosignatures through time and space?
- Can we detect previously unknown preservation mechanisms of biosignatures in the subsurface?

THEME 4: Earth Dynamics: Core to Crust

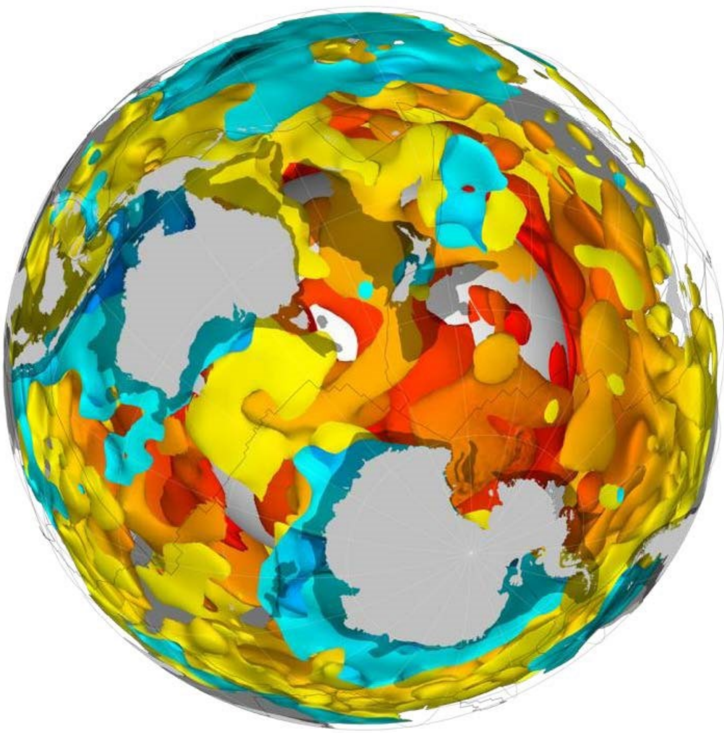


Figure 15: Shear wave tomography is a window into the deep Earth (Source: Earthbyte).

The long term exchanges of mass and energy among the Earth's core, mantle, and crust is a fundamental driver of plate tectonics, and have produced all the characteristic solid, liquid, and gaseous natural features of Planet Earth (Figure 15). These include the elevated continents, depressed ocean basins, chains of volcanoes, earthquakes, oceans, and atmosphere. The exchanges of solids, fluids, and heat via chemical, physical, and biological processes have operated throughout much of geological time, are episodic, and continue today.

Major knowledge gaps in our understanding of how the Earth works, what makes it unique, and which can be addressed through sampling of the ocean crust, are framed in terms of four research challenges. As well as being a worthwhile standalone research endeavor, this research theme has an underpinning relationship to the other themes. A useful and powerful attribute of this theme is its long-term (deep time) perspective on various issues. Without this perspective and context, we cannot properly understand the present day condition of Planet Earth. Advancing knowledge in the Earth Dynamics theme will impact positively on society, because other geoscientists use the fundamental and baseline results in their more applied hazards and climate-related research.

Challenge 12: What controls the life cycle of ocean basins and continents?

Since the development of plate tectonic theory, it has been realized that a long-term cyclicity characterizes the opening and closing of ocean basins (the Wilson cycle) and the dispersal and amalgamation of supercontinents. These cycles are driven by processes that take place at plate boundaries, most notably at mid-ocean spreading ridges and subduction zones (Figure 16). While the first-order tectonic features of Planet Earth's surface such as crustal types and plate boundaries have been established, many second order features are still only poorly understood. Examples include why supercontinents break up, and what controls the style and duration of breakup; how subduction zones initiate, evolve, and terminate; what governs the lifespan of a magmatic arc and why arcs split in different ways; and what drives the interplay between magmatism and deformation at convergent and divergent plate margins. Furthermore, many processes, causes, effects, rates, and relative contributions of fundamental plate drivers remain obscure, yet are amenable to investigation by appropriate experiments and data acquisition including scientific ocean drilling.

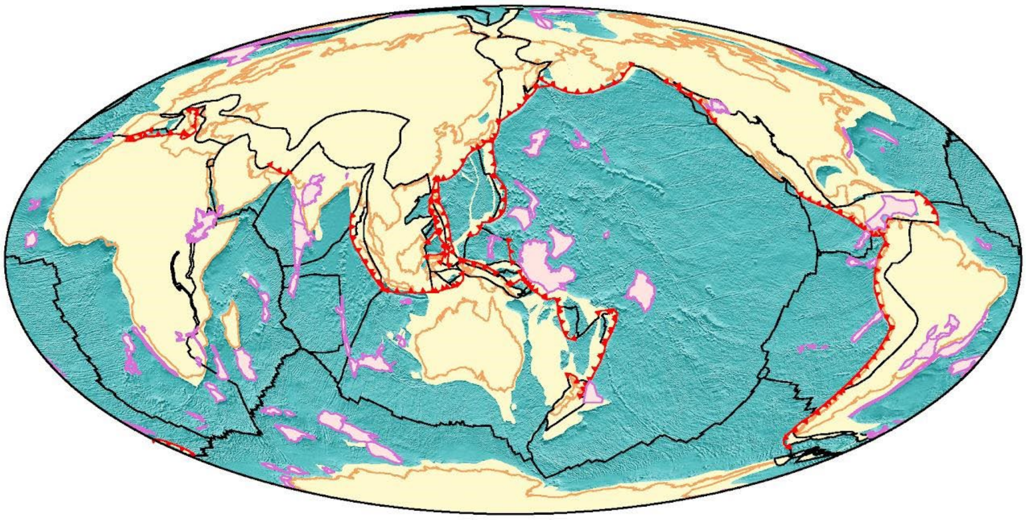


Figure 16: Earth's present day surface structure. Oceanic crust (with bathymetry gradient) in blue, continental crust in light yellow, Large Igneous Provinces in light pink, subduction zones in red, and other plate boundaries in black (Source: M. Seton).

The life cycle of ocean basins and continents constitutes a large, multifaceted challenge covering continental rift and margin, island arc, backarc basin and mid-ocean ridge tectonic settings, and magmatic, accretionary, collisional, and plate kinematic processes. Results from this challenge are used as input by other challenges (e.g., thermal and mechanical properties of lithosphere provide insights into earthquake mechanisms).

ANZIC PRIORITIES

Understanding the life cycle of ocean basins and continents is a challenge of particular relevance to ANZIC scientists. Both Australia and Zealandia have broad continental shelves displaying an array of margin types including volcanic, non-volcanic, and highly extended; and both were formerly part of the supercontinent Gondwana and have played a crucial role in changes in Cenozoic ocean circulation and climate. The region also offers natural laboratories to study subduction initiation in its infancy (Puysegur and Hjort trenches), subduction polarity reversal (Solomon Islands), and the early stages of orogeny (Timor). These regions are natural choices for global case studies of continental margins and convergent systems.

Challenge 13: How do the core and mantle interact with the Earth's surface?

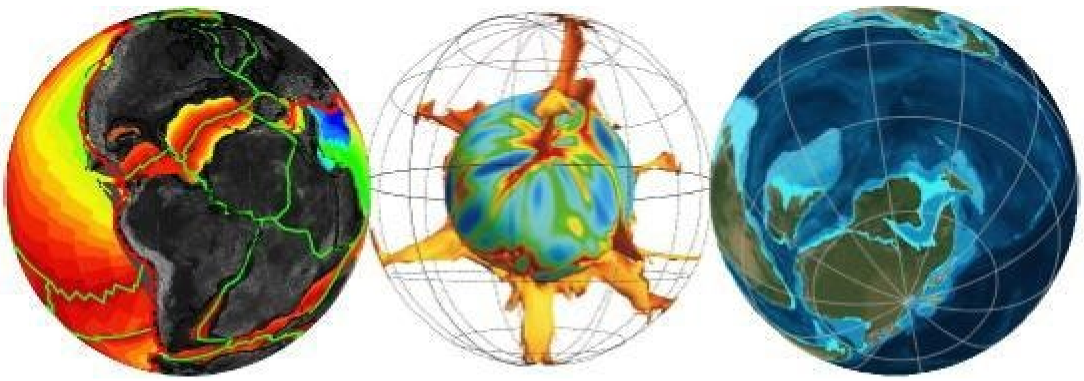


Figure 17: Geodynamic models connect the core, mantle, and crust. Analysis of scientific ocean drilling samples provides a way to validate these models (Source Earthbyte).

The connections between Earth's deep interior and surface strongly influence everything from our planet's topography, magnetic field intensity, environments, biodiversity, climate through to energy and mineral resources. Major planetary-scale disruptive events, such as changes in the Earth's magnetic field direction and intensity, the breakup of continents, global climate crises, and mass extinctions, are all expressions of these interactions. But how do these interactions work and what are their temporal and spatial rates and scales? Although recent advances in simulation and modelling of mantle dynamics and the core-mantle geodynamo have provided conceptual breakthroughs, targeted scientific ocean drilling is required to ground-truth models (Figure 17).

Key questions for this challenge include:

- Does the Earth's deep interior anchor plate tectonics and thus, can we develop an ancient GPS for our planet? How have the edges of Large Low Shear wave Velocity Provinces (LLSVPs) morphed and migrated through time, or have they remained fixed?
- What is the control of mantle plume activity on plate tectonic boundaries and motions - and vice-versa? To what extent do plumes affect rates and directions of plate tectonic motion and plate deformation, and have these massive outpourings of volcanism caused major perturbations to past global climate and ocean health?
- Can dramatic changes that have punctuated steady-state Earth be linked to major geomagnetic excursions and reversals? Can we even predict when geomagnetic excursions and reversals will occur in the future? What links the Earth's magnetic field, atmosphere, and life?

ANZIC PRIORITIES

This challenge is of particular interest to the ANZIC community and a research priority. The region between Australia and New Zealand is uniquely placed at the edge of a modern-day LLSVP within a zone of anomalous mantle and where a mantle plume(s?) has formed a series of age-progressive seamount trails. Australia's only active volcanoes, at Heard and McDonald islands, are modern examples of plume volcanism tied to the long-lived Kerguelen plume. Major seismic and volcanic hazards in New Zealand are directly related to the interaction of a LIP, the Hikurangi Plateau, with a subduction zone.

Challenge 14: What are the pathways, magnitudes and rates of physical and chemical transfers between the geosphere, hydrosphere, and biosphere?

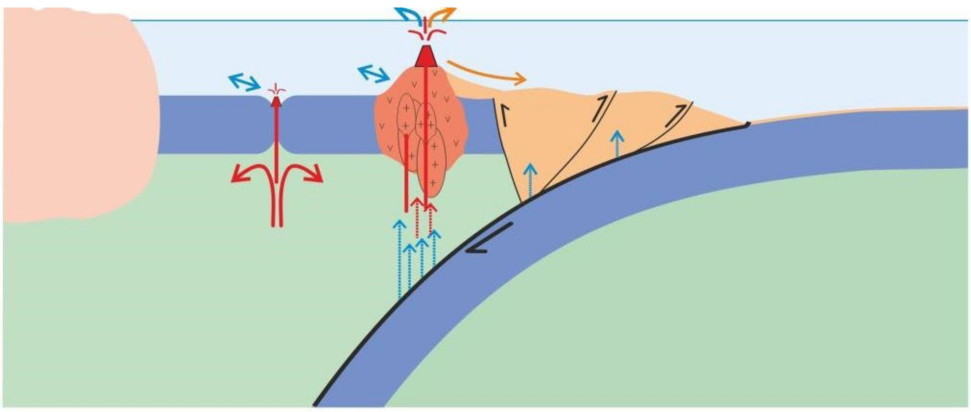


Figure 18: Principal physical and chemical transfers to and from the solid Earth at tectonic plate boundaries. Green = the mantle, blue = oceanic crust, pink = continental crust, orange = sediments, red = arc crust, and light blue = water. Pathways of aqueous fluids (blue arrows), magma (red arrows), and sediments (orange arrows). Source: N.Mortimer.

The deep Earth is constantly exchanging heat and mass with the oceans and atmosphere. These processes are enhanced at subduction zones, mid-ocean ridges, and back-arc basins. In the so-called subduction factory, volatiles such as water and carbon dioxide enter the deep Earth via subduction of crust, sediment, and contained water (Figure 18). Material leaves the deep Earth via magmatism in chains of arc volcanoes and rift basins, and via associated subaerial and submarine hydrothermal systems. The other major place that heat and elements reach the surface of the planet is at submarine mid-ocean ridges and back-arc basins, also via volcanoes and hydrothermal systems. While these broad settings are readily identified, the quantity, episodicity, and means of transfer of material, especially of magma, aqueous fluids, and of concentrated metals, is poorly understood.

Research in this challenge addresses how mantle volatile composition affects arc lava chemistry, the location of the ultimate source of metals deposited at hydrothermal vents, the role of extremophile microorganisms in fixing metals, and the pathways and rates of transfer of solid and fluid material (including CO_2 and CH_4) between different reservoirs.

ANZIC PRIORITIES

This is a challenge of particular relevance to ANZIC. Research results from modern day volcanic arcs and hydrothermal systems are highly relevant to improving understanding of ancient onland metalliferous ore deposits. Australia has a resource-dominated economy that benefits from improved insights into wealth-generating ore deposits. ANZIC scientists have established track records of research on the active submarine geothermal systems of the Manus Basin and Kermadec Arc. The geochemical results from this challenge are also important in improving knowledge of natural chemical baselines, transfer mechanisms, and fluxes relevant to research challenges on ocean health and climate.

Challenge 15: What are the composition, structure, and dynamics of Earth's upper mantle?

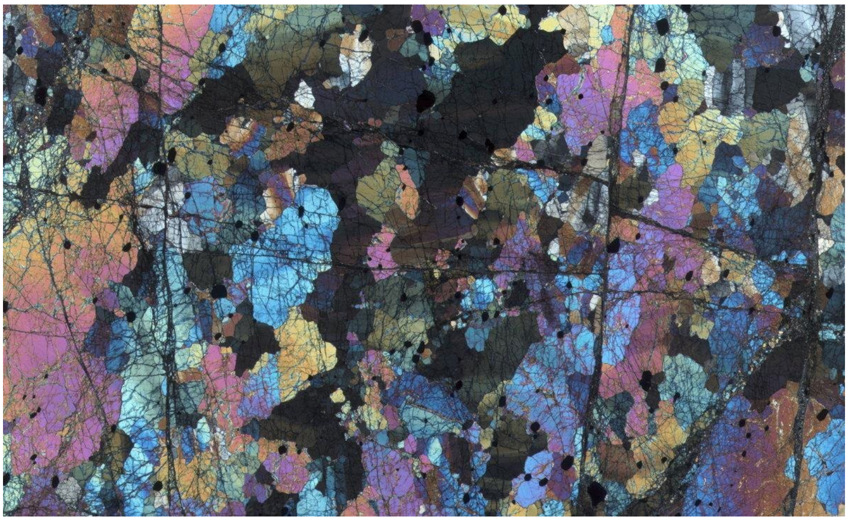


Figure 19: Thin section of Permian mantle: peridotite from the Dun Mountain Ophiolite Belt, New Zealand. Source: N.Mortimer.

The Earth's rigid crustal shell, with its tectonic plates, surface environments, and life, sits on top of the convecting mantle. Our knowledge of the present day mantle is framed mainly in terms of deep geophysical properties and their interpretations and is generally assumed to comprise the rock peridotite (Figure 19). However, density and seismic velocity variations used to define the crust-mantle boundary can arise from a combination of hydration and/or thermal effects as well as rock type. Direct sampling of the mantle is typically limited to rock outcrops in deformed ophiolite belts and from xenoliths in some lavas. However, these direct samples are ancient, not *in situ*, and may have been formed and preserved because of unusual or atypical tectonic settings.

Obtaining *in situ* samples of the upper mantle, a priority when scientific ocean drilling first started more than 50 years ago, remains a worthy objective. The key is to drill a continuous section that is transitional to overlying oceanic crust.

Questions that scientific ocean drilling can address include:

- Do ancient ophiolites represent typical oceanic crust?
- What are the mechanisms that drive upper mantle geochemical and isotopic depletion?
- On what spatial scales is the composition of Earth's mantle homogeneous and heterogeneous?

Considerable planning and technical advances (e.g., drilling depth) are necessary to achieve this challenge. Several potential sites in the Northwest and Northeast Pacific Ocean where mantle is drillable have already been identified.

THEME 5: Natural Hazards

Stresses and instabilities that accumulate over geological time can release energy on human timescales with devastating consequences to life and to critical infrastructure. Recent, catastrophic events have highlighted our lack of understanding of the fundamental processes behind many of the geohazards we face. The 2011 Tōhoku earthquake shocked the seismological community by involving large (<50 m) slip to trench, which contributed to the generation of the deadly tsunami that followed. Landslides and tsunami on volcanic flanks, similar to the 2018 Anak Krakatau event could greatly impact populated areas in the southwest Pacific and Indian Ocean region.

Other significant natural hazards, such as catastrophic storms and wild fires, have varied in frequency and intensity over geological time and these have left a record in marine sediments that can be examined to determine their spatial and temporal variability with changing climate (linked to Theme 2). Despite the social significance of these hazards to society in the Australasian and southwest Pacific region, many of the basic physical processes controlling the occurrence and magnitude of these natural events remain poorly understood. Scientific drilling plays a crucial role in addressing this need.

Over the past decade, scientific ocean drilling has permitted rapid advances in the understanding of plate boundary properties and earthquake processes, landslide mechanisms, and submarine volcanic processes. This has been achieved by focusing on a range of hypotheses-driven science questions. For example, borehole observatories have provided key data sets regarding the occurrence of slow slip events at the offshore Nankai Trough and Costa Rica subduction zones, illuminating how plate motion is accommodated near the trench in these hazardous locations (Davis et al., 2015; Araki et al., 2017). Such borehole observatories are revealing processes in real time, permitting tests of new hypotheses on what controls fault locking and release during slow and fast rupture. The Japan Trench Fast Drilling Project (JFAST) Expedition, a rapid response IODP effort following the March 2011 Tōhoku earthquake, gathered important data about the rupture mechanism and physical properties of the fault, revealing how such large slip to the trench was able to occur. The recent IODP Expedition 376 (May-July 2018) drilled five sites at Brothers volcano recovering~ 220 m of volcanic rocks from an active submarine caldera, showing that ocean drilling can provide important information to elucidate processes related to submarine volcanism in such a challenging environment.

Although much headway has been made on many of the challenges advanced in the IODP Science Plan 2013-2023 (Earth in Motion), these issues remain highly relevant and important, with many unanswered questions, and numerous new questions raised by recent events. Major gaps in our understanding of the magnitude, frequency, and impacts of such natural hazards requires information on the processes behind such events that can only come from scientific ocean drilling. Below, we outline four key Challenges in this area that can be addressed with scientific ocean drilling.

ANZIC PRIORITIES

The Hazard Theme has particular relevance to the ANZIC consortium because of our proximity to tectonically active plate boundaries. For ANZIC the research priorities in this theme are:

1. Understanding, monitoring and forecasting destructive earthquakes throughout the SW Pacific/SE Indian Ocean region, and identifying their tsunamigenic potential.
2. Identifying and quantifying risks to life and critical communications infrastructure from submarine slides on Australia's continental margin.
3. Tracking the marine record of catastrophic storms, floods and bushfires on the Australian and New Zealand continents through time and extrapolating this record forwards in the context of future climate extremes.

Challenge 16: Mechanisms and frequency of destructive earthquakes

The 2004 M9.2 Sumatra and 2011 M9.0 Tōhoku earthquakes occurred in places where such extreme events were largely unexpected, based on conventional wisdom at the time. While some seismologists hold the view that any subduction zone can produce a magnitude 9 earthquake, others suggest that the physical characteristics of subduction zones lead to different seismic outcomes, and/or likelihood of large earthquake ruptures. Some appear to creep slowly, some fail frequently in small earthquakes, and others are capable of accumulating and releasing centuries of elastic strain in catastrophic large earthquakes. It is also possible that most subduction zones may exhibit all these behaviours at various points in time, throughout the earthquake cycle. Addressing the temporal and spatial variability of plate boundary slip behaviour, and the mechanisms behind this are critical for assessment of seismic and tsunami hazards at plate boundaries worldwide.

Scientific ocean drilling methods are particularly well-suited to investigating processes occurring in the shallow (<5 km) portions of plate boundary fault zones. The unexpected, recent discovery of a range of near-trench slip behaviours at subduction zones, including episodic slow slip (Davis et al., 2015; Wallace et al., 2016; Araki et al., 2017), and massive, near-trench seismic slip during the Tōhoku earthquake (Fujiwara et al., 2011). Rather than faults neatly falling into seismogenic versus creeping categories, a spectrum of fault behaviours is now observed on the shallow portion of plate boundary faults, which may be governed by a range of factors including lithology, pore fluid pressure, and stress conditions (Saffer and Wallace, 2015; Chester et al., 2013). The physical processes dictating the spectrum of fault slip modes is not yet understood. This globally important problem can only be addressed with an integrated, system-level approach combining geological and geophysical evidence for past and present plate boundary behaviour, with geophysical and scientific drilling to ground-truth the physical conditions that exist on the plate boundary.

Key questions for this challenge include:

- Which subduction zone segments are more likely to produce large earthquakes and what properties govern that likelihood and frequency?
- What are the physical processes that control subduction interface slip behaviour?
- What is the role of slow slip events in the earthquake cycle?
- Under what physical conditions do so-called “tsunami earthquakes” occur, whereby the tsunami is much larger than expected given the earthquake’s magnitude?

Refining and extending our paleoseismic records of past earthquakes are critical for improving our understanding of the magnitude and frequency of earthquakes and informing our understanding of earthquake rupture segmentation. Great subduction earthquakes beneath continental margins leave tell-tale geological signatures of sudden vertical movement of coastal geomorphology and sedimentary environments, whilst co-seismically triggering sediment-laden offshore turbidity flows that transport and redeposit sediment (turbidites) into slope basins. However, at present we lack comprehensive data sets that allow conclusive distinctions between quality and completeness of the paleoseismic archives, as they may relate to different sediment transport, erosion and deposition processes versus variability of seismogenic behaviour across different segments of subduction zones. Nevertheless, many recent studies, which are mostly based on conventional shallow piston cores (Goldfinger et al., 2003), demonstrate the potential of this research concept extended further back in time (targeting deeper records). At many subduction zones in the western Pacific, scientific drilling has the potential to develop long, robust records of past earthquakes and integrate margin-wide off- and on-shore geological records of major paleoearthquakes spanning many seismic cycles (c. 10,000 years), informing probabilistic seismic and tsunami hazard models.

Understanding the factors that control slip behaviour along the shallow reaches of subduction zones is crucial for evaluating tsunami hazard. tsunamigenic regions lie offshore, often in deep water (>3000m). This type of region also provides the source for tsunami earthquakes, which are shallow, long duration earthquakes that generate disproportionately large tsunami relative to the amount of ground shaking. Two tsunami earthquakes offshore Gisborne, New Zealand, in 1947 are excellent examples of the mysterious arrival of disproportionately large (6-10 m) tsunami after only moderately sized earthquakes (Local Magnitude < 6.0) (Bell et al., 2014). Global tsunami earthquake distributions span a diverse range of physical settings and do not appear to be influenced by whether the deeper portion of the subduction zone fault has a history of great earthquakes (e.g. northeast Japan), or slips via smooth, aseismic creep (e.g. North Hikurangi: Figure 20). Hence, a major unknown presently limiting global assessments of tsunami hazard is if the potential for near trench rupture is prevalent across all subduction zones (either in conjunction with slip along the deeper megathrust, or independently as near-trench tsunami earthquakes), or if unique physical characteristics locally promote this mode of failure. Scientific drilling can enable direct comparison of physical properties between regions with a history of tsunami earthquake rupture (e.g. Tōhoku, N. Hikurangi, Nicaragua, Java) with other subduction settings (such as Barbados and Cascadia) that have not produced these events.

IODP CORK (Circulation Obviation Retrofit Kit) observatories provide long (>10 years) time series of *in situ* physical and chemical properties beneath the seafloor, and are one of the only reliable means for undertaking long-term monitoring of deformation processes at offshore plate boundaries. Such observatories have revealed the existence of episodic slow slip events near the trench at the Nankai and Costa Rica subduction zones, opening our eyes to the spectrum of behaviour of the shallow plate boundaries there. IODP scientific drilling has a unique, much needed role to play in using observatories to resolve the nature of contemporary deformation at offshore plate boundaries, and to reveal the relationship between slow slip and seismic slip. Increasing the number of subseafloor observatories at plate boundaries, particularly in the Pacific Rim region, will make major contributions to global efforts to characterize (for the first time) the spectrum of slip behaviour on offshore plate boundaries, and the role of this in the hazard and risk posed to Pacific Rim nations.

Assessing great earthquake potential remains critically dependent on resolving what factors determine whether a fault can lock up and accumulate elastic stress, or has a tendency to creep or frequently fail in small earthquakes. Geodetic research along subduction zones in southwest Japan, New Zealand, and South America reveal sharp and pronounced lateral changes in fault locking, and provide an opportunity to isolate the variables that control these changes in fault locking/seismic potential. Scientific drilling in transects that span locked-unlocked transition zones will probe the characteristics that control these transitions, and will provide underpinning petrophysical data necessary to extract quantitative information on physical properties along the deeper portions of megathrust faults from marine geophysical data.

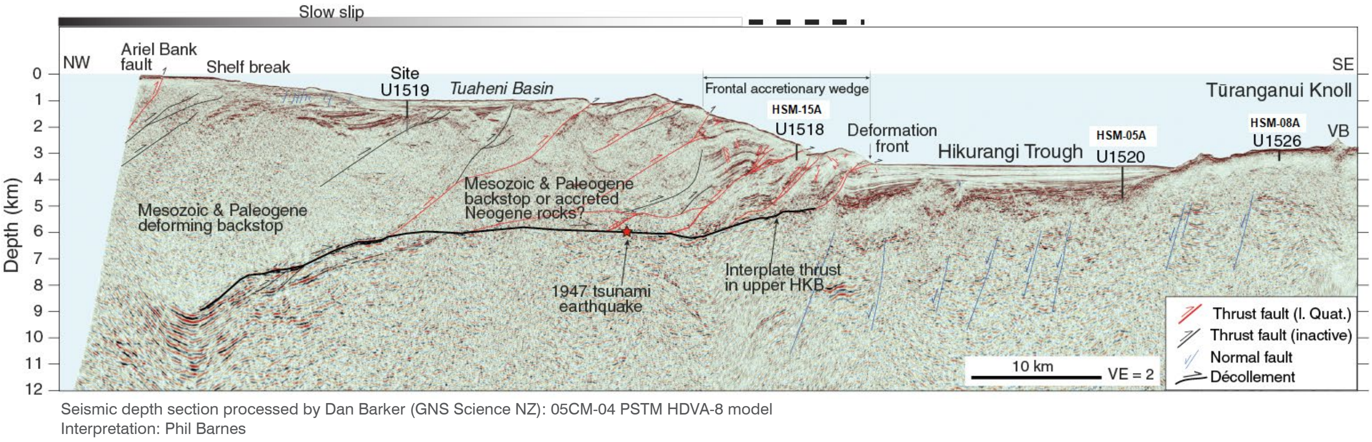


Figure 20: Seismic section of northern Hikurangi margin transect investigated by IODP expeditions 372/375, showing locations of intraplate and frontal wedge fault system, and the incoming sediment section. This margin is a priority for future deep riser drilling. From Wallace et al., 2019.

Challenge 17: Impacts of submarine and coastal volcanism

Volcanic hazards extend beyond the risks from ash clouds, air fall, pyroclastic flows and lava streams on land. Phreatic eruptions rise from the seabed and pose a hazard to shipping and to seafloor pipelines and communication cables. The precursors to, and evolution of, these events are still poorly known owing to the scarcity of sub-marine and sub-seafloor observations. Most consequentially, collapse of the submerged flank or crater wall of a large volcanic edifice may trigger a tsunami that reaches land nearby, and the largest events of this type are known to have affected entire ocean basins in the past. Despite many studies in this field over the past three decades, we still have a poor understanding of where and how marine-volcanic hazards are manifest.

17.1 Recognizing the tsunamigenic potential of volcanic caldera and flank collapse

Volcanic island landslides, their associated tsunamis, and volcanic eruptions pose significant natural hazards to both life and infrastructure. Lateral flank collapse of shield volcanoes can yield enormous landslides with volumes more than 300 km^3, such as those in the Hawaiian, Canarian, Cape Verdean, and Réunion archipelagos (McGuire, 2006). These are among the largest mass movements on Earth, whose size is far larger than any subaerial landslide. Such voluminous landslides are especially hazardous because they may cause high-amplitude tsunamis on entering the ocean and be directly associated with major volcanic eruptions (Figure 21) (Hunt et al. 2018). However, the relationship between volcanic island landslides and large explosive, often caldera-forming, eruptions is poorly known. Furthermore, the relationship between hydrothermal and volcanic processes is still poorly understood in the submarine environment. Hydrothermal circulation is a very efficient way to cool down the magma body feeding a submarine volcano, however, major collapses can be induced by hydrothermal pressurization (Reid, 2004) and weakening of volcanic rocks induced by hydrothermal alteration (Lopez and Williams, 1993).

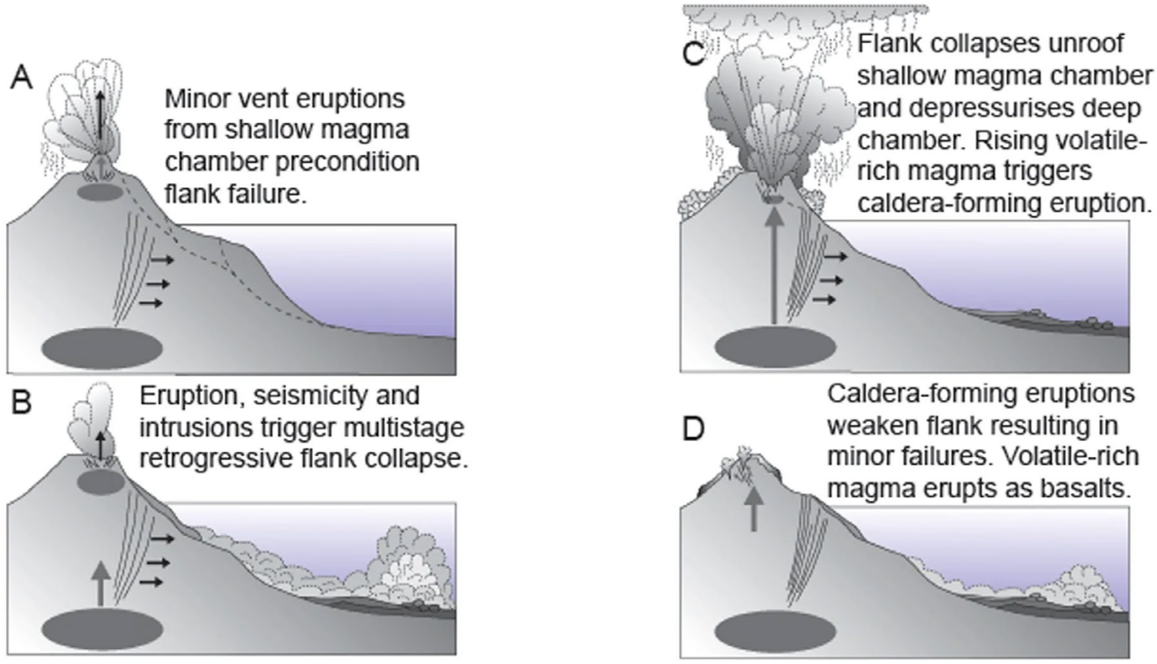


Figure 21: Chronology of a cataclysm. From Hunt et al., 2018.

Drilling in proximal and distal locations on submarine flanks and adjacent basins can help constrain timing, sizes and mechanisms of collapse events. Volcanic island flank collapse leads to decompression of relatively shallow magma chambers likely present during caldera-forming eruptions. While landslides perhaps induce eruptions, the style and explosivity of those eruptions are likely constrained by the properties of the magma chamber (Hunt et al., Nature SR, 2018). Thus, the composition and facies of submarine volcanic sediments preserve a chronology of volcanic eruptions and landslides. Coring and downhole logging and reveal facies characterizing different flow events that can be accurately dated. The drilling and seismic data can be used to calibrate and improve models of volcanic island hazards. (Locations – Kermadec Arc Islands, New Britain Arc, PNG)

In addition, submerged volcanic eruptive processes and transport and deposition of the eruptive products is a poorly understand problem. The Kermadec arc is an ideal location for such an effort, because (a) there are a large number of submarine volcanoes that have always been submarine and have produced eruptions with significant volume, (b) submarine calderas such as Macauley, Havre and Healy would be an excellent locale to investigate pyroclastic transport and depositional processes into the sea (arcuate sediment waves at Macauley are observed on the order of 100 m high and 1 km wavelength), and (c) 80% of the Kermadec volcanoes are hydrothermally active providing a natural laboratory to investigate the relation between hydrothermal processes and flank collapses.

17.2 Understanding the mechanism of phreatic eruptions.

While over 70% of volcanism on Earth occurs in the marine realm, the previous IODP science plans have not specifically addressed the topic of phreatic eruptions in the world oceans and seas, or Surtseyan eruptions in shallow waters. Improvements in seismic imaging have revealed the 3D structures of submarine volcano fields in several ocean basins and margins that show the growth of volcanic cones and feeder systems that have been arrested at key stages of temporal evolution. Submerged volcanic eruptive processes and transport and deposition of the eruptive products is a poorly understand problem. In addition, submerged volcanic eruptive processes and transport and deposition of the eruptive products constitute a poorly understand problem. The Kermadec arc offers prime opportunities to advance understanding of the problem due to its many submarine volcanoes characterized by large eruption volumes and it submarine calderas (e.g., Macauley, Havre, Healy) that have generated pyroclastic flows. Furthermore, 80% of Kermadec volcanoes are hydrothermally active, thereby providing natural laboratories to investigate the relation between hydrothermal processes and flank collapses. Drilling to collect core and downhole logs will enable the stages of submarine eruptions to be documented and hazard potential to be assessed.

Key questions for this challenge include:

- How large and explosive are submarine eruptions?
- How do gases released by the magma drive eruption behaviour in the sea?
- How far do the volcanic products spread out underwater?
- What is the relationship between volcanic island landslides and large explosive, often caldera-forming, eruptions?
- What is the relationship between hydrothermal processes and submarine volcano flank collapses?
- What are the processes contributing to submarine volcanic eruptions and subsequent deposition of products and are the eruptive products emplaced all at once, or do they occur in multiple episodes?

Challenge 18: Mechanism of submarine slope failures.

Submarine slides and related mass transport deposits are almost ubiquitous around the margins of the world's ocean basins. While many slope failures are triggered by large and rapid sea level changes associated with glacial cycles, other occurrences are more sporadic or locally triggered by high rates of sediment loading, or significant earthquakes. The range of slide types and the complexity of their evolution in time and space, as they progress and disperse downslope, is now being recognized. Movements of some of the largest submarine slides have been truly catastrophic events in Earth's history, while smaller movements have been observed on human timescales: even modest sized turbidite flows have disrupted infrastructure and damaged submarine pipelines and cables. Preserving life has become more challenging as sea level rises and increases the vulnerability of many coastal communities. Protecting infrastructure has become more important as our economy and our way of life relies increasingly on intercontinental networks of fibre optic cables.

18.1 Risk factors and triggering mechanisms of destructive and tsunamigenic landslides

Proximal causes of marine slope failure include rapid sea level changes, variations in sedimentation rate and changes in pore fluid pressure along decollement horizons. However, these causative agents rarely act alone. For example, adjacent to glaciers we may see changes in melting rate, eustatic sea level and local isostatic sea level, potentially accompanied by a change in water chemistry from perturbed hydrogeology, all act in concert.

To truly be able to quantify the risks from submarine slides on different ocean margins, representative examples should be chosen of the following submarine failure categories:

1. Sediment overload type failure away from glacial forcing and seismic triggering.
2. Retrogressive submarine slides associated with headwall erosion.
3. Seismically triggered events: liquefaction type and slide type. These have resulted in significant fatalities, e.g. in Indonesia and Papua New Guinea. Sometimes rapid response is needed.
4. Slides associated with basal pore pressure changes.
5. Gas hydrate and shallow-gas related slides, e.g. Cape Fear slide, which remains undrilled but has been a conspicuous target for over two decades during which our understanding of natural gas hydrate systems has advanced significantly. Expedition 372 drilling shed some light on a submarine slide in a gas hydrate zone, but not as predicted.

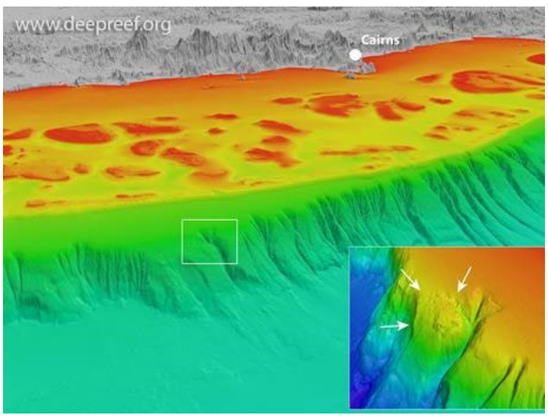
The value of logging while drilling technologies to image slide materials was highlighted in expedition 372 and is applicable to other settings. New sampling technology, such as vibracore is required to obtain good quality cores to study fabrics and physical properties of incohesive, uncemented sediments. To understand cause and effect of pore pressure fluid flow and submarine seepage, erosion and blow-outs we require a step change in technology for pore pressure and temperature measurement, such as Mini-CORKS and rig-deployable piezocone/penetrometers.

The Australian Continental margin offers a range of settings, and spectacular “drilling ready” examples of several different styles of slope failure.

- Northeast Margin from New South Wales to Queensland has classic examples of large block failures from the continental shelf margin, that have been well imaged by multibeam bathymetry, sub-bottom profiling and some deeper seismic (Fig. 22a). The overloading of the shelf edge with northwards transported sediment provides the apparent root cause of the instability, but the timing of events and present level of risk are unknown. The poorly understood cause and effect relationships between the block slides and the pockmark fields warrant further investigation with shallow coring, tiltmeters, piezocone and ultimately non-riser drilling.

- The S margin is characterized by a variety of submarine failures, ranging from block slides in Gippsland, Otway and Bremer basins, to sheet slides and debris-flow mass transport complexes on the Ceduna delta. This area offers opportunities to combine source to sink understanding of slides (see below) together with collection of Mesozoic to Neogene history of continental break up and oceanic circulation developments.

(a)



(b)

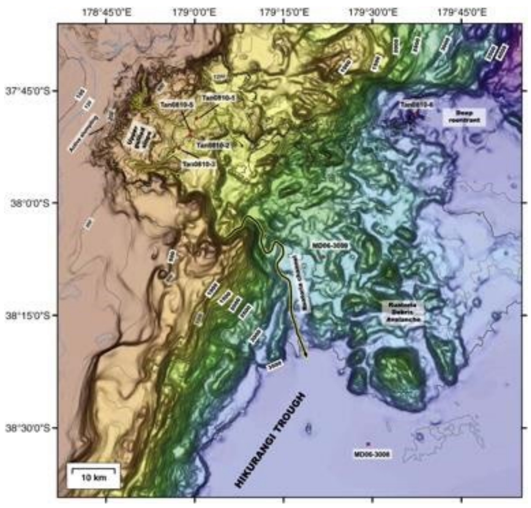


Figure 22: (a) Slope failures associated with pockmarks offshore northern Queensland, Northeast Australia. Source: Deepreef Explorer (b) The giant Ruatoria subsea avalanche offshore NE New Zealand. Source: Pouderoux et al., 2012.

- The NW margin has examples of major slide MTD (mass-transport deposits) complexes that are spectacularly well imaged in extensive multibeam and industry quality 3D seismic. These affects both carbonate and clastic substrates and in several places sequences of currently active and palaeo slope failures can be accessed within 600-800m of the seabed.
- The Hikurangi margin of New Zealand contains a spectacular assemblage of slope failure and MTD types, many of which are exceptionally well imaged by multibeam, 2 and locally 3D seismic. Expeditions 372 and 375 opened up some ground truth of processes in these slides and opens the door to further investigations of remarkable structures such as the Ruatoria slide (Fig. 22b).

18.2 Evolution of mass transport deposits from source to sink

Integrating technologies enables data collection and synthesis from proximal to distal regions of a mass transport system. Deep ocean drilling, coring and downhole measurements from IODP platforms compliment the capabilities of bathymetric and seismic imaging, seabed coring and ROV (Remotely operated vehicle) investigation of associated pockmarks and seepages.

18.3 Measurement and monitoring of pressure and strain fields in regions of active slope movement

Slides deemed to present a potential risk can be instrumented with tiltmeters but these only indicate movements once they have started. Precursors to major slide events, such as changes in pore fluid pressure, can be monitored using instrumented boreholes deployed from ocean drilling platforms.

Challenge 19: Magnitudes, impacts and frequency of natural disasters

Natural disasters such as bushfires, catastrophic floods and droughts affect most habitable regions on Earth. Their frequency and intensity are expected to increase in our changing climate and risk management strategies for natural disasters is a priority for many countries with growing human population living on floodplains and coastal areas. Scientific drilling and monitoring at key sites of the world oceans and continental shelves is essential to understand the magnitudes, impacts, and frequency of natural disasters. Marine sediment records of natural disasters from the geological past are also useful to understand the causes of rapid climate changes affecting life on Earth. One example is the ongoing debate on what caused the cold event Younger Dryas at the end of the last glacial period 12,000 years ago; a meteorite impact or the catastrophic drainage of Lake Agassiz in North America (Daulton et al. 2017). Planning for ocean drilling under this challenge should aim at identifying the spatial and temporal distribution of past natural disasters to inform the future.

9.1 Tracing the impacts of mega-storms, floods and wildfire through time in marine sediments

Terrestrial dust, sediment from megastorms and floods and charcoal from wildfires (Scott 2010) are ultimately stored in the ocean. Therefore, ocean drilling recovers critical time series from sediments and marker biota such as corals (McCulloch et al. 2003) and fire biomarker (e.g., Lopes dos Santos et al. 2013), that can be combined with modern observations, historical data, and continental proxies, to generate a comprehensive understanding of the mechanisms and physical processes driving natural disasters, megafauna extinctions and human migration pathways. There is scope for continent to ocean transect, mission-specific platforms and collaboration with the International Continental Drilling Program (ICDP). Areas of interest are near large river mouths, such as the Bay of Bengal and the Gulf of Mexico, and downwind major dust emission zones, such as the Atlantic Ocean for Saharan dust and the Southern Ocean for Australian dust.

Technology and Engineering

The legacy platform

In order to optimize the use of scientific ocean drilling data produced through time, the implementation of a user-friendly online portal is proposed. This portal would allow the visualization of drilling sites and offer easy and fast access to shipboard measurements and various datasets (genomics, meta-data, chemical, and physical measurements). This platform will also integrate a scientific ocean drilling DNA database to facilitate the development of a global biogeographical map of the deep biosphere and the assessment of the biosphere response to environmental changes over time. This legacy platform should also include the development of new technologies and workflows, including "biobanking DNA" so that as the 'omics technologies rapidly evolve, the samples can be re-interrogated to answer research questions we either don't have yet or are unable to answer due to present technological restrictions. There is also a need to include technologies from the emerging eDNA field and include different markers, metagenomics, and transcriptomics for the microbiology field of research. In addition, in order to address the research challenges identified for the new "Ocean Health Through Time" theme, it appears necessary to combine deep drilling campaigns with collection of additional water column samples/measurements and ensure the recovery of the top surface sediments. The recovery of these "Anthropocene sediments" can be achieved through the complementary use of multicorers.

The workflows should also be amended so that they include standardization of methods (collection, wet-lab analysis, and bioionformatics processing) to allow for broad-scale comparisons to be effectively conducted. This is crucial to assess biosphere variations along gradients and comparison with other programs (e.g., ICDP, the Australian microbiome, etc.).

Finally, a strong science outreach component should be incorporated in this legacy platform, not only during the scientific ocean drilling expeditions but also afterwards, in order to increase the global impact of the research conducted on core material and borehole data.

The synergy platform

Dedicated non-riser and riser scientific ocean drill ships offer outstanding potential for complementary and synergistic marine science data and sample acquisition. In particular, frequent expeditions to remote, understudied regions of the ocean basins and drilling at a single site for days to weeks to months present extraordinary opportunities for adding significant value to primary expedition goals, two of which are highlighted below.

Seabed 2030

Scientific ocean drilling vessels equipped with multibeam echosounders, Autonomous Surface Vehicles (ASVs), and/or Autonomous Underwater Vehicles (AUVs) can contribute strongly to the goals of Seabed 2030 (https://seabed2030.gebco.net/) by actively surveying the global ocean floor. The goal of the Nippon Foundation-GEBCO Seabed 2030 project is to complete the bathymetric map of the world ocean floor at previously unachieved depth-dependent resolutions. Collation of all bathymetric data in August 2018 when Seabed 2030 commenced revealed that only just over 6% of the world's ocean floor has been directly sampled acoustically, with most gaps in water depths >3000 m, which represents 75% of the area of the global ocean. The number of vessels transiting the vast areas of the world's oceans outside of main shipping lanes, fishing grounds, and seafloor pipeline/cable laying routes is limited, so the lack of data is a problem of access. We propose that all permanent scientific ocean drilling platforms be installed with multibeam echosounders, ASVs, and/or AUVs to map the ocean floor. Multibeam data would be acquired during all transits. During drilling, coring, logging, and other on-site operations, each drilling platform would serve as a 'mother duck' while one or more vehicles would be deployed as 'baby ducks'. scientific ocean drilling in collaboration with Seabed 2030, can help realize the goal of completely mapping the global seafloor by 2030.

Ocean Health, Ocean Change, Biodiversity, and Benthic Habitats

Remotely Operated Vehicles (ROVs) typically deployed from ocean drilling platforms worldwide, but heretofore rarely utilized by scientific ocean drilling, constitute a technology that would significantly advance the Ocean Health Through Time and Global Climate themes as well as contribute to the global biodiversity and habitat mapping communities. During drilling, coring, logging, and other on-site operations, ROVs equipped with multicorers can recover the critical sediment-water interface commonly lost with advanced piston coring methods. Studies of this interface enable reconstruction of ocean changes to the present day, provide information on anthropogenic additions to the sediment record, advance understanding of modern depositional systems, and assist in interpretation of deeper time proxies from older sediment. ROVs equipped with cameras can image biodiversity and benthic habitats, both the subject of major international research efforts.

Benefits and Applications

The International Ocean Discovery Program (IODP) connects constitutes a global community of thousands of scientists, multiple research vessels, and three core repositories with state-of-the-art laboratories, open access samples and data, and borehole experiment and monitoring sites. The scope and scale of this global endeavor offer unparalleled benefits and applications.

Education and Training

Graduate students, and early-career scientists deeply engage with scientific ocean drilling research. Working together at sea and ashore with international teams of scientists and engineers is a consummate educational experience and training ground for future generations of Earth system scientists. Undergraduate students and schools have opportunities to interact with science teams through outreach efforts during expeditions and while research vessels are in local ports.

Public Outreach

Recognition of the ocean, its health, and its importance in the Earth system is growing. scientific ocean drilling has a critical role in informing, influencing, and inspiring the global citizenry about the Earth system through public communication, the media, public institutions, and social networking.

Research Synergies

Research themes of scientific ocean drilling share objectives with Australian and New Zealand national research priorities, publicly funded research agencies, industry, and international research programs. Scientific ocean drilling offers critical geological and biological samples, ground truth of geophysical data, and boreholes for experiments and monitoring for collaborators.

Resource Understanding

Scientific ocean drilling provides basic research understanding for numerous proven and potential geological and biological resources. These include conventional hydrocarbons and gas hydrates, seafloor metal deposits, relationships between microbial communities and hydrocarbons, potential CO_2 storage environments. Additionally, advances in the understanding of deep sub-seafloor biosphere microbial communities has potential for the development of new medical and commercial compounds.

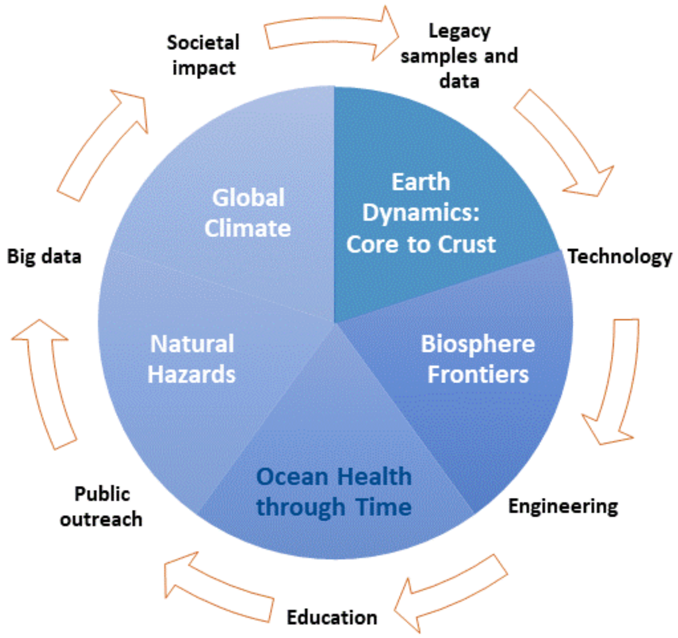


Figure 23. Ocean Planet derived themes supported by broad universal underpinnings.

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Appendix 1.

Pre-workshop white paper submissions.

White paper submission

1. Kliti Grice & Anais Pages	A new era of biogeoscience - At the limits (or nor	Curtin University & CSIRO
2. Linda Armbrecht & Laura Weyrich	Applications of improved ship-board sampling	University of Adelaide
3.David Haig	Identify Gaps in scientific/commerical drilling in	University of Western Australia
4. Fabio Caratori Tontinin & Cornel de Ronde	Splitting of a proto-arc and the evolution of a young	GNS Science
5. Eelco Rohling	Drilling around Antarctica /revisting the	Australian National University
6. Vanessa Lucieer, Jo Whittaker, Mike Coffin and Geoffroy Lamarche	The challenge of building the global ocean map - the autonomous future of bathymetric mapping	University of Tasmania
7. Vanessa Lucieer, Jo Whittaker, Mike Coffin	The challenge of building global ocean map - 75% deeper than 3000m	University of Tasmania
8. Dan Bassett	Hikurangi subduction inputs	GNS Science

Appendix 2.

Ocean Planet Workshop attendees.

ANZIC Ocean Planet Workshop Attendees

Name		Institution
Jake	Andrae	University of Adelaide
Sarah	Andrew	Australian National University
Leanne	Armand	ANZIC
Dan	Bassett	GNS Science
Karl	Bischoff	UWA
Helen	Bostock	National Institute of Water and Atmospheric Research
Fabio	Caratori Tontini	GNS Science
Ben	Clennell	CSIRO
Mike	Coffin	IMAS/University of Tasmania
Marco	Coolen	Curtin University
Cornel	De Ronde	GNS Science
Paul	Dennis	The University of Queensland
Elizabeth	Dowding	UNSW
NIicholas	Dyriw	Queensland University of Technology
Chris	Elders	Curtin University
Steven	Eggins	Australian National University
Nobu	Eguchi	JAMSTEC/Guest
Bethany	Ellis	Australian National Univeristy
Robert Emo	Emo	Queensland University of Technology
Neville	Exon	Australian National Univeristy
Calum	Fox	WA-OIGC, Earth and Planetary Science
Kliti	Grice	Curtin University
Sean	Gulick	University of Texas at Austin/Guest
Ron	Hackney	Geoscience Australia
Katie	Harazin	Australian National University
Andrew	Heap	Geoscience Australia
Stuart	Henrys	GNS Science
Simon	Holford	University of Adelaide
Matthew	Jeromson	University of Canberra
Martin	Jutzeler	University of Tasmania
Myra	Keep	University of Western Australia
Mark	Kendrick	Australain National University
Joseph	Knafelc	Queensland Univeristy of Technology
Anthony	Koppers	Oregon State University/Guest

Name		Institution
Kelly-Anne	Lawler	Australian National University
Agathe	Lise-Pronovost	University of Melbourne
Helen	McGregor	University of Wollongong
Robert	McKay	Victoria University of Wellington
Mardi	McNeil	Queensland University of Technology
Jim	Mitchell	Flinders University
Nick	Mortimer	GNS Science
Robert	Musgrave	Geological Survey of NSW
Clive	Neal	University of Notre Dame/Guest
Yona	Nebel-Jacobsen	Monash University
Luke	Nothdurft	Queensland University of Technology
Anais	Pages	CSIRO
Joanna	Parr	CSIRO
Ian	Poiner	ANZIC
Alix	Post	Geoscience Australia
Rachel	Przeslawski	Geoscience Australia
Marianne	Richter	Monash University
Christina	Riesselman	University of Otago
Henrik	Sadatzki	Australian National University
Aleksey	Sadekov	University of Western Australia
Maria	Seton	University of Sydney
Eva	Sirantoine	University of Western Australia
Craig	Sloss	Queensland University of Technology
Yohey	Suzuki	The University of Toyoko/Guest
Asrar	Talukder	CSIRO
Chris	Turney	University of NSW
Jodie	van de Kamp	CSIRO
Lloyd	White	University of Wollongong
Morgan	Williams	CSIRO
Nicky	Wright	Australian National University
Jim	Wright	Rutgers University/Guest
Greg	Yaxley	Australian National University
Song	Zhao	Australian Nationa University

Appendix 3.

The published EOS Meeting Report.

https://eos.org/meeting-reports/australia-new-zealand-plan-for-future-scientific-ocean-drilling

Australia–New Zealand Plan for Future Scientific Ocean Drilling

Australian–New Zealand IODP Consortium Ocean Planet Workshop; Canberra, Australia, 14–16 April 2019

The iconic Sydney Opera House provides a beautiful backdrop for the drilling vessel ***JOIDES Resolution***, flagship of the IODP. Credit: Ian Edwards

By Millard F. Coffin, Joanna Parr, and Leanne Armand 29 May 2019

A multidisciplinary community workshop has defined scientific themes and challenges for the next decade (2023–2033) of scientific ocean drilling using the capabilities of current and anticipated platforms of the International Ocean Discovery Program (IODP).

The workshop, attended by 75 mostly early-career and midcareer participants from Australia, New Zealand, Japan, and the United States, featured nine keynote presentations. Working groups identified important themes and challenges that are fundamental to understanding the Earth system and are addressable only by scientific ocean drilling.

IODP is the largest international program in the ocean and Earth sciences and among the largest international scientific research programs in any discipline. IODP explores Earth's history and dynamics using oceangoing research platforms to recover geological, geobiological, and microbiological information preserved in seabed sediment and rock and to monitor subseafloor environments through the global ocean.

Australia and New Zealand are 2 of 23 member nations of IODP—led by the United States, Japan, and Europe—and participate via the Australian–New Zealand IODP Consortium (ANZIC). ANZIC comprises 16 universities and four publicly funded research agencies in the two countries.

The ANZIC Ocean Planet Workshop program was built around five scientific themes: Biosphere Frontiers, Earth Dynamics: Core to Crust, Global Climate, Natural Hazards, and Ocean Health Through Time. Workshop sessions focused on these themes and 19 associated scientific challenges. Underpinning the themes and challenges are legacy samples and data, technology, engineering, education, public outreach, big data, and societal impact.

The ANZIC Ocean Planet Workshop program was built around five scientific themes: Biosphere Frontiers, Earth Dynamics: Core to Crust, Global Climate, Natural Hazards, and Ocean Health Through Time.

Although all challenges are important, the asterisks that follow denote those of particular relevance and interest to ANZIC.

Biosphere Frontiers addresses the habitable limits for life*; the composition, complexity, diversity, and mobility of subseafloor communities*; the sensitivity of ecosystems to environmental changes; and how the signatures of life are preserved through time and space*.

Earth Dynamics: Core to Crust encompasses the controls on the life cycle of ocean basins and continents*; how the core and mantle interact with Earth's surface*; the rates, magnitudes, and pathways of physicochemical transfer among the geosphere, hydrosphere, and biosphere*; and the composition, structure, and dynamics of Earth's upper mantle.

Global Climate entails coupling between the climate system and the carbon cycle; the drivers, rates, and magnitudes of sea level change in a dynamic world*; the extremes, variations, drivers, and impacts of Earth's hydrologic cycle*; and cryosphere dynamics*.

Natural Hazards involves the mechanisms and periodicities of destructive earthquakes*; the impacts of submarine and coastal volcanism; the consequences of submarine slope failures for coastal communities and critical infrastructure*; and the magnitudes, frequencies, and impacts of natural disasters*.

Ocean Health Through Time comprises the ocean's response to natural perturbations in biogeochemical cycles*; the lateral and vertical influence of human disturbance on the ocean floor; and the drivers and proxies of evolution, extinction, and recovery of life*.

A workshop report is in preparation, to be made available on the ANZIC website. This workshop is one of several held in 2019 by IODP member nations and consortia. Together, these workshops aim to formulate the next decadal science plan for scientific ocean drilling, which in turn will guide the focused planning of specific drilling, logging, and monitoring projects.

—Millard F. Coffin (mike.coffin@utas.edu.au), Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Australia; Joanna Parr, Commonwealth Scientific and Industrial Research Organisation, North Ryde, New South Wales, Australia; and Leanne Armand, ANZIC Office, Australian National University, Canberra, ACT, Australia

Citation: Coffin, M. F., J. Parr, and L. Armand (2019), Australia–New Zealand plan for future scientific ocean drilling, *Eos, 100*, https://doi.org/10.1029/2019EO125141. Published on 29 May 2019.

Photo credit: Ian Edwards

Australian and New Zealand IODP Consortium

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