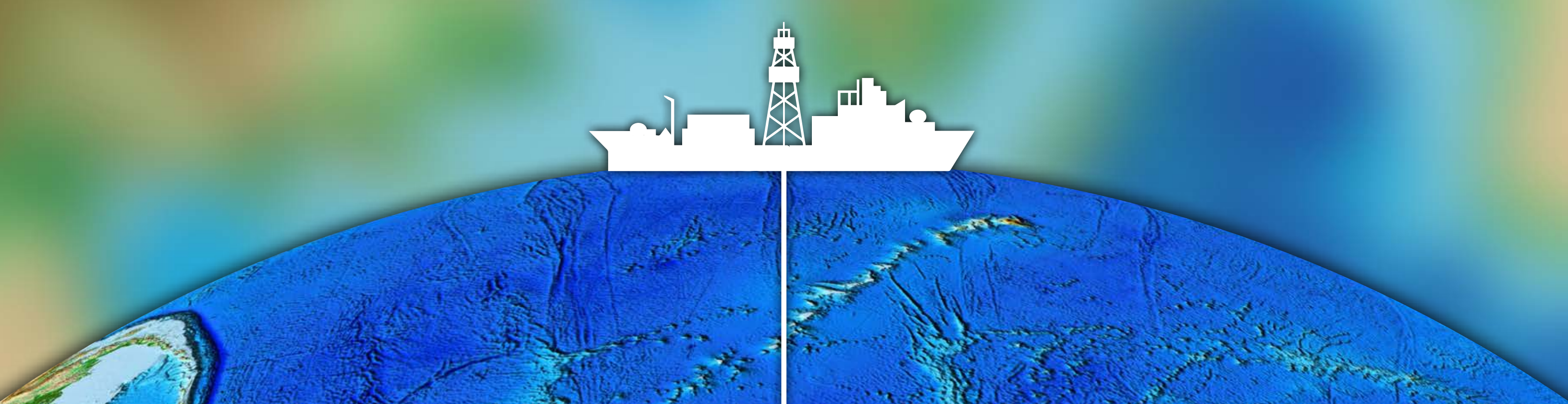
EXPLORING EARTH
BY SCIENTIFIC OCEAN DRILLING



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EXPLORING EARTH
BY SCIENTIFIC OCEAN DRILLING

2050 SCIENCE FRAMEWORK

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Mission

The *2050 Science Framework for Scientific Ocean Drilling* guides multidisciplinary subseafloor research into the interconnected processes that characterize the complex Earth system and shape our planet's future.

Vision

To be globally recognized as the authoritative source of information about ocean and Earth system history and its links to society.

Who We Are

We are an international scientific community pioneering global-scale interdisciplinary research below the seafloor of the world ocean.

WE RESEARCH the processes that connect the solid Earth, ocean, life, climate, and society.

WE EXPLORE the interconnected Earth in places that can only be accessed and understood through scientific ocean drilling.

WE TRAVERSE TIME to reveal the many interactions that shaped Earth's geologic past to illuminate our future.

WE COMMUNICATE knowledge gained through scientific ocean drilling to the global community.

INTRODUCTION

SCIENTIFIC OCEAN DRILLING THROUGH 2050

PRELUDE

Two hundred million years of Earth history are locked in sediments and rocks beneath the world ocean. Scientific ocean drilling provides access to this archive, allowing scientists to examine the interconnected processes that characterize the Earth system and shape our planet's future. The disciplinary breadth and global scope of scientific ocean drilling requires—and greatly benefits from—international collaborations that reach across, and in many cases beyond, the boundaries of all Earth science disciplines.

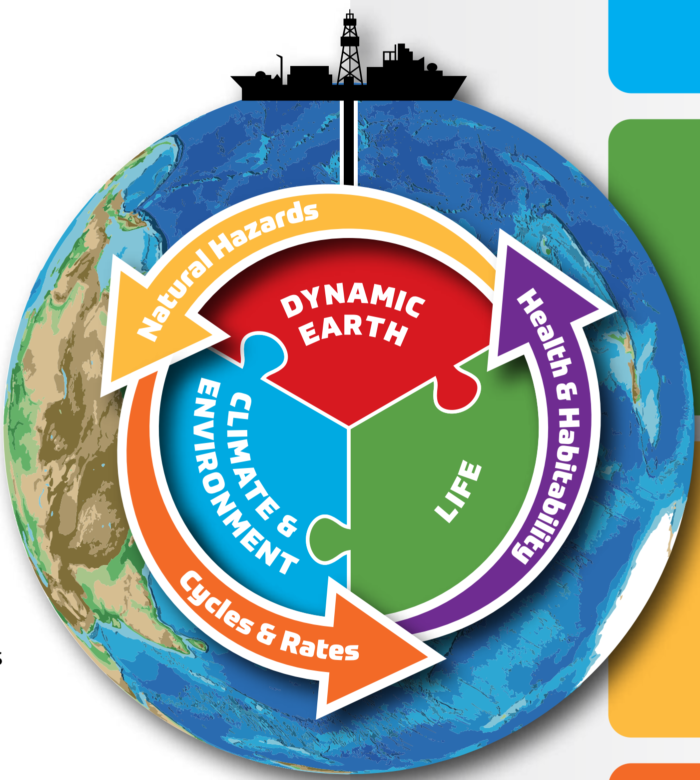
Scientific ocean drilling has fundamentally transformed our understanding of Earth. The earliest scientific drilling into oceanic crust in the South Atlantic Ocean verified the seafloor spreading hypothesis and revealed the relative youth of the seafloor compared to the ~4.5 billion year age of Earth. Scientific ocean drilling has allowed scientists to decipher the timing of the waxing and waning of Southern and Northern Hemisphere glaciation and to link that behavior to global, natural phenomena. Analyses of carefully collected and curated samples recovered by scientific ocean drilling have pushed the boundaries of knowledge of Earth's climate system, providing geologic context for interpreting anthropogenic impact on climate and the environment. Core analyses have also expanded understanding about the limits of life on Earth, having revealed a vast biosphere deep beneath the seafloor.

Over the coming decades, scientific ocean drilling is poised to contribute vital knowledge to address issues ranging from the mechanics of fault slip at subduction zones that lead to great earthquakes and tsunamis, to the high-CO_2 climate systems of past "greenhouse" worlds and their global repercussions. A new phase of scientific ocean drilling will provide data needed to improve the accuracy of computer models that predict future climate, including the pace of rising sea levels and melting of glacial and polar ice. Scientific ocean drilling is the only tool available for exploring life in the oceanic crust of our planet—the largest biome on Earth—providing a glimpse of the types of microbial life that might exist elsewhere in our solar system and beyond. In conjunction with new analytical techniques and innovative big data approaches, scientific ocean drilling will provide a unique lens into deep geologic time and a means to collect detailed information about currently active Earth processes and ground truth data for improving predictive Earth models. By addressing key questions about Earth's past, present, and future through interdisciplinary research expeditions and ensuing analyses, scientific ocean drilling will lead to a more profound understanding of Earth as one integrated, interconnected system.

This international *2050 Science Framework: Exploring Earth by Scientific Ocean Drilling* provides guidance to current and future generations of ocean drilling scientists on the research objectives that should be pursued. It focuses on the many ways in which scientific ocean drilling will increase understanding of the fundamental connections among Earth system components while addressing a range of challenging natural and human-caused issues facing society. The *Framework* calls for strong collaboration among Earth science disciplines and allied international research programs to meet scientific goals and promotes communication of scientific ocean drilling results to a broad global audience. Because this *Framework* has a long time horizon, progress toward achieving it goals will be assessed every five years. It will be a living online document to enable necessary adjustments and encourage the evolution of research areas as science advances and societal needs evolve.

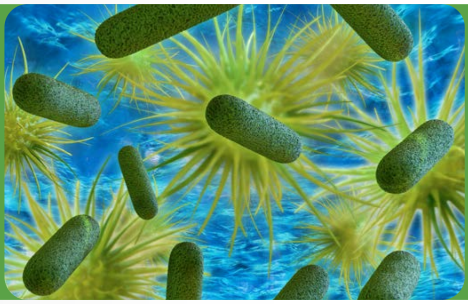
TOOLS FOR PROBING THE INTERCONNECTED EARTH SYSTEM

The dynamic Earth, its climate and environment, and all life that emerged and evolved on this planet are linked in myriad ways. These pieces of the Earth system in turn are connected to the cycles and rates governing the planet's processes and feedbacks, the location and intensity of natural hazards, and the health and habitability of the global ocean. To investigate how the interconnected Earth system works and to provide the ground truth needed to test Earth models, scientists rely upon highly specialized ocean drilling platforms equipped to collect continuous cores of sediment and rock and samples of fluids and microbes from beneath the seafloor, as well as deploy state-of the-art instruments and long-term observatories within subseafloor boreholes.



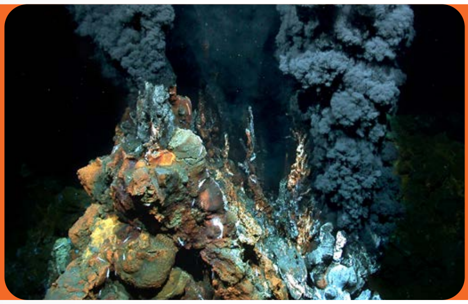
Dynamic Earth. Scientific ocean drilling provides the means to deploy long-term instruments and sample deep into Earth to reveal the dynamic interconnections between tectonics, convective mantle processes, earthquake and volcanic hazards, our planet's climate system, and Earth's habitability.

Climate and the Environment. Scientific ocean drilling provides access to long-term and high-resolution archives of the processes that govern the global circulation of the ocean and atmosphere, the dynamics of abrupt tipping points in ecosystems, and the global metronome of orbital climate cycles. Marine sedimentary records reveal the rates at which ice sheets melt, sea levels rise and fall, monsoon systems switch on and off, and past greenhouse warming occurred.



Life. Scientific ocean drilling cores contain details about the evolution, biodiversity, and productivity of marine organisms and the role life plays in the changing Earth system. Deep drilling and monitoring in borehole observatories advance research into biodiversity and evolutionary developments in the marine biome, the distribution of deep microbial life across ocean basins, the limits of life on Earth, and the possibility of life on other worlds.

Natural Hazards. Scientific ocean drilling recovers sediment and rock cores that inform us about hazards related to past earthquakes, tsunamis, volcanic eruptions, submarine landslides, and sea level rise. Borehole instrumentation and cabled monitoring stations, in conjunction with observations made on land, allow us to better evaluate future risks of natural hazards to society.



Cycles and Rates. Scientific ocean drilling acquires detailed information about the rates and magnitudes of energy, chemical, nutrient, and fluid exchanges between Earth's sediments and rocks, ocean, atmosphere, and life. These data reveal how global cycles moderate Earth's climate, form natural resources, and control the long-term evolution of life on Earth.

Health and Habitability. Scientific ocean drilling gathers critical information needed to more accurately predict Earth's response to natural and anthropogenic disruptions to the interconnected life-sustaining systems of our planet. This knowledge helps us evaluate our planet's future habitability.

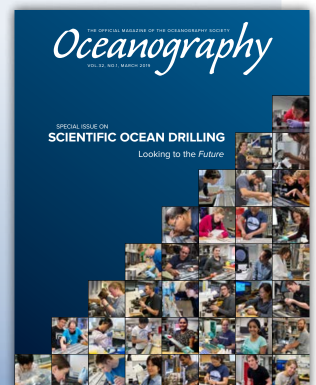
Scientific Ocean Drilling Discoveries

Over the past five decades, scientific ocean drilling has expanded our understanding of the Earth system by piecing together the basic rhythms of climate, the movement of tectonic plates, and the history of life in the ocean. Scientific ocean drilling has demonstrated that minor variations in Earth's orbit (called Milankovitch cycles) have controlled the timing of ice ages of the past 2.6 million years, the pulses of growth and decay in the Antarctic ice sheet over the past 50 million years, and changes in global monsoonal precipitation patterns. Drill cores have also revealed the increased strength and permanency of El Niño-Southern Oscillation conditions during warmer global climate intervals and that high atmospheric CO_2 concentrations are implicated in the much warmer ice-free "greenhouse" worlds of the Eocene (34–56 million years ago) and Cretaceous (66–145 million years ago). Moreover, scientific ocean drilling has shown that the Cretaceous was marked by multiple episodes of global ocean anoxia, that massive amounts of carbon released from marine sediments may have exacerbated temperature rise at the end of the Paleocene (56–66 million years ago), and that the rate of sea level rise during the last deglaciation was greater than 10 times the modern rate of over 3 mm/yr. As global deglaciation and temperature rise continue over the next decades, scientific ocean drilling data sets are important for predicting future changes in the rate of sea level rise.

Launched early in the era of plate tectonic theory development, scientific ocean drilling has also revealed much about how deep Earth mechanisms operate. It has confirmed that magma-dominated rifted margins represent the birth places of new ocean basins and that oceanic plateaus are the equivalent of continental flood basalts, forming through short-lived massive volcanism. It has shown that the Hawai'i and Louisville mantle plumes exhibited significant differential movements, providing insight into the nature and velocities of the large-scale mantle flow over the last 80 million years. Scientific ocean drilling has also repeatedly transformed our understanding of how oceanic crust forms at both fast and slow spreading mid-ocean ridges, how the asthenospheric mantle may get structurally exhumed at ultraslow spreading ridges, how subduction zones are initiated, and how marginal and full-scale ocean basins evolve. Coring through megathrust splay faults and installing borehole observatories and cabled monitoring have contributed to our understanding of the mechanisms of giant subduction earthquakes and "slow slip" earthquake phenomena.

Perhaps most unexpectedly, scientific ocean drilling over the last two decades has demonstrated that the deepest reaches within marine sediments, and even the rocky oceanic crust beneath it, are full of life. This subseafloor realm harbors the largest and deepest biome on Earth with untold new varieties of Archaea, Bacteria, Eukarya, and viruses. New drilling approaches allowed collection of uncontaminated samples, and great advances in DNA research and genomic sequencing accelerated understanding of the diversity and function of life that can subsist under harsh conditions over geologic time.

These examples are among a multitude of discoveries and scientific advances made over 50 years of scientific ocean drilling. Many more can be found in the March 2019 special issue of *Oceanography* on "Scientific Ocean Drilling: Looking to the Future" (see https://tos.org/oceanography/issue/volume-32-issue-01).



FRONTIERS IN SCIENTIFIC OCEAN DRILLING: THE 2050 SCIENCE FRAMEWORK

The overarching goal of the *2050 Science Framework* is to guide future subseafloor research that will reveal the key linkages, processes, feedbacks, and tipping points in the complex Earth system. Building on the results from 50 years of scientific ocean drilling, and taking advantage of advances in drilling, logging, and observatory technologies as well as the development of novel laboratory techniques and the growth in big data analytics, scientific ocean drilling is poised to advance knowledge at the next frontier—understanding Earth as an interconnected system.

As CO_2 levels in Earth's atmosphere are predicted to continue to rapidly increase in the very near term, it is critical to collect a wide range of paleoclimate records to test contemporary models that provide competing forecasts and that lay out different future scenarios for sea level rise, global ocean circulation, ocean acidification, ocean oxygenation, coral reef health, and expanding aridity patterns across continents. Systematically targeting pre-Holocene epochs and recovering high-resolution sediment sequences over decadal to millennial timescales in strategic locations around the world, possibly in grids or along transects, will provide the required synthesized global paleoclimate database. Comparing those paleoclimate records with their terrestrial counterparts over widely ranging spatial and temporal scales will enhance understanding of the Earth system and its responses to change.

The next generation of scientific ocean drilling must also address many fundamental, unanswered questions about the life cycle of oceanic crust and the large-scale structure and functioning of Earth itself. A key exploration goal is to investigate the nature of the Mohorovičić seismic discontinuity, or "Moho," and determine whether it indeed represents the crust-mantle boundary or it represents different phenomena in different tectonic settings. Drilling will collect critical details about how oceanic crust forms and evolves over tens of millions of years as it interacts with the hydrosphere and biosphere. It will examine how new plate boundaries initiate, how they evolve, and why they cease to exist. Other frontiers require us to further develop our understanding of how Earth's mantle operates and why most mantle plumes appear to form along the edges of large low shear wave velocity provinces that are located near the 2,900 km deep core-mantle boundary. These questions all have implications for how individual components of the Earth system connect.

Major gaps still exist in our knowledge about the processes and timescales of recovery of the Earth system following mass extinction events caused by both terrestrial and extraterrestrial natural phenomena. As we may be living through the sixth mass extinction event on Earth and the first caused by humans, it is critically important to establish the baseline state of our ocean's health and examine potential responses by the Earth system to comparable major perturbations, such as the Paleocene-Eocene Thermal Maximum 55.8 million years ago when CO_2 was rapidly released into the atmosphere.

Other key frontiers for future scientific ocean drilling include deepening our understanding of the profound threats to society posed by sea level rise, the increasing frequency and magnitude of extreme monsoonal rains and large-scale regional droughts, the deterioration of coral reef health, massive volcanic eruptions, and major submarine landslides. Subseafloor data are critically needed to assess what governs the occurrence of Earth's devastating giant earthquakes and tsunamis at subduction zones.

Scientific ocean drilling also seeks to advance knowledge of fundamental issues in science, such as those concerning the origins, evolution, and rules of life on Earth and elsewhere in the universe; how and if the ocean basins may provide long-term subsurface repositories for CO_2 sequestration; how large-scale geologic events such as earthquakes, landslides, and plate tectonic movements may have shaped Earth's ecosystems including subseafloor microbial communities; and how the health of the global ocean is modulated by the climate system and anthropogenic influences.

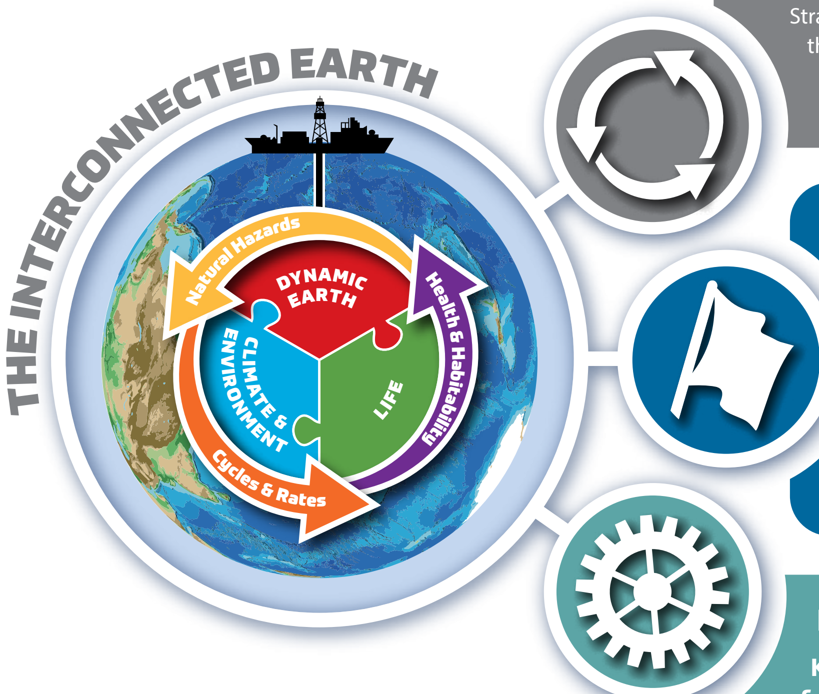
2050 SCIENCE FRAMEWORK COMPONENTS

The *2050 Science Framework* captures these exciting frontiers in seven *Strategic Objectives*, five *Flagship Initiatives*, and four *Enabling Elements*. The *Strategic Objectives* comprise broad Earth science research areas that form the foundation of scientific ocean drilling through 2050. Each objective focuses on understanding the interconnections within the Earth system. The objectives are wide-ranging and aspirational to allow new science to emerge through bottom-up proposal development and peer review. Collectively, the *Strategic Objectives* cover the interconnected processes and feedbacks of the full Earth system that can be uniquely investigated with scientific ocean drilling.

The *Flagship Initiatives* comprise long-term research efforts that require multi-expedition scientific ocean drilling over 10- to 20-year time intervals. Each multidisciplinary research endeavor aims to test scientific paradigms and hypotheses that inform issues of particular relevance or interest to society. The *Flagship Initiatives* typically combine research goals from multiple *Strategic Objectives*. Their implementation will be shaped by science proposals that develop coordinated strategies that include long-term planning, technology development, and innovative applications of existing and new scientific ocean drilling data.

The *Enabling Elements* serve to significantly advance the goals of scientific ocean drilling through numerous and varied broader impacts and outreach initiatives, partnerships and collaborations with organizations that have complementary scientific goals, and continued technology development and innovative applications of advanced data analytics.

The 2050 Science Framework Structure



STRATEGIC OBJECTIVES

Broad areas of scientific inquiry that focus on understanding the interconnected Earth system.

Strategic Objectives are multidisciplinary, cutting across the traditional themes of previous scientific ocean drilling efforts and are open-ended to encourage innovation and evolution of scientific ideas.

FLAGSHIP INITIATIVES

Long-term drilling endeavors that aim to inform issues of particular interest to society, typically combining goals from multiple Strategic Objectives.

Flagship Initiatives will require the community to develop strategies and technologies to implement multiple coordinated expeditions, taking advantage of the 25-year timeframe of the *Science Framework*.

ENABLING ELEMENTS

Key facets of scientific ocean drilling that facilitate our research activities, enhance our scientific outputs, and maximize their impact.

Enabling Elements include links with major allied programs, effective strategies to communicate results to the public, and the generation of new opportunities through novel technology and data approaches.

ENDURING PRINCIPLES

Implementation of the *2050 Science Framework* requires an international approach and a cohesive set of guiding principles for bringing online future scientific ocean drilling programs. These eight *Enduring Principles* follow current strengths in scientific ocean drilling.

Open access to samples and data. International scientists, facility operators, funding agencies, and program member offices must commit to continuing to provide free and open access to all samples in all core repositories and to all data deposited in internationally recognized online data repositories. Open access ensures equity: researchers from any institution, whether they participated on a scientific ocean drilling expedition or not, can request samples and access data for their use. It also allows future generations of scientists and students to apply new analytical techniques to core samples, while the availability of FAIR (findable, accessible, interoperable, reusable) data will allow use of advanced data analytics and modeling to test hypotheses and gain novel insights into the interconnections in the Earth system.

Standard measurements. Numerous Earth science data sets and observation types are unique to scientific ocean drilling and can only be collected by seagoing expeditions using highly specialized drilling platforms. These high-quality comparative data sets are the gold standard of scientific ocean drilling and a major requirement for addressing the research goals in the *2050 Science Framework*. To permit integrative data analytics and predictive modeling efforts, all data must be made available in standardized formats and collected by applying standardized analytical approaches.

Bottom-up proposal submissions and peer review. A strength of scientific ocean drilling has always been its "bottom-up" ethos and focus on transformative frontier research. Decisions about deployment of its drilling platforms are reached through an open, meritocratic, peer-reviewed proposal system that ensures that the best science is accomplished by incorporating the perspectives of hundreds of scientists at the cutting edges of their fields. Future scientific ocean drilling will also be directed by community-generated proposals targeting the *Strategic Objectives* and *Flagship Initiatives*. International collaborative proponent teams will submit research proposals aimed at transforming the aspirational science goals outlined in this *2050 Science Framework* into successful expeditions and strategies. The evaluation of proposals and scheduling of future expeditions will occur through international science advisory panels, external peer review, and facility boards.

Transparent regional planning. To successfully implement the *2050 Science Framework*, future scientific ocean drilling expeditions need access to the global ocean, including exclusive economic zones and sovereign continental shelves, which will require an international community that engages local and regional stakeholders. Transparent regional planning by facility boards allows proponent teams to develop proposals in support of strategically timed scientific ocean drilling around the world using an array of specialized ocean drilling platforms.

Promoting safety and success through site characterization. Safe and successful operation of scientific ocean drilling expeditions requires comprehensive pre-expedition site characterization and expert assessment. By leveraging access to integrated data sets of seismic reflection profiles and grids, bathymetry, and other types of seabed surveys, the data used in site review provide assurance that drilling occurs in the correct geographic locations and to the requisite depths, while recovering the appropriate sediment, rock, fluid, and/or biological samples necessary to achieve the goals laid out in the *2050 Science Framework*. Site characterization ensures that drilling data are interpreted in the appropriate scientific context.

Regular framework assessments. Progress toward achieving the goals of the *2050 Science Framework* will be assessed every five years via a programmatic review. The review will permit the international scientific ocean drilling community to make necessary adjustments and propose new *Strategic Objectives* and *Flagship Initiatives* as science advances and as societal needs evolve.

Collaborative and inclusive international programs. Scientific ocean drilling addresses truly global science questions. To make significant progress on the science goals encapsulated in the *Strategic Objectives* and *Flagship Initiatives* requires collaborative and inclusive approaches through a united collective of international programs.

Enhancing diversity. Future scientific ocean drilling must commit to training and mentoring the next generation of scientists, enhancing diversity in that community, and supporting education of a scientifically literate world. Scientific ocean drilling will be a leader in driving the push to widen participation in the Earth and ocean sciences among future generations of scientists and in removing internal barriers to becoming and staying involved.

1 HABITABILITY AND LIFE ON EARTH

Defining the conditions for, and the role of, life in the marine realm. Earth is the only planetary body known to support life. Understanding what makes our planet habitable, and where and how life originated and evolved, requires examining Earth's records of habitability and life through time and across its myriad different environments. Scientific ocean drilling provides access to the subseafloor environment, providing materials critical to advance understanding of the requirements for and limits of life on Earth. Cores contain details about how life in the ocean and on land has reacted to past abrupt environmental changes, the environmental parameters that led to mass extinctions, the conditions that fostered evolution of our own species, and the global drivers of production, biodiversity, radiation, and extinction. In comparison with most terrestrial records, marine sediments have excellent chronologies and contain diverse microfossil groups and novel microbial communities that retain critical environmental information.

2 THE OCEANIC LIFE CYCLE OF TECTONIC PLATES

Investigating the genesis, aging, motion, and destruction of oceanic lithosphere. Earth repaves more than half its surface every ~200 million years. The formation, evolution, and destruction of oceanic lithosphere is an integral part of the plate tectonic cycle and establishes boundary conditions for Earth's climate system. It drives the global cycling of energy and matter that buffers Earth's environmental conditions and makes Earth's surface habitable. Oceanic lithosphere cycling produces critical economic resources and governs the occurrence of earthquakes, tsunamis, and volcanoes that pose hazards to society. To date, we have only explored a small fraction of Earth's oceanic lithosphere and to relatively shallow depths. To answer fundamental questions about our planet's central rock cycle and plate tectonics requires scientific ocean drilling of crustal sections that span the life cycle of oceanic lithosphere and the full spectrum of plate accretion modes, plate boundary types, intraplate volcanic processes, and subduction styles.

3 EARTH'S CLIMATE SYSTEM

Examining variations in ice sheets, ocean and atmospheric dynamics, and sea level. Marine sediments contain the most complete record of the processes, mechanisms, and impacts of natural climate variability and long-term changes to Earth's climate system on timescales from annual to hundreds of millions of years. Scientific ocean drilling can increase the continuity, resolution, and accuracy of paleoclimate reconstructions to enhance our understanding of how Earth's climate system operates. A key focus will be to document the onset, interconnectivity, and resilience of potentially vulnerable components of the modern climate system, including the global ocean meridional overturning circulation, sea ice and ice sheets, and patterns of precipitation and aridity. By targeting how the climate system operates across a wide array of past climate states, scientific ocean drilling will obtain the data necessary to calibrate and improve numerical models used to project future climate impacts and inform mitigation strategies.

4 FEEDBACKS IN THE EARTH SYSTEM

Constraining the processes that regulate or destabilize the Earth system. Feedbacks are pervasive, critical interconnections among different parts of the Earth system. Over long timescales, feedbacks have been responsible for reconfiguring of continents, climate alternating between greenhouse and icehouse states, and the evolution of vastly different biota during different geologic periods. On shorter timescales, feedbacks between the atmosphere, ocean, and cryosphere have accelerated the growth and decay of ice sheets, a complex process accompanied by large changes in temperature, precipitation, sea level, and vegetation. On human timescales, changes in ocean circulation and resultant increases and decreases in heat storage in the deep ocean have caused rapid and sustained shifts in high-latitude temperatures and precipitation. Great strides have been made in identifying feedbacks in the Earth system, but our knowledge of how these feedbacks operate and interact and the timescales over which given modes are stable is limited. By providing access to records that contain evidence of key Earth system processes, scientific ocean drilling makes vital contributions to our understanding of the feedbacks that control our planet's functioning.

5 TIPPING POINTS IN EARTH'S HISTORY

Using Earth's geological past to illuminate future environmental change. Parts of the Earth system, particularly, ice sheets, ecosystems, and ocean circulation do not respond linearly to external forcings. Changes may be gradual before a critical threshold is reached—a "tipping point"—beyond which the system changes rapidly and often irreversibly into a new state. Because of the interconnected nature of the Earth system, when a tipping point is crossed in one part, it could trigger a cascade of tipping points being exceeded elsewhere in the system. Scientific ocean drilling can recover sedimentary and rock records that elucidate the environmental boundary conditions when tipping points were crossed, the rates at which the Earth system built up to tipping points, and how long it took for the system to attain a new stable state. Lessons learned from the past can help us understand why certain Earth system components have tipping points and not others, how exceeding tipping points affects ecosystem function, and what drives species to extinction. Identifying tipping points before Earth exceeds them will provide the information society needs to decide how to address the consequences of today's changing climate.

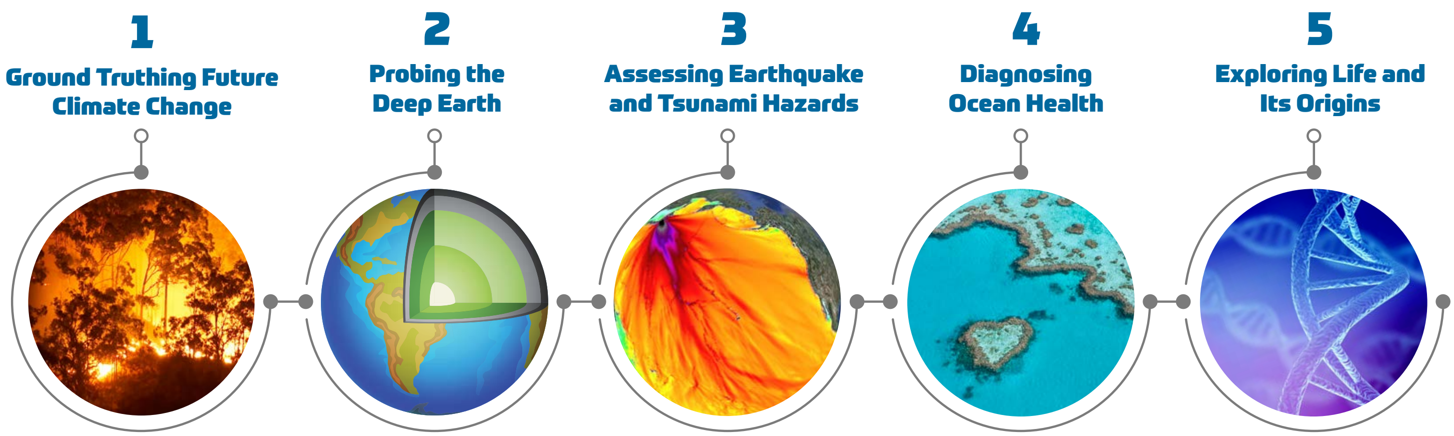
6 GLOBAL CYCLES OF ENERGY AND MATTER

Determining the role, mechanisms, and magnitude of Earth system cycles. Energy and matter use multiple pathways to cycle among Earth system reservoirs. Such cycles are responsible for the continuous sculpting of our planet's surface, opening new ocean basins, building mountains, and eroding continents. They also drive the chemical evolution of the atmosphere and ocean, control the physical and chemical conditions that allow life to develop and evolve, regulate the recovery from major perturbations in Earth's climate, generate natural hazards that threaten global communities, and contribute to the accumulation of key resources, including fresh water and critical metals. Scientific ocean drilling supplies important details and critical missing information about the rates and magnitudes of energy, chemical, nutrient, and fluid transfers among Earth's rocks, ocean, atmosphere, and life. These data can reveal how global cycles control Earth's evolution over a wide range of spatial and temporal scales.

7 NATURAL HAZARDS IMPACTING SOCIETY

Understanding natural hazards in the marine environment. Earthquakes, landslides, tsunamis, volcanic eruptions, mega-floods, and other extreme natural events directly threaten communities, infrastructure, and the environment. Significant progress has been made in the investigation of such hazards through scientific ocean drilling, particularly in subduction zones. However, we remain largely uninformed about the subseafloor conditions that influence natural hazards in the marine environment. There are major knowledge gaps in understanding the mechanisms that control hazard recurrence, timing, and possible precursors, and how to assess their future likelihood. Scientific ocean drilling can help close knowledge gaps by installing subseafloor observatories to monitor in situ conditions before, during, and after hazardous events and by probing the stratigraphic record of prehistoric submarine and terrestrial hazardous events to understand processes and evaluate long-term magnitude-frequency correlations.

FLAGSHIP INITIATIVES



1 GROUND TRUTHING FUTURE CLIMATE CHANGE

In 2020, atmospheric CO_2 concentrations have already exceeded 410 ppm and, without action to reduce anthropogenic CO_2 emissions, could surpass 900 ppm by 2100. Paleoclimate data collected through scientific ocean drilling established that atmospheric CO_2 exceeded 410 ppm more than 3 million years ago. Values approaching 900 ppm were only realized during the hot "greenhouse" climate of the Eocene ~50 million years ago. Numerical climate and Earth system models are used to simulate Earth's response to projected increases in atmospheric greenhouse gas concentrations. Projections based on those models can provide information about shifts in rainfall and temperature patterns and rising sea levels that can be used in the design of mitigation and adaptation strategies. Scientific ocean drilling provides the robust baseline data on global climate evolution over extended geologic time periods that are critical for improving climate model performance.

IMPACT. High-density, global scientific ocean drilling networks and transects will enable a more robust identification of feedbacks and tipping points in Earth's climate system and improve modeling and IPCC assessments of climate sensitivity to atmospheric greenhouse gases, ocean circulation changes, and other geologic boundary conditions.

2 PROBING THE DEEP EARTH

Scientific ocean drilling has long aspired to penetrate deep into Earth's oceanic crust and its underlying mantle. Since the Mohorovičić seismic discontinuity ("Moho") was postulated in 1909, we still haven't confirmed that it forms the fundamental boundary between Earth's crust—oceanic or continental—and mantle and if it varies globally. Understanding the nature of this seismic boundary in Earth's overall structure is fundamental, as the creation of new oceanic crust in response to mantle upwelling and convection makes Earth unique among our solar system planets. New multidecadal scientific ocean drilling strategies seek to probe the deep Earth and to finally reach the upper mantle via a series of interconnected, ambitious expeditions that will take full advantage of emerging drilling, coring, logging, and monitoring technologies.

IMPACT. Deep scientific ocean drilling will provide a pathway to Earth's deep interior where the rocks contain fundamental information on Earth's formation and evolution, geodynamic behavior, and the interrelationship between geological, geochemical, and climate cycles.

3 ASSESSING EARTHQUAKE AND TSUNAMI HAZARDS

Undersea earthquakes and associated tsunamis cause some of our planet's deadliest and costliest natural disasters over the past 20 years. The 2011 magnitude (M_w) 9.0 Tōhoku-oki earthquake and tsunami in northern Japan took over 15,000 lives, with economic losses estimated at US$235 billion. The 2004 M_w 9.2 Sumatra-Andaman earthquake and tsunami in the Indian Ocean killed more than 230,000 people in 15 countries and caused losses of ~US$15 billion. Undersea landslides and gravity flows can endanger coastal and offshore infrastructure and telecommunications, as happened in the pair of M_w ~7 earthquakes that severed 22 seafloor cables near Taiwan in 2006. The potential for such earthquake, tsunami, and landslide hazards along many of the world's subduction zones remains poorly known. A complete understanding of the processes leading to the occurrence of large earthquakes requires high-resolution, continuous measurements of changes in Earth's crust for many decades, over different stages of the earthquake cycle, collected at different locations globally.

IMPACT. By directly accessing, sampling, instrumenting, and monitoring dangerous offshore and nearshore fault zones worldwide, scientific ocean drilling will enable more reliable forecasts and assessments of the risks to vulnerable populations and infrastructure posed by subduction zone earthquakes and tsunamis and will facilitate improved hazard preparedness and response.

4 DIAGNOSING OCEAN HEALTH

Ocean warming, acidification, deoxygenation, and rising and falling nutrient levels are causing global changes in marine ecosystems. Declining ocean health can lead to devastating losses in biodiversity, habitats, productivity, and fisheries, putting life at risk. Similarly, in the pre-Anthropocene epochs, episodes of rapid global warming and cooling, ocean anoxic and acidification events, as well as meteorite impacts and intervals of flood basalt volcanism perturbed ocean ecosystems. Scientific ocean drilling retrieves sediment records that preserve key information about the responses of biological activity in the ocean to natural cycles and catastrophic perturbations over geologic time. By targeting critical periods in Earth history, we can assess the impacts of cataclysmic environmental changes on marine ecosystems and food webs.

IMPACT. By diagnosing ocean health through geologic time, scientific ocean drilling will help inform society about drivers in the Earth system that regulate ocean health, the warning signs of decline, and how long it may take for the ocean to recover from perturbations.

5 EXPLORING LIFE AND ITS ORIGINS

Marine sediments and oceanic crust host a complex, active, globe-spanning ecosystem in which microorganisms live, interact, evolve, and die. The features and strategies that enable deep life to persist in these geologic habitats, what communities form under these extremely energy-limited conditions, and what geochemical and biochemical processes create their novel biosignatures remain largely unknown. To sample, monitor, and analyze a representative range of Earth's diverse subseafloor environments and the multitude of microbial communities that they inhabit in Earth's interior requires sustained scientific ocean drilling exploration.

IMPACT. Scientific ocean drilling will significantly advance understanding of the rules of life, the limits of life, and the origins and evolution of life on Earth. It also offers the opportunity to establish what life might look like in analogous environments on other worlds and what new organisms and novel biological functions useful in geobiotechnology reside in Earth's subseafloor.

ENABLING ELEMENTS

1 BROADER IMPACTS AND OUTREACH

Scientific ocean drilling targets a broad array of topics that are of great interest and importance to society, contributing vital data that will improve climate models, advance earthquake knowledge, and provide insight into the possibility of life on other worlds. It is a proven model for global collaborative research and an incubator for disciplinary partnerships in science and engineering. Widely recognized as a preeminent training ground for the next generation of Earth scientists, scientific ocean drilling will capitalize on its international, cross-disciplinary shipboard and shore-based science parties to advance participation of traditionally underrepresented groups. Using a variety of social media and web-based platforms, data and results will be broadly disseminated to educators, policymakers, and the public, securing scientific ocean drilling's position as the authoritative source of information about the Earth system.

2 LAND TO SEA

The scientific ocean and continental drilling communities have built two of the most successful, long-lasting, international collaborative programs in the Earth sciences. Strengthened collaborations between these programs will advance their closely allied objectives to investigate the interconnected global Earth system. Future collaborative land-to-sea drilling campaigns will answer fundamental questions about Earth dynamics and natural hazards, as well as explore the connections between plate tectonics, Earth's climate system, ecosystems, life and habitability, sea level change, and subseafloor freshwater flow across the coastline.

3 TERRESTRIAL TO EXTRATERRESTRIAL

Future collaborations between international space agencies and scientific ocean drilling will benefit efforts to better understand planetary evolution and structure and to assess the potential for life elsewhere in the solar system and beyond. Such collaborations will also enhance understanding of the hazards posed by past extraterrestrial impacts and the recovery of life after such events. Perhaps most importantly, integration of modern satellite data with historic paleoclimate records from scientific ocean drilling will be a powerful new approach to understanding Earth's interconnected processes today and climate evolution into the future.

4 TECHNOLOGY DEVELOPMENT AND BIG DATA ANALYTICS

Future developments in drilling technology, monitoring, and observatory science are essential to achieve the goals laid out in this *2050 Science Framework*, as is strengthened collaborations with engineers, computer scientists, and Earth system modelers. Progress increasingly depends on the ability to compile, integrate, and analyze multiple large data sets, including those generated through core analyses and in situ borehole measurements, which are then linked to regional geophysical observations. Technological developments and big data analytics will drive progress in future scientific ocean drilling.

SCIENTIFIC OCEAN DRILLING: LOOKING AHEAD

Scientific ocean drilling is a crucial capability for exploring how the Earth system works. It allows us to obtain unparalleled samples from beneath the seafloor and assemble authoritative data sets that are essential for revealing the many complex interactions between the solid Earth, ocean, life, climate, and society. Using age transects across ocean basins, continuous deep time slices preserved in sediment and rock cores, a global distribution of research sites, and an array of active observatories and cabled instrumentation, scientific ocean drilling will paint a detailed picture of the complex Earth system in the geologic past, with a vision to the future. Research conducted within the *2050 Science Framework* will provide critical contributions to our understanding of ongoing environmental change, allowing society to improve its resilience to natural hazards, sustainably use marine resources, and consider how to protect the future habitability of our planet. This research aligns with the goals of the United Nations Decade of Ocean Science for Sustainable Development.

The long timeframe of the *2050 Science Framework* permits pursuit of the foundational Earth research covered in the *Strategic Objectives* and *Flagship Initiatives* and encourages innovation and discovery through multidisciplinary, multinational, and societally relevant research. Implementation of this *Framework* relies heavily on the continued cooperation and coordination among numerous partner countries. To increase the yield of our future international scientific endeavors requires collaboration and knowledge sharing with other Earth and space science programs and a concerted effort to train the next generation of marine geoscientists and microbiologists.

Looking ahead, scientific ocean drilling is positioned to continue to be a major contributor to studies of how the linkages, processes, feedbacks, and tipping points in the interconnected Earth system will impact humankind in the future. Effective outreach and public engagement will deliver the important results of our research to the broadest audiences. Rectifying the underrepresentation of minorities in leadership roles and enhancing our efforts to remove barriers that hamper participation by historically underrepresented populations in science, technology, engineering, and mathematics will be critical to the success of future scientific ocean drilling. Through the *2050 Science Framework* we are ready to significantly advance the many frontiers in the study of the interconnected Earth system.

STRATEGIC OBJECTIVES

The *Strategic Objectives* comprise broad Earth science research areas that form the foundation of scientific ocean drilling through 2050. Each objective focuses on understanding the interconnections within the Earth system.

1 **Habitability and Life on Earth**

2 **The Oceanic Life Cycle of Tectonic Plates**

3 **Earth's Climate System**

4 **Feedbacks in the Earth System**

5 **Tipping Points in Earth's History**

6 **Global Cycles of Energy and Matter**

7 **Natural Hazards Impacting Society**

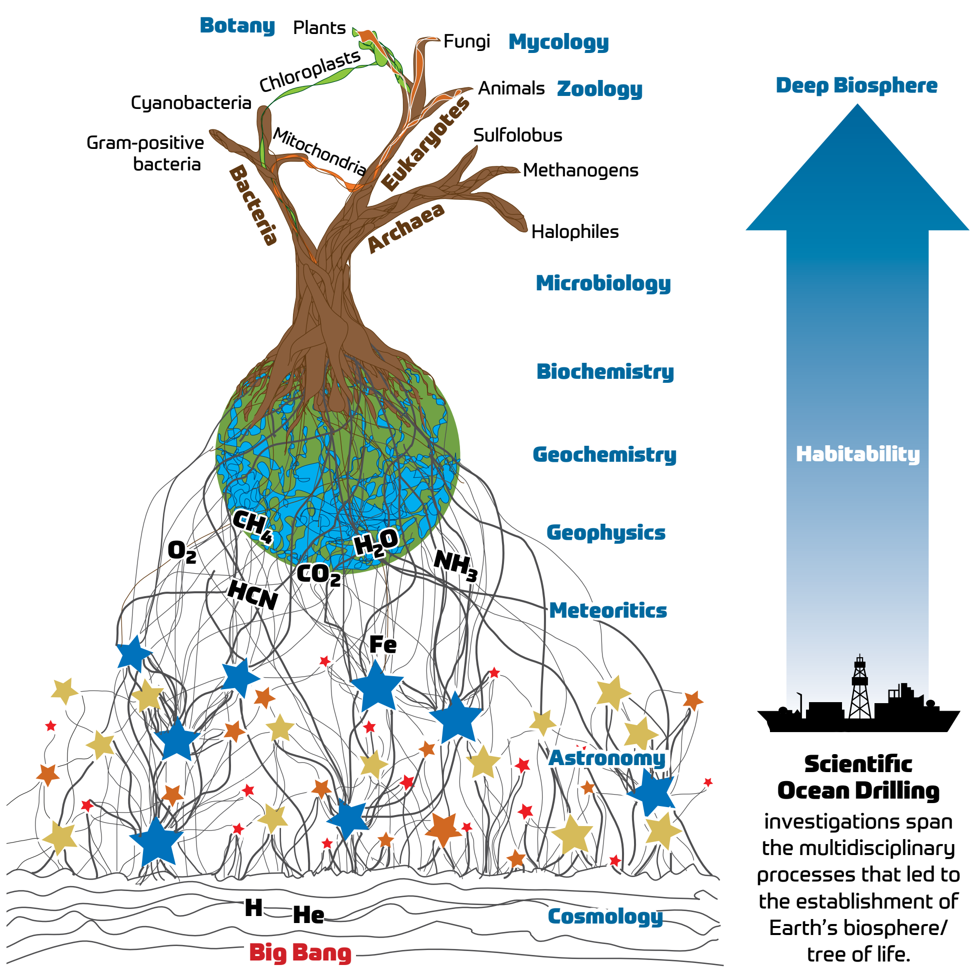
STRATEGIC OBJECTIVE 1

HABITABILITY AND LIFE ON EARTH

Defining the conditions for, and the role of, life in the marine realm

SUMMARY

Earth is the only planetary body known to support life. Understanding what makes our planet habitable, and where and how life originated and evolved, requires examining Earth's records of habitability and life through time and across its myriad different environments. Scientific ocean drilling provides access to the subseafloor environment where a large portion of Earth's biosphere thrives, providing materials critical to advance understanding of the requirements for and limits of life on Earth. Long, continuous sediment and rock cores recovered through scientific ocean drilling contain details about how life in the ocean and on land has reacted to past abrupt environmental changes, the environmental parameters that led to mass extinctions, the conditions that fostered evolution of our own species, and the global drivers of production, biodiversity, and radiation. In comparison with most terrestrial records, marine sediments have excellent chronologies and contain diverse microfossil groups and microbial communities that retain critical environmental information.



A habitable world. Starting at the Big Bang, a cascade of physical and biogeochemical processes led to Earth becoming a habitable planet and enabled the emergence of life—with the tree of life taking root approximately 4 billion years ago. Biologists have reconstructed the terrestrial phylogenetic tree of life based on the molecular fossils inside the DNA of living cells. Scientific ocean drilling provides access to subseafloor environments and biosphere communities to investigate the conditions and processes that were required to develop and maintain a habitable world and understand how it evolved. *Modified from Lineweaver and Chopra (2012), https://doi.org/10.1146/annurev-earth-042711-105531*

HABITABILITY AND THE DEEP BIOSPHERE

The marine deep biosphere affords key opportunities to investigate habitability on Earth and to consider the habitability of other worlds. Subseafloor environments span high pressures, extreme heat, exceedingly low carbon availability, and nutrient stress—yet, life survives. By investigating how organisms manage to exist under these challenging conditions and by identifying the deep subsurface boundaries of the biosphere, scientific ocean drilling will significantly advance our understanding of the requirements for life. This knowledge in turn can be applied to studies of the nature and extent of life on Earth and **life's origins** and inform the search for **extraterrestrial life**.

Scientific ocean drilling reaches otherwise inaccessible habitats of the deep biosphere to investigate how environmental conditions directly influence the distribution, diversity, and survival strategies of microbial life in subseafloor environments.

Limits of life on Earth. Habitability is an essential concept for developing understanding of the evolution and persistence of life on Earth. It is defined as the ability of an environment to permit at least one organism to survive, maintain, grow, and reproduce. To date, we do not know what precise combination of conditions is required to make an environment habitable. As we venture into **deeper and hotter environments** through scientific ocean drilling, we will better determine those conditions. Liquid water is currently recognized as one critical component to sustain carbon-based life as we know it, yet its presence alone is not sufficient. Other parameters that likely influence habitability include temperature, pressure, pH, salinity, metal concentrations, mineralogy, and ultraviolet radiation. Using an integrated approach of host substrate and microbiological sampling with in situ measurements and microbial growth experiments, we will investigate the conditions necessary for habitability in the deep biosphere and how the balance between the supply of reactants and available energy control the pace and variety of microbial metabolisms. To make progress in these frontier investigations, new DNA- and RNA-based analytical approaches in metagenomics, proteomics, lipidomics, and other potential omics techniques can be applied in conjunction with scientific ocean drilling to explore the limits of life.

Extreme subseafloor biosignatures. The discoveries that microbial communities persist under energy-limited conditions in subseafloor sediments for many millions of years, and that life even inhabits the underlying solid rocks previously regarded as lifeless environments, have challenged our understanding of life in general. Major questions about the microbes, their communities, and their energy sources remain unanswered. The slowest rates at which individual cells can respire, replace biomass, and reproduce remain unknown. The physiological adaptations and metabolic strategies that allow organisms to persist at extremely low energy fluxes for many millions of years are not yet identified. How the nature and supplies of bioaccessible energy vary across the globe, and their relationship to geologic setting and local physico-chemical conditions, to date are not comprehensively explored. It remains unknown why microbial food sources such as buried organic matter can consistently go unconsumed for tens of millions of years.

To resolve these questions, we will characterize the sources of energy and nutrients that sustain microorganisms in subseafloor environments. This knowledge will allow us to characterize the crossover between habitats whose energy ultimately derives from the Sun and habitats in which life relies on heat and energy supplied by Earth itself. This also allows us to define the "bottom of the deep biosphere" that is the boundary beyond which life can no longer survive—a goal not yet achieved. Scientific ocean drilling offers opportunities to access samples from depths several kilometers below the seafloor and uses innovative interdisciplinary approaches to study the presence or absence of microbial communities in extreme subsurface environments. Identifying the biotic/abiotic contributions to the local chemical conditions in the **deeper and older oceanic crust** will provide crucial insights into the chemical, biological, and environmental limits of life; the key requirements for habitable conditions; and possible "biosignatures" that allow us to fingerprint where life thrives.

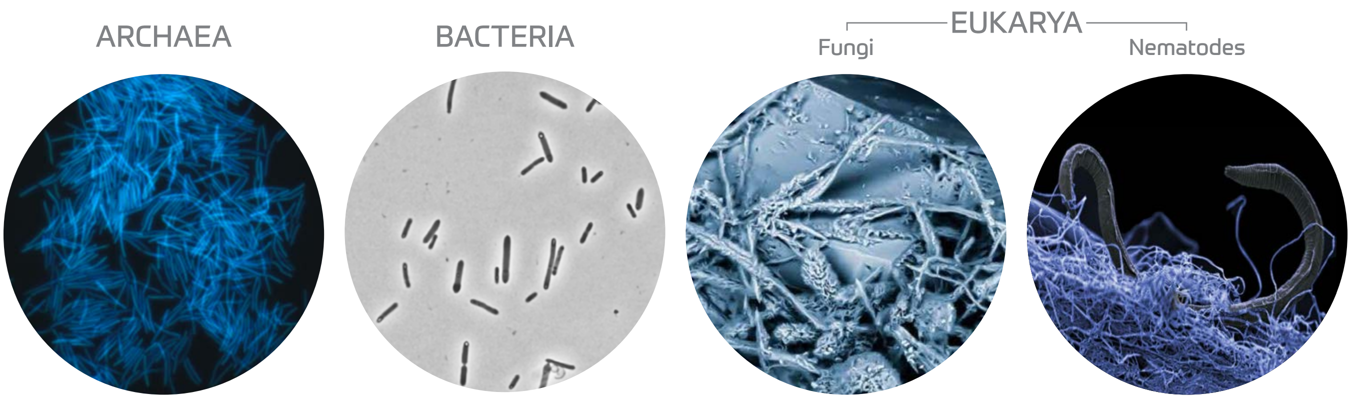
TYPES OF LIFE INHABITING THE SUBSEAFLOOR

Subseafloor sediment and underlying rocky substrates are inhabited by all three major domains of life: Archaea, Bacteria, and Eukarya. Unique viruses are also known from sediments and upper crustal rocks. The adaptions of microorganisms in the "deep biosphere" to the environments they inhabit, the environmental properties that limit their extent, the nature of their community interactions, and how they live, die, and evolve are all largely unknown. For example, little is known about the strategies that subseafloor organisms use to optimize their consumption of highly limited resources. Furthermore, while life inhabiting tens of sedimentary subsurface environments has been investigated, only a handful of **upper crustal** subsurface communities have been studied. Scientific ocean drilling reaches otherwise inaccessible habitats of the deep biosphere to investigate how environmental conditions directly influence the distribution, diversity, and survival strategies of microbial life in subseafloor environments. Our future research on the deep biosphere will promote holistic understanding of the deep biome, allowing more comprehensive understanding of all life on Earth and the role of the deep biosphere in the evolution of the oceanic crust and the global ocean, and comparisons with microbial communities in terrestrial hot springs and the deeper realms of Earth's continental crust.

THE ROLE OF MICROBIAL LIFE IN EARTH HISTORY

About four billion years ago, environmental conditions on Earth vastly differed from today. No ocean existed, and the atmosphere lacked oxygen and contained abundant reduced gases released through intense volcanism. In the absence of an ozone layer, Earth was exposed to harmful radiation from the Sun. Yet, in this harsh environment, microbial life started evolving. Through their photosynthetic activity that resulted in the production of oxygen, primordial microorganisms began changing Earth's history. Deposition and burial of the reduced organic matter in the ocean left the liberated oxygen in the surface world, where it increased to higher and higher atmospheric concentrations during Earth's great oxidization event. Through this process, these organisms also became indirectly responsible for the formation of the protective ozone layer, allowing Earth to become a habitable world for larger, more complex, multicellular organisms. Primordial life thus made possible the evolution of complex life—including humanity—and it plays a crucial role in the ongoing oxidation of Earth's surface.

Microbial influence on biogeochemical cycles. Residing at the interface between a biologically dominated surface world and the abiotic deep subsurface world, subseafloor life strongly impacts **global cycles of energy and matter**. Subseafloor metabolic activity also plays key roles in other major biogeochemical cycles. It is the principal sink of sulfur and bioavailable nitrogen from the world ocean and is also a primary source of ocean alkalinity, directly affecting atmospheric CO_2 concentration. Microbes play crucial roles in the formation and destruction of major economic resources, including deposits of hydrocarbons, phosphate, barite, dolomite, manganese nodules, and deep-sea metals such as cobalt-rich crusts that may coat much basalt outcropping on seamounts. Microbes also are agents consuming pollutants in natural aquifers and nearshore environments and they may be crucial players in bioremediation as they promote calcification that could help mitigate the escape of CO_2 from sequestration reservoirs.



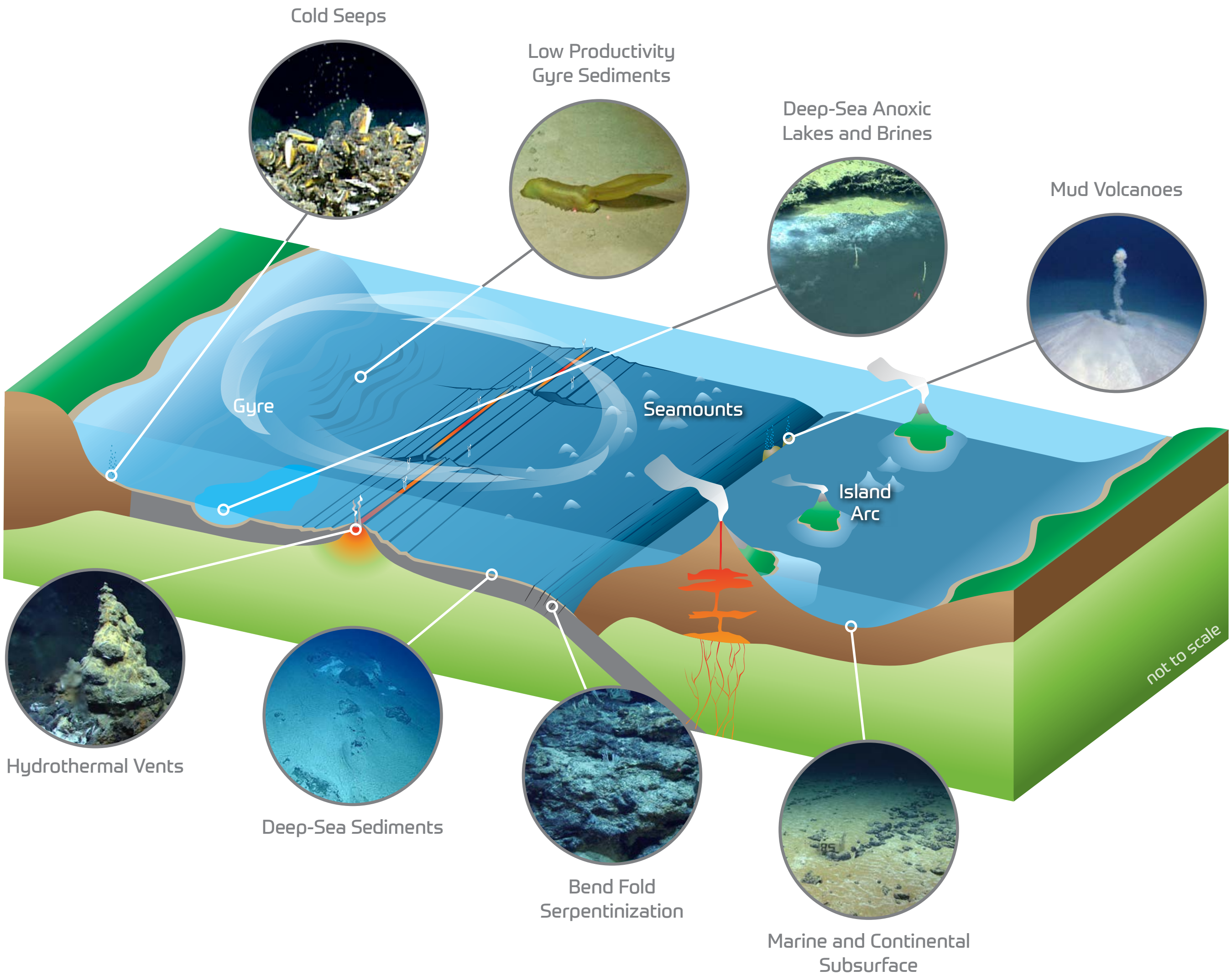
Subseafloor sediment and underlying rocky substrates are inhabited by all three major domains of life: Archaea, Bacteria, and Eukarya. Here, we show some examples of organisms found in subsurface environments.

Effects on climate and ocean health. The effect of subsurface communities on ongoing **climate change**, and vice versa, remains unexplored. Microbial communities in subseafloor sediment are known sources of greenhouse gases such as methane and CO_2 and can also act as "greenhouse gas sinks" by consuming methane and preventing it from being released into the atmosphere. Microbes also may increase the alkalinity of seawater and thus drive carbonate formation. Much remains to be learned about the rates of these processes, the interactions between the subseafloor biosphere and biogeochemical cycling, and how subseafloor life will respond to anthropogenic influences and stresses on ocean health. Scientific ocean drilling will explore the coevolution of the biosphere and geosphere over time and quantify the impact of life on biogeochemical cycles and climate.

THE MARINE BIOME AND THE BIOLOGICAL PUMP

The ability of the marine biosphere to buffer changes in atmospheric gases is critical to sustaining planetary habitability and regulating **Earth's climate system**. But the mechanisms that influence the so-called "biological pump" remain poorly understood. It is hypothesized that the makeup of the plankton community and ecosystem changes in ocean frontal systems play key roles in this process, as they may regulate biological production and the net carbon flux into the sediments on the seafloor.

Past records of ocean productivity. Biological production may respond to basin-scale changes in oceanographic conditions, such as those of the North Atlantic Oscillation,



Examples of extreme environments in the marine realm. Scientific ocean drilling reaches otherwise inaccessible habitats of the deep biosphere to investigate how environmental conditions directly influence the distribution, diversity, and survival strategies of microbial life in subseafloor environments. *Illustration by Geo Prose, inspired by Figure 1 in Merino et al. (2019), https://doi.org/10.3389/fmicb.2019.00780* the Pacific Decadal Oscillation, the Indian Ocean Dipole, and the El Niño-Southern Oscillation. It is likely that analogues to these cycles govern regional or inter-basin productivity, perhaps on million-year and glacial/interglacial timescales. For example, scientific ocean drilling records have revealed 400,000-year to 3 million-year cycles of diatom production in the Pacific, yet the causes of such cycles will remain unknown until we obtain high-quality records from other ocean basins to resolve whether these cycles are synchronous or lag one another.

Biological pump efficiencies. A relatively unexplored aspect of the marine biome is how the **biological pump** is linked to **Earth's climate evolution**. For example, most of the large increase in atmospheric CO_2 during Pleistocene glacial and interglacial cycles can be attributed to changes in biological pump efficiency. Conversely, the greenhouse ocean of the Eocene appears to have been richly productive, with nearly all productivity recycled in the warm ocean, diminishing any biological pump effects. These changes in carbon burial efficiency rates likely relate to climate-driven changes in the physiological activity and composition of life in marine food webs. This connection raises a number of questions. Did changes in the global dominance of different plankton groups in the past have similar impacts on food webs and nutrient cycling? Did changes in ocean circulation or temperature drive shifts in the dominance of different plankton groups? Was the Eocene ocean with its apparently high production (but low carbon burial) a harbinger of climate change? Novel techniques applied to marine sedimentary ancient DNA research may shed light on some of these questions by allowing detection of plankton groups beyond the skeletal fossil record, enabling more accurate reconstructions of past marine ecosystems, improving estimates about past productivity and, ultimately, our understanding of the biological pump.

Marine biodiversity and food webs. Scientific ocean drilling has recovered unparalleled records of the origins of biological diversity in the ocean. Molecular taxonomies increasingly show that marine biodiversity is even greater than we suspected based on conventional micropaleontology. Other environmental clues within cores have also been understudied. Fossilized teeth, otoliths, and scales from fish and sharks are a common feature of deep-sea cores, particularly in pelagic clay, but despite their potential to provide key information on vertebrate evolution and production, their record is only now starting to be explored. Similar gaps exist in our knowledge of biogenic silica-rich sediments that are dominated by radiolarians and diatoms and that are formed away from high productivity regions near continents, ocean upwelling zones, and divergence in ocean currents. Future drilling targeting carbonate-poor and silicate-rich sediments deposited in deep ocean water below carbonate compensation depths will revolutionize our understanding of marine food webs and how vertebrate diversity—the foundation of modern fisheries—has responded to shifts in climate and primary production. As new analytical techniques are developed to interrogate chemical and isotopic compositions of these understudied sedimentary archives, we can better assist in **diagnosing ocean health** through time and identifying crucial **tipping points** in Earth's history.

Our Ancestral Migrations

Scientific ocean drilling has provided archives of terrestrial climate and ecosystem changes that have been critical to understanding the context of human evolution. Research on the global history of human origins commonly relies on land-derived signals preserved in marine sediments. Pollen, charcoal, dust flux, leaf wax, and volcanic ash layers recovered from marine drill cores help construct a global picture of the evolution of terrestrial ecosystems, allowing us to link archaeological records to the highly resolved global marine timescale. Marine records of terrestrial proxies go back further in geologic time, provide a direct regional-scale to global context, and have better deep-time chronologies than anything we can derive from terrestrial archives. Archaeology and ancient DNA have revealed repeated migrations of our ancestors, as well as the rich history of hominid biodiversity and population crises in our not-so-distant past. Scientific ocean drilling is a key tool for exploring the environmental history of these events in human origins, with direct implications for the habitability and life on and in the terrestrial Earth.

PLANETARY PROCESSES IMPACTING SUBSEAFLOOR HABITABILITY

The extent to which **plate tectonics and other geologic processes** influence the habitability, distribution, and diversity of subsurface communities remains a frontier in scientific ocean drilling and the Earth sciences. In highly dynamic regions, such as mid-ocean ridges where new oceanic lithosphere is created and subduction zones where this lithosphere reenters the mantle, magmatism and fluid migration lead to large spatial variations in temperature, pressure, pH, redox, and salinity conditions. These processes create a highly variable succession of habitats that host radically different subseafloor communities over relatively short distances. Scientific ocean drilling will provide a **deeper understanding** of the complex exchanges that occur between the subseafloor biosphere, lithosphere, and atmosphere that led to the development of our habitable world.

To improve our understanding of these interconnections, scientific ocean drilling will need to target new habitats in geologic settings with diverse sets of environmental conditions. For example, it will be crucial to explore connections between **earthquakes and tsunamis** and subseafloor life. Fault movement can produce hydrogen that feeds subsurface microbes and may release gas hydrates, and deep communities may migrate through and colonize newly formed fractures in Earth's lithosphere. In addition, earthquakes may cause sediment remobilization and with that transpose organic matter and its incumbent microbial communities from shallow to deeper ocean floor environments. On larger scales of time and distance, we will investigate the effects of large igneous province emplacement, seamount and island arc volcanism, and meteorite impacts on distributions of subsurface communities. The intricacy of potential connections between geologic events and the subseafloor biome requires collaboration among geologists, geochemists, geophysicists, hydrogeologists, biogeochemists, and biologists to obtain a holistic understanding of these complex **feedbacks in the interconnected Earth system**.

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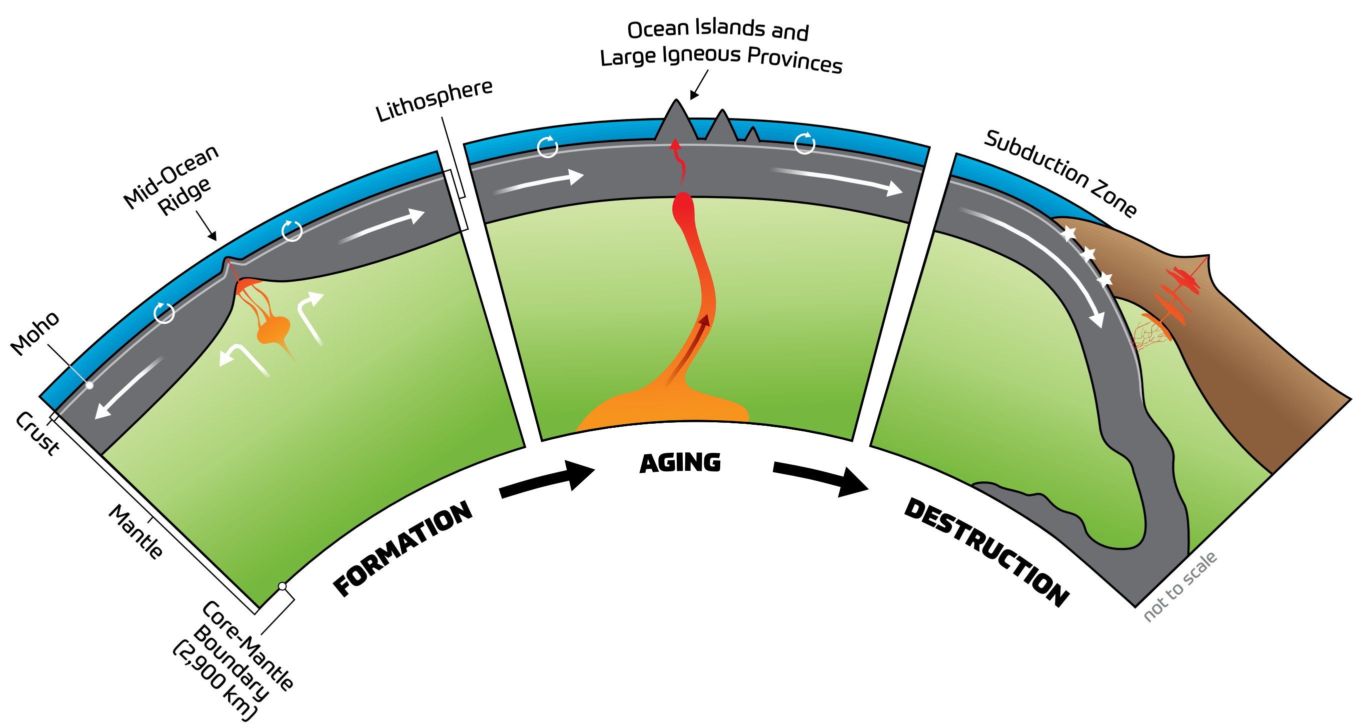
STRATEGIC OBJECTIVE 2

THE OCEANIC LIFE CYCLE OF TECTONIC PLATES

Investigating the genesis, aging, motion, and destruction of oceanic lithosphere

SUMMARY

Earth repaves more than half its surface every ~200 million years. The formation, evolution, and destruction of oceanic lithosphere is an integral part of the plate tectonic cycle and establishes boundary conditions for Earth's climate system. It drives the global cycling of energy and matter that buffers Earth's environmental conditions and makes Earth's surface habitable. Oceanic lithosphere cycling produces critical economic resources and governs the occurrence of earthquakes, tsunamis, and volcanoes that pose hazards to society. To date, we have only explored a small fraction of Earth's oceanic lithosphere and to relatively shallow depths. To answer fundamental questions about our planet's central rock cycle and plate tectonics requires scientific ocean drilling of crustal sections that span the life cycle of oceanic lithosphere and the full spectrum of plate accretion modes, plate boundary types, intraplate magmatic processes, and subduction styles.



Scientific ocean drilling collects fundamental data on the plate tectonic cycle. This schematic depicts the three main phases in the life of an oceanic plate: (left) formation at the mid-ocean ridge, (middle) aging as it moves away from the mid-ocean ridge, and (right) destruction at a subduction zone. The oceanic plate is dark gray, the continental lithosphere is brown, and an upwelling mantle plume is orange. The white arrows show plate motion, white circular arrows depict hydrothermal circulation, and white stars are large earthquakes. *Illustration by Geo Prose, inspired by Figure 1 in Crameri et al. (2019), https://doi.org/10.1016/j.tecto.2018.03.016*

EXAMINING THE PLATE TECTONIC LIFE CYCLE

The formation of new oceanic crust at mid-ocean ridges, its subsequent aging over tens to hundreds of million years, and its eventual destruction in subduction zones, recycling through Earth's mantle, and upwelling via deep mantle plumes comprise the largest-scale **cycle of matter and energy** on Earth. Scientific ocean drilling enables us to better understand the relationships and **feedbacks** between this plate tectonic cycle and environmental changes over a wide range of geologic timescales. We have limited knowledge about how the plate tectonic cycle regulates **Earth's climate system**, produces critical mineral resources, and generates **natural hazards**. We have an incomplete understanding of the far-field tectonic and magmatic processes that may cause major changes in plate tectonic motions, that may stop portions of the plate cycle, and that may be implicated in the initiation of new ocean basins. We also don't fully comprehend how oceanic crust accretes and varies along ~60,000 km of the mid-ocean ridges on Earth; how it is chemically, physically, and biologically altered as it matures; and what fraction may or may not be recycled into the mantle.

The complex processes governing oceanic crust accretion and aging are recorded by differences in rock chemistry, mineral composition, rock alteration, deformation fabrics, microbial communities, and more. By sampling oceanic crust across diverse plate tectonic environments, and by fully integrating scientific ocean drilling results with seafloor mapping and sampling and regional geophysical studies, we can provide important constraints on the life cycle of oceanic crust, beginning with continental rifting and the formation of oceanic crust at mid-ocean ridges, through its final recycling at subduction zones. The processes accompanying the destruction of plates in subduction zones are best studied by drilling and coring in volcanic arcs, back-arc basins, mud volcanoes, and the upward-bulging downgoing oceanic plates.

CONTINENTAL BREAKUP AND NEW OCEAN BASINS

When continental lithosphere is stretched beyond its breaking point due to distant tectonic and/or underlying magmatic forces, it ruptures into separate, diverging land masses. Continental rifting and thinning accompany the stretching, resulting in the formation of sedimentary basins. If extensional deformation continues—and the rifting doesn't fail or stop—the continents break up and new ocean basins form. The continental margins generated by these processes are the primary Earth sedimentary sinks and have high energy resource potential. Scientific ocean drilling allows us to investigate and test the various models that have been developed over the last decades for continental breakup and ocean basin formation.

Initial ocean crust formation. Following initial pre-breakup extension, the mantle upwells beneath the rift, partially melting to form magma that becomes the earliest crust that will floor the new ocean basin. This initial crust, now typically buried by kilometers of sediment, can be sampled by scientific ocean drilling to decipher the amount, type, and duration of magmatism; the rate of extension; and the distribution of faulting as the continents rift and break up. Scientific ocean drilling thus can provide critical information on the structure and thermal evolution of newly formed continental margins in order to decipher the underlying geodynamic and plate tectonic processes.

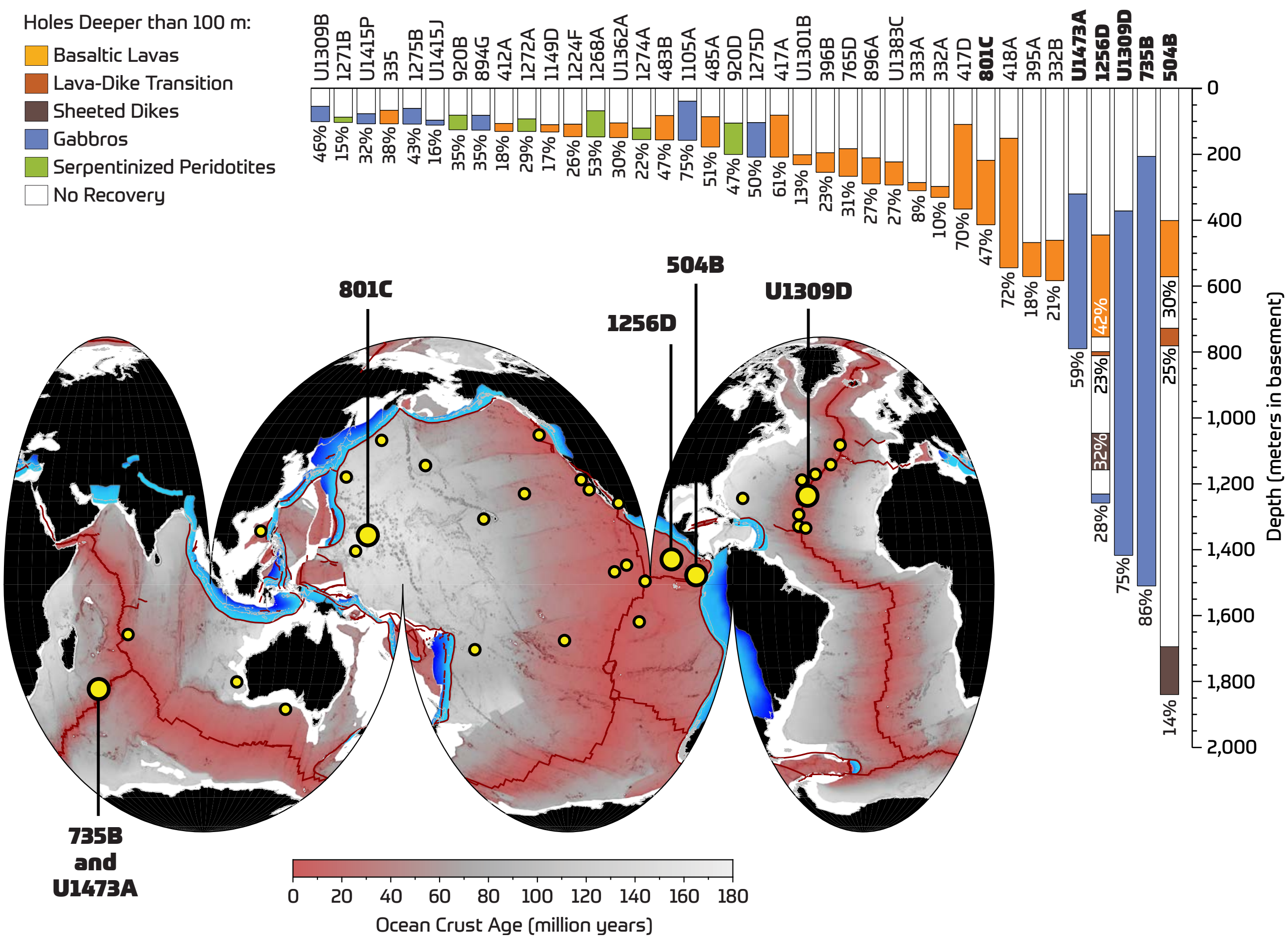
Fundamental rifting modes. In some cases, flood volcanism accompanies continental breakup, with mantle plumes providing an excessive magma supply. In other cases, continental breakup is dominated by faulting and the development of shallow rift basins. Scientific ocean drilling can show whether pre-existing structural weaknesses in the continents determine the pattern of breakup and whether deep-sourced mantle plumes drive breakup or alternatively are initiated by it. Integration of geophysical and coring data from multiple locations—that cover a range of continental extension patterns and related magmatic production—will permit determination of uplift and subsidence rates, sedimentation histories, and deformation patterns, and the timing, volume, chemistry, and style of magmatism. These results provide insight into the fundamental modes of continental rifting and breakup, from magma-rich to magma-deprived, and the sometimes rapid transition between these two rifting end members.

THE GENESIS OF OCEANIC CRUST

Scientific ocean drilling and associated marine geological and geophysical studies have revealed that the architecture of the oceanic crust is highly variable. Magmatically robust fast-spreading ridges appear to produce relatively simple layered crust of basalts, dikes, and gabbro.

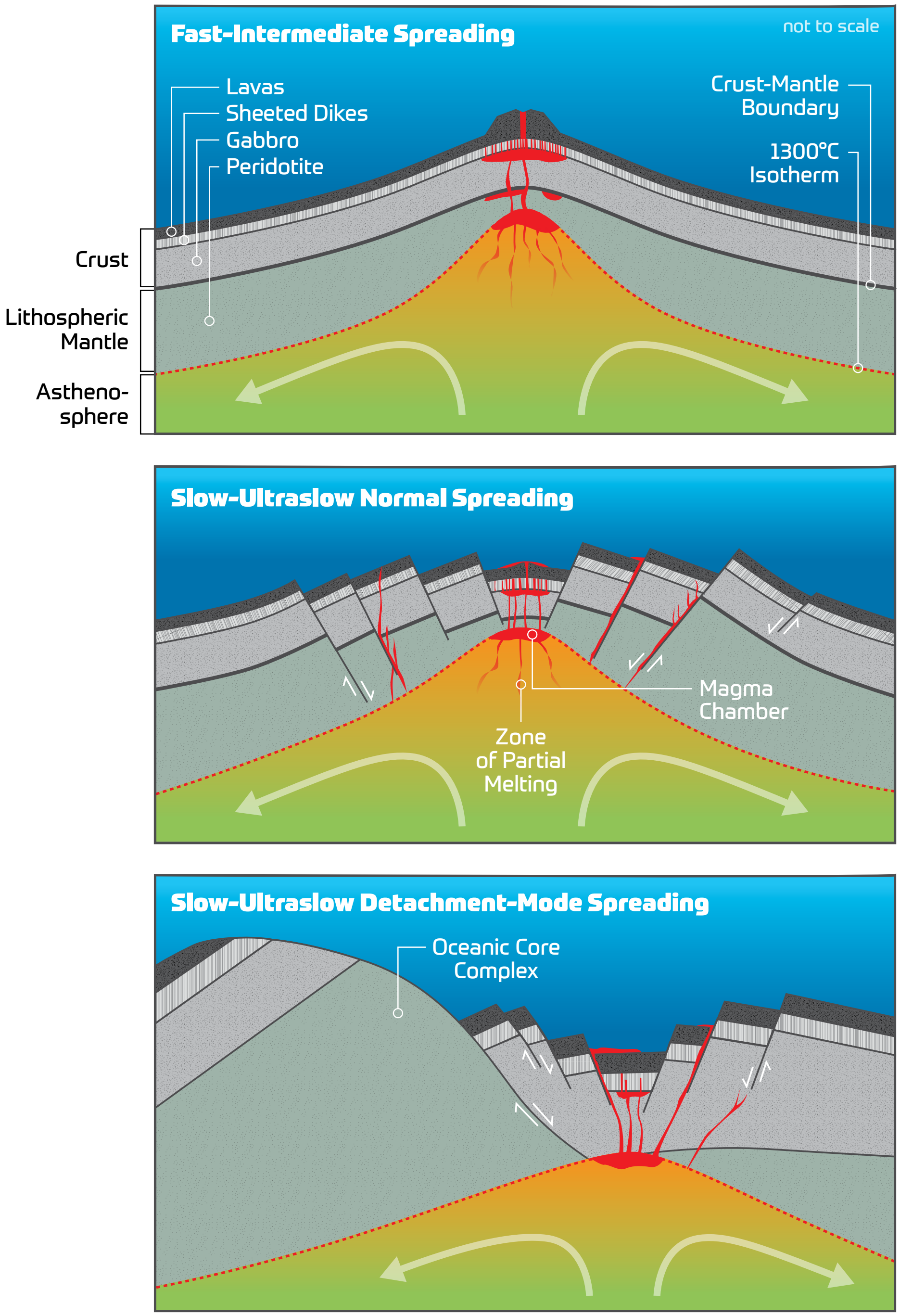
Transforming Our Knowledge of Earth's Interior

The transfer of residual internal heat from Earth's formation 4.5 billion years ago, along with energy released by radioactive decay of isotopes, powers the plate tectonic cycle. Volcanism is the most obvious manifestation of this energy transfer. More than 80% of Earth's volcanism occurs along globe-encircling mid-ocean ridges, creating new oceanic crust. The motion of plates across Earth's surface, predominantly driven by the pull of rigid cool lithospheric slabs as they sink into the mantle at subduction zones, causes oceanic gateways to open and close, which in turn affects ocean circulation, ocean chemistry, and climate on geologic timescales. Scientific ocean drilling has transformed our knowledge of Earth's interior by pushing the boundaries of science exploration deep into oceanic crust. Since confirming seafloor spreading in 1968, scientific ocean drilling has delivered critical information about the processes that govern plate tectonics and its impact on the interconnected Earth system. Ocean drilling has shown that the volume, composition, and architecture of the oceanic crust varies radically with seafloor spreading rate and the nature of the underlying mantle.



Compilation showing scientific ocean drilling holes that penetrated >100 m into intact oceanic crust and tectonically exposed lower crust and upper mantle from 1968 to 2018. The bar chart provides the number designation for each hole and the recovery (in percent) for each basement lithology. The yellow dots indicate the locations of these drill holes on the global map of ocean crustal age; holes that have been particularly instrumental in informing our understanding of the formation of oceanic crust are labeled (504B, 735B, 801C, 1256D, U1309D, and U1473A). This compilation does not include "hard rock" drill holes into seamounts, oceanic plateaus, back-arc basement, hydrothermal mounds, or passive continental margins. The locations of plate boundaries (red) and subducting slabs (blue shading) are also shown. Note that the majority of drill holes are in crust younger than 40 million years. *Sources: Michibayashi et al. (2019), https://doi.org/10.5670/oceanog.2019.136; Hayes (2018), https://doi.org/10.5066/F7PV6JNV; Müller et al. (2016), https://doi.org/10.1146/annurev-earth-060115-012211*

This pattern is different for slow-spreading systems where tectonic extension usually dominates, leading to heterogeneous crustal structure, the formation of short-lived microplates, or even the absence of a magmatic crust. In ultraslow spreading environments, tectonic movements may cause low-angle detachment faulting that typically results in exposure of mantle rocks such as peridotites and pyroxenites at the seafloor.



Moho's unknown character. We have limited knowledge of how ultramafic rock types of the upper mantle relate to the position of the Mohorovičić seismic discontinuity ("Moho") under slow-spreading ridges and how the Moho differs in the faster-spreading systems. By comparing **ocean crustal sections** collected from different spreading regimes, scientific ocean drilling can shed light on the differences in ocean crustal genesis as a function of spreading rate, mantle potential temperature, and mantle source composition over time, and establish the relative importance of ridge magmatism and tectonic extension in creating oceanic crust and in determining the **location and character of the Moho**.

Lower crust magmatic processes. It also remains unclear how magma is distributed throughout the lower crust—in sections deeper than 1 km—and how hydrothermal circulation and serpentinization, which may extract significant amounts of heat from these systems, mobilize and concentrate economically important metals and modulate deeper magmatic processes. Acquisition of **long, deep crustal sections** will permit a better understanding of what processes drive variations in crustal accretion and serpentinization and how this interplay controls the exchanges of heat, mass, elements, critical metals, and volatiles between Earth's mantle and its crust, ocean, and atmosphere.

Scientific ocean drilling and associated marine geological and geophysical studies have revealed differences in the structure of oceanic crust formed under fast, slow, and ultraslow spreading regimes. The large white arrows depict asthenospheric upwelling and flow induced by plate spreading. The small white arrows indicate relative fault motion. The base of the lithosphere is conventionally defined as the 1300°C isotherm. *Illustration by Geo Prose, inspired by van Wyk de Vries and van Wyk de Vries (2018), https://doi.org/10.1016/B978-0-12-809749-6.00007-8*

OCEANIC CRUST MATURATION

Throughout its life, the oceanic crust forms the key boundary between the ocean and the mantle. Off-axis magmatism and tectonics structurally modify the crust as it matures, and thermally driven fluid circulation within the crust and seawater at the seafloor chemically modify the crust over millions of years. Thus, oceanic crust that is 100 million years old or older has a very different composition, structure, density, and strength compared to young crust. To assess changes in past ocean chemistry and understand the physical and chemical nature and hydration state of the oceanic crust entering subduction zones requires drilling age transects into mature oceanic crust. Samples recovered will also provide information helpful for determining the occurrence and magnitude of past **natural hazards** such as earthquakes and explosive volcanism.

Fluid circulation and cooling plates. We now recognize that oceanic crust is a highly permeable aquifer through which seawater-derived fluids circulate. High-temperature (up to 400°C) "black smoker" hydrothermal vents along mid-ocean ridges are the most obvious manifestation of such thermally driven fluid circulation, but we know from scientific ocean drilling that hydrothermal fluxes through the maturing ridge flanks are many orders of magnitude more voluminous. Conductive heat flow deficits indicate that fluid circulation is diminishing over geologic time, but it seems to persist through oceanic crust at temperatures much less than 100°C and crust as old as 65 million years. Future scientific ocean drilling will determine when and how this threshold from advective to purely conductive heat loss is crossed remains uncertain.

Old crust and CO_2 sequestration. Key information on hydrogeology, thermal history, geochemistry, critical metal deposition, and microbial transitions across the aging ridge flanks is absent because our current sampling of old (>35 million years) in situ upper oceanic crust is biased toward areas with anomalously thick overlying sediments and crust created at intermediate- to fast-spreading rates. Scientific ocean drilling needs to fill these critical gaps by exploring a variety of the older ridge flank segments. Acquisition of oceanic crust samples will also allow us to quantify the extent to which crustal aging buffers Earth's climate system through **inorganic $CaCO_3$ precipitation** and thus how much atmospheric CO_2 becomes sequestered in oceanic crust.

SERPENTINIZATION PROCESSES

Up to a quarter of the seafloor formed at slow- and ultraslow-spreading mid-ocean ridges is estimated to be made up of a diverse patchwork of peridotite and gabbroic lithologies. This variability indicates that oceanic crust may be more heterogeneous and more reactive than originally hypothesized for a classically layered crust typically formed at fast-spreading ridges. Changes in physical and chemical properties due to hydration—in a process called serpentinization—thus may be much more extensive in oceanic crust, even to greater depths and into the underlying mantle, yet this hypothesis is largely untested. Scientific ocean drilling permits investigation of serpentinization processes in different tectonic environments, for different crustal ages, and to **greater crustal depths**. Key unknowns include how serpentinization of slow-spreading oceanic crust may affect global biogeochemical cycles and plate rheology and structure. We also still need to determine why serpentinization fronts in oceanic crust appear to be so abrupt that seismically they may rival the Moho's signature.

…we can explore the links between serpentinization, aging oceanic crust, the mantle, and ocean, and their impacts on geochemical cycles, natural resources, and life.

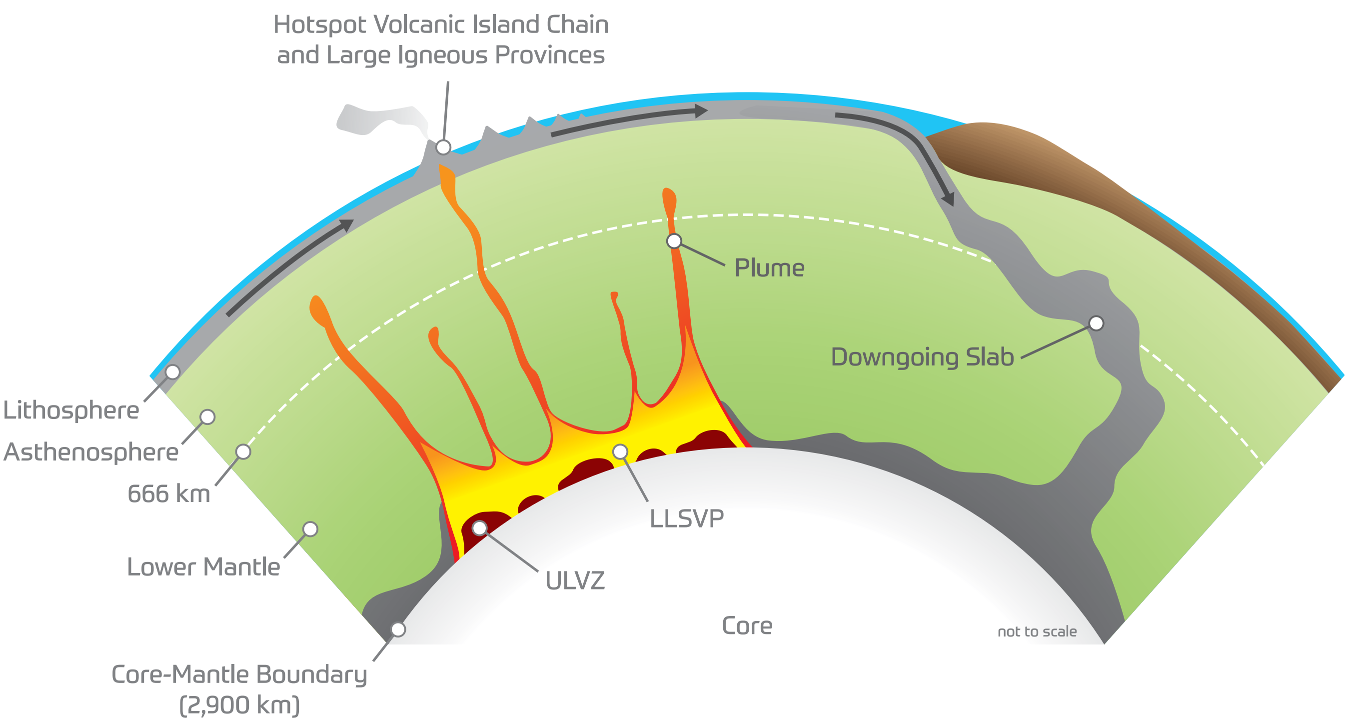
Bend faults and petit spots. In other instances, during the final act of lithospheric aging and just prior to subduction, the flexing or bending of the downgoing plate may initiate new or reactivate old faults that provide late-stage bidirectional pathways for fluid flow. These new avenues for seawater penetration lead to the formation of submarine mud volcanoes and serpentinization in the uppermost mantle. This bend faulting also provides pathways for melts, as the uplifted bulge may trigger decompression melting in the asthenosphere, leading to small-scale but potentially widespread formation of "petit spot" volcanoes.

Serpentinization fueling microbial life. Serpentinization may play a critical role in providing environments for microbial life in newly generated oceanic crust to more than 100 million-year-old oceanic crust. At slow-spreading mid-ocean ridges where melt supply is limited, serpentinization of mantle rocks exposed to seawater weakens the rock, releases heat, and produces a mix of chemicals (including hydrogen and abiotic methane) that is the building block for unique, yet poorly understood, ecosystems, in conditions that may resemble those of early Earth. The role serpentinization plays **supporting microbial life** is an ongoing scientific ocean drilling research area.

Crustal aging and serpentinization. By drilling age transects across multiple ocean basins, from mid-ocean ridges, to subduction zones, to passive margins, we can explore the links between serpentinization, aging oceanic crust, the mantle, and ocean, and their impacts on geochemical cycles, natural resources, and life. Integrated coring and in situ geochemical and **microbial monitoring** and hydrological experiments along transects will target critical gaps in ocean crustal sampling with regards to crustal age, spreading rate, later intraplate volcanic overprinting, and sediment thickness. Such systematic sampling is essential to determine the range of crustal serpentinization effects across the full age spectrum and ocean crustal styles.

HOTSPOT VOLCANISM AND LARGE IGNEOUS PROVINCES

As oceanic crust spreads away from mid-ocean ridges, it commonly traverses "hotspots" in the underlying mantle where narrow plumes of material may be upwelling within Earth's interior. When these hotspots are long-lived, they mark tectonic plates with age-progressive volcanic chains for up to 80 million years or longer, but they also may produce short-lived, high-volume oceanic plateaus. Although tens of thousands of volcanic seamounts and many large igneous provinces (LIPs) are found in the ocean basins, scientific ocean drilling has explored fewer than a dozen hotspot systems. Major gaps in our knowledge remain about the deep mantle heritage and the chemical, isotopic, and mineralogical makeup of mantle sources that feed hotspots. Scientific ocean drilling offers opportunities to learn about the origin and mobility of mantle plumes, whether two large low shear wave velocity provinces (LLSVPs) in the deepest mantle regions (imaged using seismology) are acting as plume nurseries, if bolide impacts may be related to the generation of some LIPs, and how LIPs and excessive intraplate volcanism may drive **Earth's climate system** past **tipping points**.



Scientific ocean drilling offers the opportunity to learn about the composition and evolution of oceanic plates, mantle anomalies, mantle plume nurseries, and oceanic volcanic chains. This conceptual sketch illustrates the connections among these elements in Earth's interior. ULVZ = Ultra low velocity zone. LLSVP = Large low shear wave velocity province. *Illustration by Geo Prose, inspired by Figure 20 in Sager et al. (2016), https://doi.org/10.1016/j.earscirev.2016.05.011*

Mantle plumes modulating Earth's climate. Long-lived mantle plumes play a significant role in broad-scale regional uplift of oceanic lithosphere, with these topographic fluctuations impacting both sedimentation and ocean circulation. For some hotspot systems, these vertical motions appear more significant when the plumes are centered on mid-ocean ridges such as Iceland today or on triple junctions such as Shatsky Rise, Kerguelen Plateau, and Broken Ridge that formed in the Cretaceous. It remains unknown whether the plume/ridge and plume/triple junction correlation is random or whether large-scale tectonics or mantle convection is responsible for the emplacement of plumes in those specific plate-boundary settings. Their effects on Earth's climate therefore remain undetermined. We also don't know why there are more LIP emplacements between 150 and 50 million years ago than between 50 million years ago and today. Scientific ocean drilling can investigate how LIP emplacements affect regional plate tectonics and mid-ocean ridge spreading, what level of topographic fluctuation results from long-lived plumes lifting up oceanic lithosphere, and how the massive magmatism constituting LIP emplacement may have affected **Earth's climate system** and global **ocean health**.

Chemically zoned and moving plumes. A new research avenue centers around understanding the spatial geochemical zonation of hotspot tracks and what it might reveal about the internal structure and composition of mantle plume stems and about LLSVPs from which they may originate. Scientific ocean drilling is essential for recovering unaltered igneous rocks that contain tiny parcels of melt trapped during crystal growth (so-called "melt inclusions") that allow us to learn about the pressure, temperature, and composition of hotspot mantle source regions. Recovery of lava erupted from seamounts and LIPs also allows us to add new paleomagnetic inclination and geochronological constraints on plume mobility—whereby scientific ocean drilling can test geodynamic computer models of deep-rooted plume stems getting deflected in the large-scale mantle flow—and help refine plate motion histories, which underpin global tectonic evolution models.

PLATE DESTRUCTION IN SUBDUCTION ZONES

At subduction zones, the majority of mature, hydrated oceanic lithosphere descends back into the asthenospheric mantle, recycling igneous rocks, sediments, water, and carbon back into Earth's interior. The subduction of oceanic lithosphere is responsible for ocean-circling chains of volcanoes and ocean trenches that extend to 2 km deeper than the height of Earth's tallest mountains. Some of the largest **earthquakes and tsunamis** occur along the roughly 42,000 km of subduction zones. Volatiles released from the downgoing hydrated oceanic lithosphere give way to gas-rich explosive eruptions that also endanger the highly populated regions bordering subduction zones.

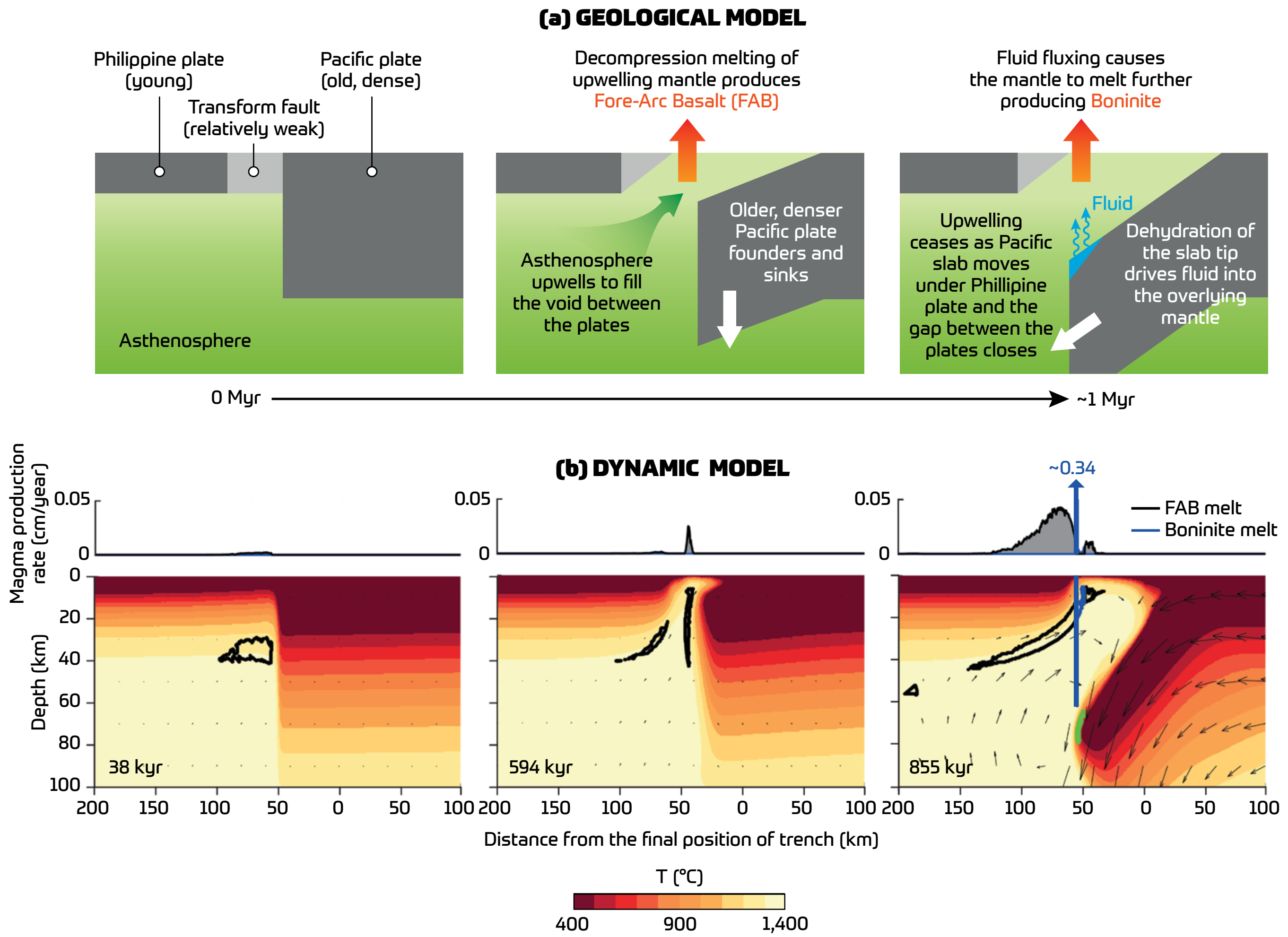
Subduction zone behavior and mantle recycling. The subduction process is remarkably variable in terms of its geometries, speeds of plate descent and trench rollback, deformation patterns, and chemical exchanges. It remains difficult to establish how the hydrated oceanic lithosphere and the overlying sediment and volcanic structures it carries will be processed in the subduction zone. We don't know how much of each component will make it into the arc volcanoes or recycled back into Earth's mantle. Scientific ocean drilling can deliver the rock and fluid samples, and the dynamic observations such as temperature and pore pressure, that are required to define subduction zone behavior and mantle recycling. Drilling allows us to assess spatial variations in subduction conditions, including enhanced deformation where a seamount or LIP sits on the downgoing slab, that may affect seismic, fluid flow, magmatic, and landscape responses.

Oceanic Crust Obduction

Not all oceanic lithosphere gets recycled at subduction zones. Oceanic lithosphere that is exposed on land is called an ophiolite (e.g., Troodos, Semail) or accreted terrane (e.g., Wrangellia, Siletz). Ophiolites provide invaluable, accessible windows into the deep Earth. Indeed, the standard model for oceanic crustal structure was long based on the Troodos ophiolite in Cyprus. However, the origins and emplacement of ophiolites, and hence their interpretation in terms of past seafloor spreading, remain controversial. **Land-to-sea** investigations, partnering scientific ocean and continental drilling, in places such as the Semail Ophiolite in Oman or the Izu-Bonin-Mariana and Japan Trenches, will provide new avenues to elucidate the origins of ophiolites. By sampling lava sequences in a range of settings, including in fore-arc and back-arc basins, we will be able to identify where and why some oceanic crust is able to avoid being recycled back into Earth's interior.

Back-arc basins. The overriding plates typically stretch, which in many cases progresses from rifting to seafloor spreading, giving rise to back-arc basins. Scientific ocean drilling provides the means to seek explanations for the seemingly contradictory occurrence of extensional stress regimes adjacent to areas of major convergence. At present, these two stress regimes are almost exclusively explored via geodynamic modeling. Scientific ocean drilling can provide constraints on variables such as basalt geochemistry, timing of cessation of arc volcanism, and temporal changes in stress regimes that are critical to testing different models of back-arc extension.

Continental crust formation. Scientific ocean drilling also helps test hypotheses concerning continental crust formation. Subduction zones not only create new continental crust; competing processes may destroy continental crust and deeply recycle it. Subduction processes preferentially filter and store certain elements within continental crust, but they also replenish the mantle. Samples collected by scientific ocean drilling will be key in illuminating how these elements are fractionated and processed during subduction and how that influences long-term mantle evolution and its overall chemical makeup. Drilling is needed to better define nascent continental crust formation in oceanic



Drilling results allow us to test subduction initiation models. International Ocean Discovery Program Expedition 352 recovered a continuous, in situ record of subduction initiation from a segment of the forearc of the Izu-Bonin-Mariana subduction system. (a) Cores show a distinct magmatic progression from mid-ocean ridge-like forearc basalts (FAB) to volatile-rich "boninite" lavas took place over approximately 1 million years (Reagan et al., 2019, https://doi.org/10.1016/j.epsl.2018.11.020). (b) Dynamic numerical modeling reveals that subduction initiation driven by internal, vertical (buoyancy) forces is needed to reproduce both the temporal and spatial distribution of magmatic products observed in the Expedition 352 cores. Previously models invoking horizontal external forces are unable to generate the lava types or their distributions. Overlain on the dynamic model results are: regions where decompression melting is occurring (black outline), regions where melting is occurring in the presence of slab fluid (blue outline), and the region of the subducting crust that has crossed its solidus (green outline). *Modified from Maunder et al. (2020), https://doi.org/10.1038/s41467-020-15737-4* arcs, and it will contribute to understanding global-scale element fractionation by adding a temporal perspective on the scale of millions of years. By combining knowledge gained from hard rocks and volcaniclastics recovered by scientific ocean drilling with that of widespread (airfall) tephra deposits on land, we can gain a better understanding of the total mass outflux in volcanic arcs that in turn will provide a missing component in modeling the overall mass balances across subduction zones.

SUBDUCTION INITIATION

The mechanics of how the subduction process starts is enigmatic. Incipient subduction zones—where oceanic lithosphere begins to descend into the upper mantle—are rare in today's plate tectonic configuration. Yet, they are ideal locations for scientific ocean drilling to test hypotheses about how differences in buoyancy, composition, and lithosphere structure across either convergent, divergent, or transform plate boundaries set the stage for subduction.

A major outstanding question is whether the start of a new subduction zone is a spontaneous tectonic event or is induced by a far-field change in Earth's plate tectonic configuration, including changes in global plate motion or the possible presence of mantle plumes. Another major question is whether there have been peaks and a periodicity in subduction initiation and related increases in arc volcanism over geologic time. Because subduction is a three-dimensional process, generating regional tectonic syntheses that combine geophysical and scientific ocean drilling results will allow us to evaluate the fundamental structural and magmatic processes involved in the birth of new subduction zones. Understanding the roles of thermal lithospheric rejuvenation, preexisting adjacent transform faults, differences in crustal age of the downgoing oceanic lithosphere, and the presence of stretched continental ribbons or transpressional margins is still strongly debated. Scientific ocean drilling also allows us to delve into the possibilities that subduction may initiate in Earth's upper mantle, that it may start synchronously along entire edges of single tectonic plates, and that initiation of subduction itself may cause major changes in the global subduction zone configuration and in the overall network of interconnected plate tectonic motions.

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STRATEGIC OBJECTIVE 3 EARTH'S CLIMATE SYSTEM

Examining variations in ice sheets, ocean and atmosphere dynamics, and sea level

SUMMARY

Marine sediments contain the most complete record of the processes, mechanisms, and impacts of natural climate variability and long-term changes to Earth's climate system on timescales from annual to hundreds of millions of years. Scientific ocean drilling can increase the continuity, resolution, and accuracy of paleoclimate reconstructions to enhance our understanding of how Earth's climate system operates. Major advancements are expected by systematically mapping out the relationship between orbital variability and Earth's climate, the roles the ocean and continental weathering play in regulating atmospheric greenhouse gases, and the coupled role oceanic and atmospheric circulation play in distributing heat and water across the planet. A key focus will be to document the onset, interconnectivity, and resilience of potentially vulnerable components of the modern climate system, including the global ocean meridional overturning circulation, sea ice and ice sheets, and patterns of precipitation and aridity. By targeting how the climate system operates across a wide array of past climate states, scientific ocean drilling will obtain the data necessary to calibrate and improve numerical models used to project future climate impacts and inform mitigation strategies.

DRILLING TO UNDERSTAND THE CLIMATE SYSTEM

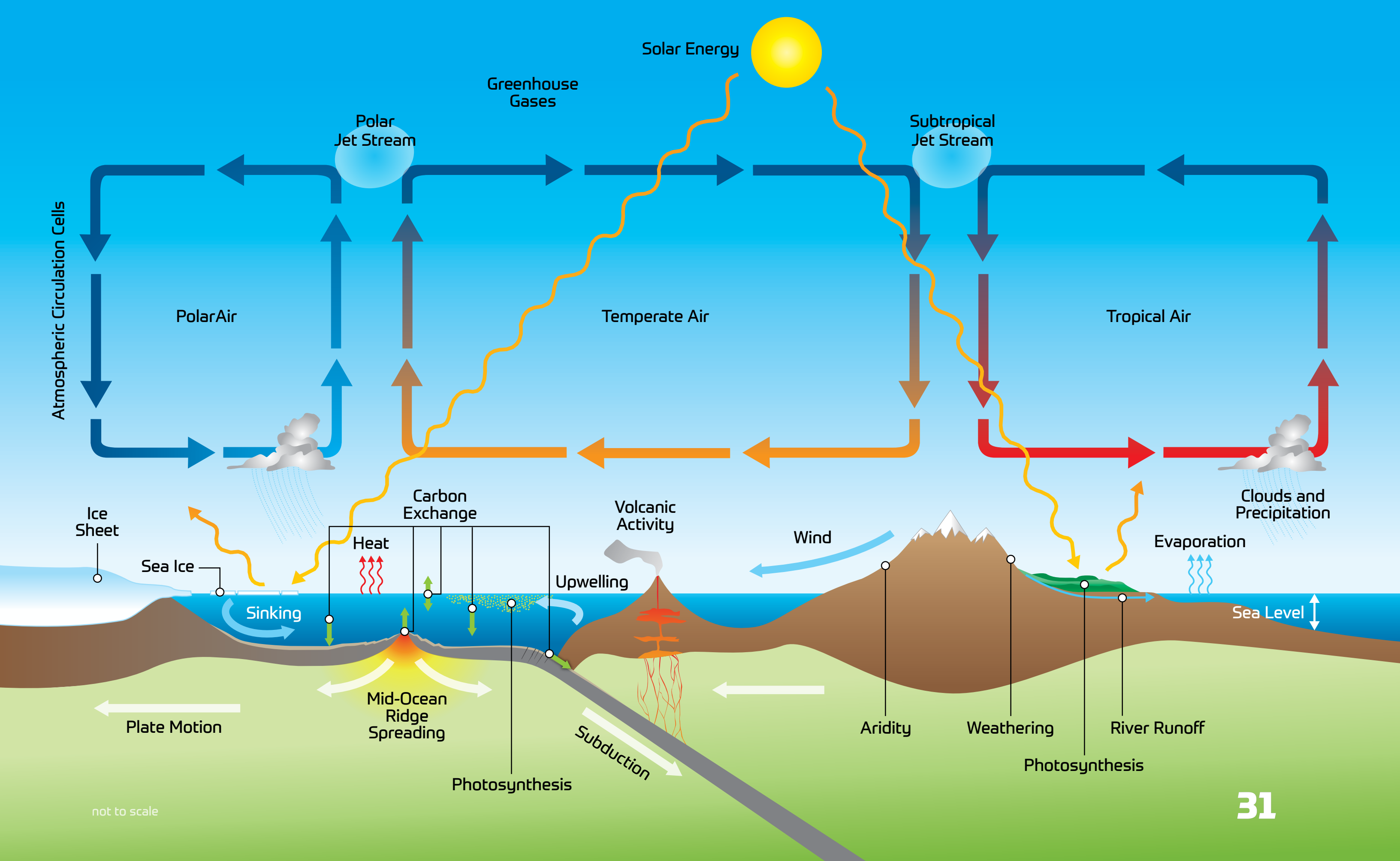
Accounting for 71% of Earth's surface area, the ocean plays a central role in the climate system. The ocean stores 1,000 times more heat than the atmosphere, redistributing this heat through ocean circulation. The ocean also plays a primary role in the **global cycling** of carbon, which is important in regulating global temperatures and Earth's climate by controlling the amount of CO_2 in the atmosphere. Ocean water also stores 60 times more carbon than the atmosphere, but beneath the ocean, even larger quantities of carbon are stored within deeply buried sediments and in the altered oceanic crust, both of which are recycled through subduction. This large marine sediment and rock sink for carbon is not well characterized. We can use physical, biological, and chemical signatures in marine sedimentary archives to reveal changes to marine environments and to terrestrial features, including vegetation, rainfall and droughts, weathering and the uplift and erosion of mountains, winds, and ice sheets. Acquisition of such information through scientific ocean drilling allows us to address important questions about Earth's climate system such as: How does the climate system operate under high atmospheric CO_2 concentrations? How does it respond to ice-free polar oceans? How resilient are low-latitude monsoon systems to elevated global temperatures and altered patterns of ocean and atmospheric circulation? How rapidly and frequently have ice sheet-driven variations in sea level occurred in the geologic past?

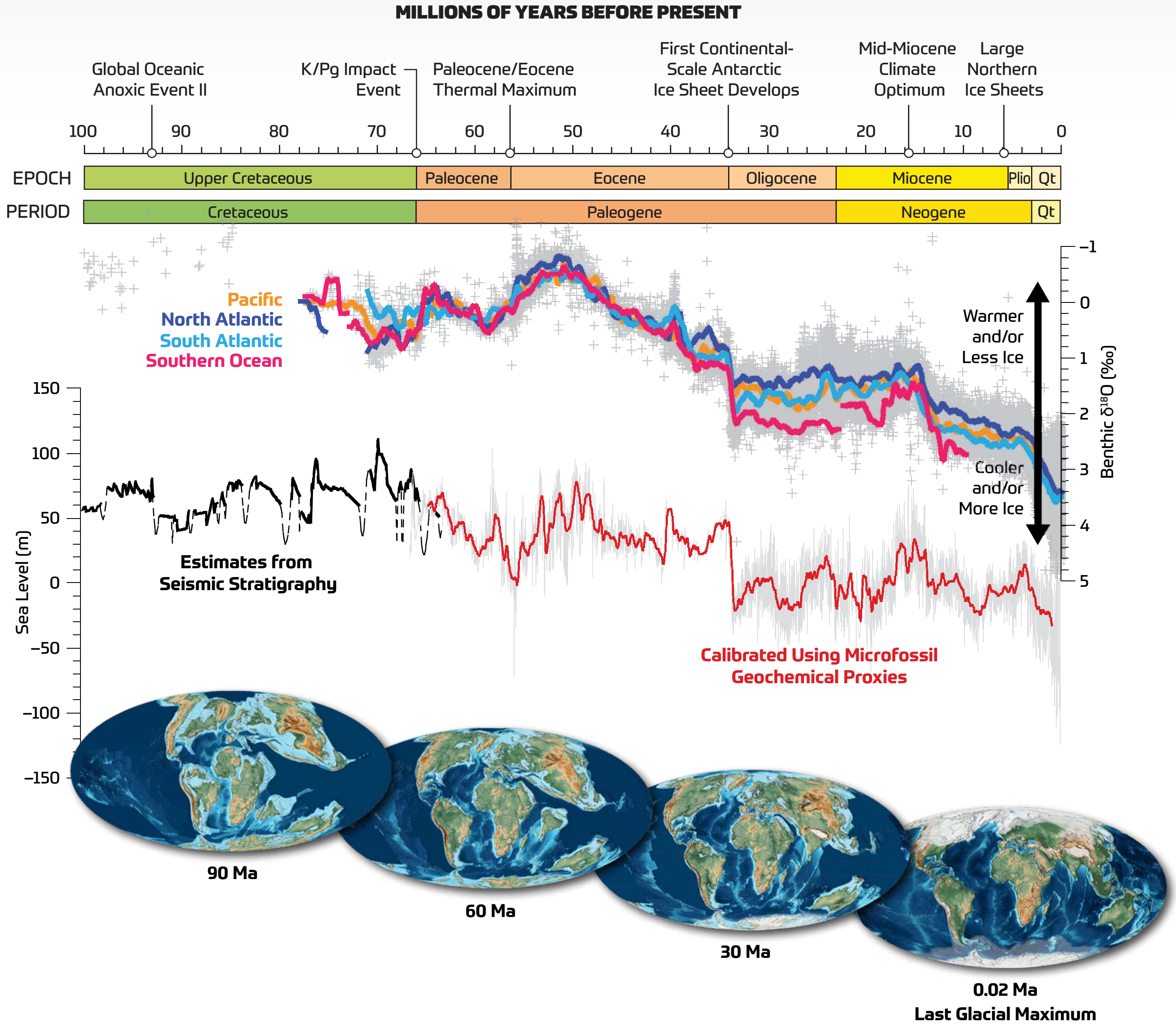
Past warmer climate analogues. More than 80% of the modern ocean basins were created during the last 100 million years. Past decades of scientific ocean drilling have allowed us to start reconstructing the warmer climates (such as during the Cretaceous, about 115–66 million years ago) that followed the breakup of supercontinent Pangaea and the birth of the Atlantic and Southern Oceans. We have started to document the long-term cooling trend and the development of continental ice on Antarctica over the past 50 million years and the development of Northern Hemisphere ice ages in the last few million years. Much remains to be discovered about the regional patterns of climate variability and change, driving mechanisms and rates of change, and the **feedbacks** and **tipping points** that cause irreversible changes.

Natural climate variability. In the past century, atmospheric greenhouse gas and aerosol levels have increased, leading to the warming of surface and deep ocean waters, accelerating rates of sea level rise, the rapid retreat of polar and glacial ice, and the emergence of more extreme and less predictable weather patterns. Climate change is threatening the infrastructure and resource dependence of communities across the planet, as exemplified by the wildfires in Australia and California and the inundation of Pacific islands by increasing sea levels. Humans are now a key factor in Earth's climate system, and to understand how we are perturbing its inner workings, we must first resolve the relationships among its basic components and elucidate the driving mechanisms of observed climate change in the geologic past. We will use the marine sedimentary archive collected through scientific ocean drilling to document the influence of orbital variability, carbon storage in the ocean, tectonic processes, and plate configurations on the magnitude and origin of natural climate variability at annual through million-year timescales. This information can be used to improve future climate change projections and determine the consequences for **Earth's habitability**.

Definition of the Climate System

Earth's climate system consists of five major components: the atmosphere, hydrosphere, cryosphere, lithosphere, and biosphere. The interactions among the components dictate the distribution of heat and water across our planet over timescales from annual and decadal to millions of years. The climate system is fueled primarily by the amount and distribution of solar energy that reaches Earth's surface. It evolves under the influence of external forcings such as volcanic eruptions and solar variations, as well as internal **feedbacks** among its components. *Illustration by Geo Prose*





One hundred million years of climate change captured in scientific ocean drilling records. Significant paleogeographic reorganization and key events in Earth history accompanied a long-term cooling trend that culminated in the development of permanent ice sheets in the polar regions. The geochemical composition ($\delta^{18}O$) of benthic microfossils shown here provides a tool for reconstructing bottom-water temperatures in different ocean basins and calibrating records of global ice volume and sea level change. (Qt = Quaternary, Plio = Pliocene). The most recent estimate of sea level change for the Cenozoic is shown and is based on a spliced record derived from multiple scientific ocean drilling cores, while estimates further back in time are largely based on seismic stratigraphy estimates. The global maps show the changing configuration of the continents and ocean through time (boundary conditions of the climate system), as well as the extent of the cryosphere. *Sources: Cramer et al. (2009), https://doi.org/10.1029/2008PA001683; Miller et al. (2020), https://doi.org/10.1126/sciadv.aaz1346; Scotese (2016), PALEOMAP PaleoAtlas for GPlates and the PaleoData Plotter Program; https://www.earthbyte.org/paleomap-paleoatlas-for-gplates/*

OCEAN CIRCULATION AS A TRIGGER FOR CLIMATE CHANGE

To understand how Earth's climate system operates requires documenting past changes in ocean circulation patterns. More solar energy reaches the tropics than the poles, resulting in a latitudinal temperature gradient that drives atmospheric and oceanic circulation and the location of windfields and biologically active oceanic frontal zones. The poleward transport of warm, salty waters, which then cool and sink at high latitudes, propels the modern global ocean thermohaline circulation. This flow transports heat, carbon, oxygen, and other nutrients around the planet, and profoundly influences precipitation and temperatures over the continents. Future scientific ocean drilling is required to identify the processes that modify ocean deepwater formation to the point that global thermohaline circulation patterns are destabilized and to determine the role the opening and closing of tectonic gateways play in modifying ocean circulation patterns over geologic timescales.

Deepwater formation and ocean circulation stability. Today, the temperature gradient between the equator and poles is amplified by the large amount of incoming solar radiation reflected back into space from polar ice caps and sea ice. This was not always the case in the geologic past and may not be so in our future. It is hypothesized that continued loss of polar ice will reduce equator-to-pole temperature gradients and produce more freshwater runoff that will impede deepwater production in the polar regions. The **tipping points** in the global ocean circulation, and the broader climatic consequences of exceeding them, are not well understood. Results from climate models that investigate these interrelated processes require **ground truthing** based on past analogues that are only obtainable through scientific ocean drilling. Future scientific ocean drilling will assess the stability of our modern global ocean circulation system in different climate states and identify mechanisms and tipping points that cause it to change. High-resolution centennial- through millennial-scale records are particularly pertinent for tracing patterns of deepwater convection during past interglacial intervals and can provide analogues of possible future perturbations to ocean circulation.

Oceanic gateway configurations. Scientific ocean drilling has shown that the locus of deepwater formation has shifted in the past between the Pacific and Atlantic Oceans. This seems to be the case in the warmer climates of the Paleogene and even the more recent Pliocene, but the mechanisms generating this dynamic behavior, and whether it acts as a trigger for or response to climate change, is uncertain. Over the geologic past, the formation and destruction of **oceanic lithosphere** has moved continents, opened and closed oceanic gateways, raised mountains, and thus changed the world's geography and topography. These changes in the shape and configuration of ocean basins are primary controls on ocean circulation patterns and can be reconstructed based on understanding the history of tectonic plate dynamics. Robust tectonic reconstructions of our ocean basins are needed to understand the mechanisms driving long-term changes in ocean circulation and the related climatic and environmental consequences. Establishing and validating the influence of seaways and bathymetric sills on global ocean circulation is particularly important as their limited geographic extent, shallow water depths, and dynamic behavior make them difficult to accurately represent in many models used to investigate the global climate system. However, we don't understand the histories behind the opening and closing of those gateways very well. For example, recently there have been strong challenges to the hypothesis that the closure of the Central American Seaway was relatively recent, and the relationship between the opening of the Drake Passage and changes to global ocean circulation is still strongly debated. New drilling strategies and targets, for example, along **land-to-sea** transects, are needed to resolve the influence of ocean basin configuration on global ocean thermohaline circulation patterns during key climate states and across critical climate transitions of the past.

We will use the marine sedimentary archive collected through scientific ocean drilling to document the influence of orbital variability, carbon storage in the ocean, tectonic processes, and plate configurations on the magnitude and origin of natural climate variability at annual through million-year timescales.

Critical Oceanic Gateways and Global Thermohaline Circulation

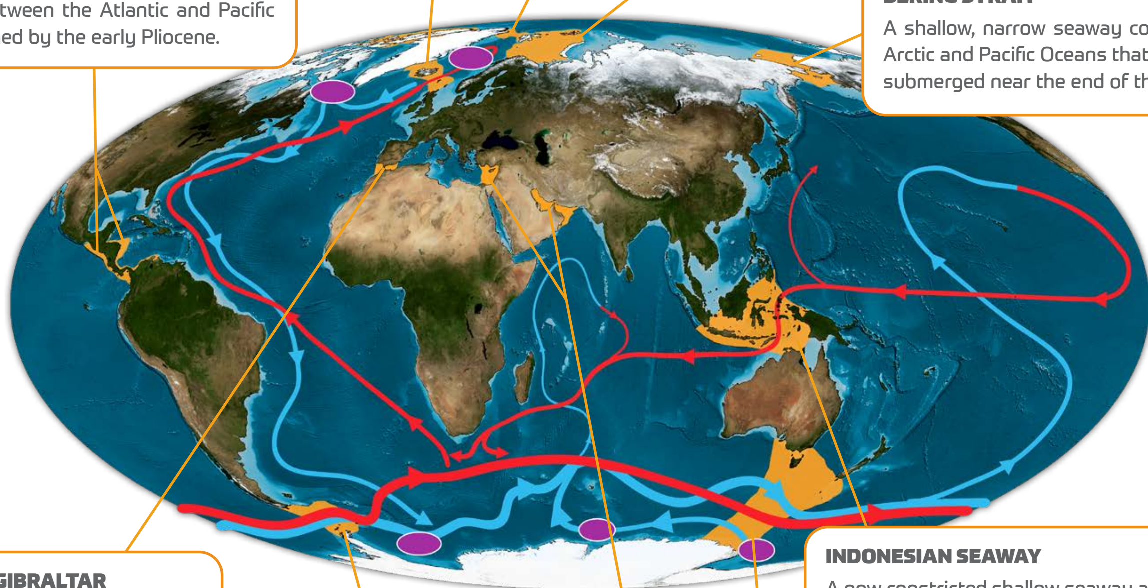
FRAM STRAIT
The only deepwater connection between the Arctic and the world ocean, allowing exchange between the Arctic and Norwegian-Greenland Sea; open since the middle Miocene.

GREENLAND-SCOTLAND RIDGE
An active seafloor ridge related to Iceland volcanism, whose dynamic topography controls exit of dense polar waters from the Nordic seas to the Atlantic; subsided through the early-middle Eocene with considerable Neogene variability.

BARENTS SEA
A shallow seaway allowing inflow of warm Atlantic waters into the Arctic. Likely aerially exposed for most of the Paleogene and Neogene, achieving its current depth due to Quaternary glacial activity.

CENTRAL AMERICAN SEAWAY
Narrow land bridge connecting North and South America and blocking low-latitude exchange between the Atlantic and Pacific Oceans; formed by the early Pliocene.

BERING STRAIT
A shallow, narrow seaway connecting the Arctic and Pacific Oceans that first became submerged near the end of the Miocene.



STRAIT OF GIBRALTAR
A narrow seaway allowing exchange between the Atlantic Ocean and Mediterranean Sea, whose closure in the latest Miocene led to the drying out of the Mediterranean.

INDONESIAN SEAWAY
A now constricted shallow seaway affecting tropical surface inflow from the Pacific to the Indian Ocean; established by the early Pliocene.

TASMAN GATEWAY
A deep oceanic gateway between Antarctica and Tasmania allowing circum-Antarctic flow; opened through the middle to late Eocene.

DRAKE PASSAGE
A deep oceanic gateway between Antarctica and South America allowing circum-Antarctic flow; opened through the late Eocene to Miocene.

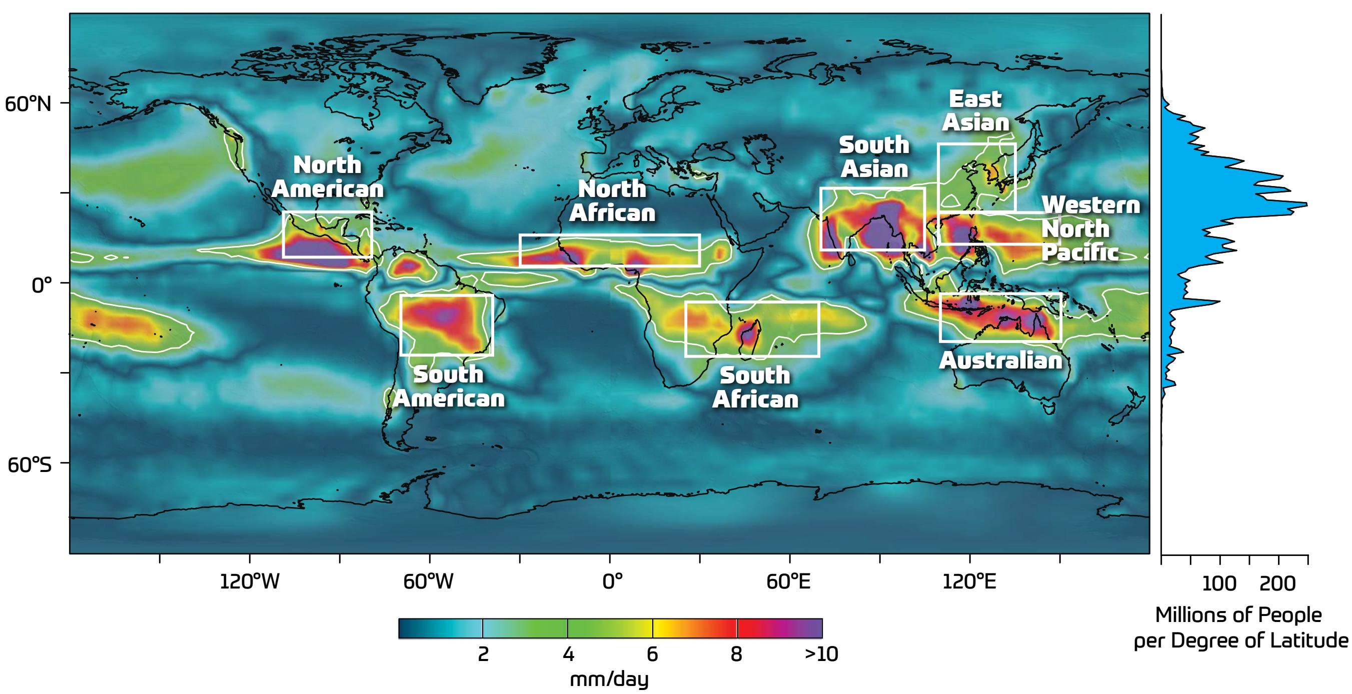
TETHYS OCEAN
A major tropical seaway that connected the Indian and Atlantic Oceans during the Cretaceous to Eocene. The eastern Tethys closed during the Oligocene to Miocene.

Changes in the shape and configuration of ocean basins are primary controls on ocean circulation patterns. Scientific ocean drilling provides the data needed to make robust tectonic reconstructions of ocean basins, permitting a better understanding of the mechanisms driving long-term changes in ocean circulation and the related climatic and environmental consequences. This figures is a simplified representation of the global ocean conveyor (blue and red arrows) and critical gateways (orange) that have influenced ocean circulation during the past 100 million years to various extents. Purple ovals are sites of deepwater formation. Red arrows = Surface currents. Blue arrows = Deep currents. Arrow width indicates relative current strength. *Illustration by Matt O'Regan. Sources: Ocean bathymetry from GEBCO, https://www.gebco.net/; Land mask from NASA Blue Marble; thermohaline circulation modified from NASA Scientific Visualization Studio, https://svs.gsfc.nasa.gov/3881.*

CHANGING PATTERNS OF RAINFALL AND DROUGHT

Given the vast societal and ecological consequences of changes in rainfall and drought patterns—and associated increases in flooding and desertification—there is a pressing need to resolve the interactions within Earth's climate system that can alter the **global hydrological cycle**. Scientific ocean drilling provides access to slowly and continuously accumulating sediments in the ocean basins that record past extreme climate episodes. Sediment proxies for rainfall allow mapping of major global monsoon systems. Mineral dust plumes originating in deserts that were blown out to sea by prevailing winds record progressions toward greater (glacial) aridity in Earth's past.

Monsoon systems. Characterized by seasonally reversing winds that bring highly seasonal and abundant rainfall to many of the most densely populated tropical and subtropical zones, monsoon systems are a critical source of water to billions of people. Monsoons are also one of the most dynamic components of the global hydrological cycle on multiple timescales. Scientific ocean drilling can provide the basic data needed for a global synthesis of monsoon variations across tectonic, orbital, and millennial timescales. Past drilling, particularly over the last 10 years, has contributed the longest high-resolution records of regional monsoon activity and documented orbital controls on its variability back into the Miocene. Future drilling is required to balance the geographic distribution of monsoon records, which are currently biased toward the Northern Hemisphere, and push the overall temporal range into the greenhouse climates of the Paleogene and Cretaceous. These longer-term records can answer important questions about how the monsoons operate in warmer climates of the past and respond to major global climate change events, including the inception of polar ice sheets and sea ice and large-scale perturbations to oceanic and atmospheric circulation. A major questions to answer is how does seasonality impact our interpretation of past monsoonal summer versus winter circulation patterns. We also need to use scientific ocean drilling and improved proxies to better differentiate between changing wind, rainfall, and ocean surface circulation patterns.

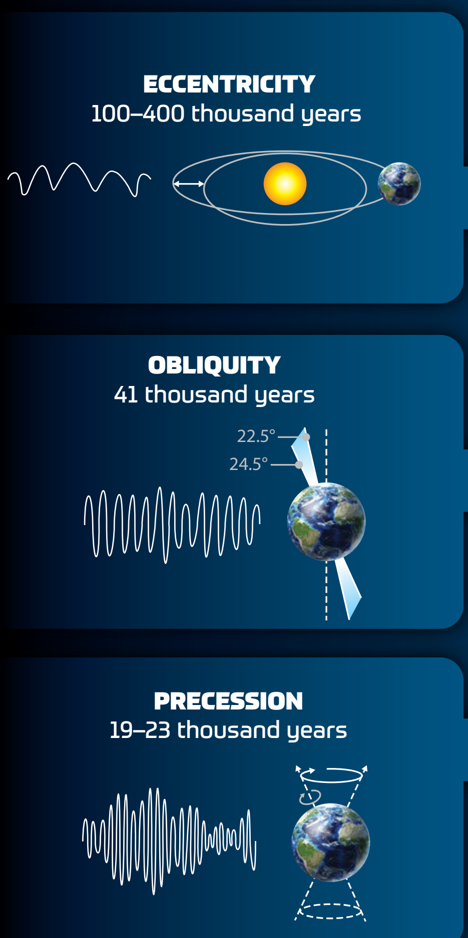


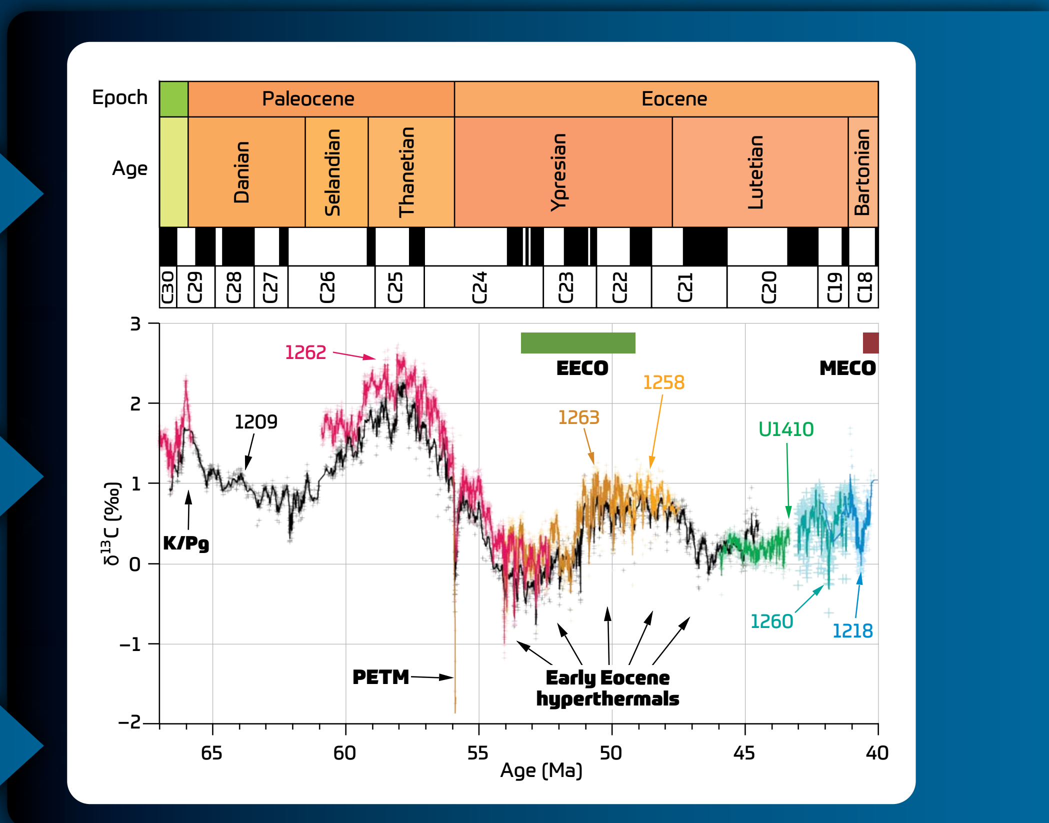
Scientific ocean drilling has contributed to investigations of monsoon systems that impact a significant portion of the world's population (plot on right). It has provided long, high-resolution records of regional monsoon activity and documented orbital controls on its variability back into the Miocene (~23 million years ago) to answer questions about how monsoons responded to past climate warming. The map shows global monsoon regions (white rectangles and labels), illustrated using the average difference in precipitation (mm/day) between Northern Hemisphere summer (June–August) and winter (December–February) between 1979 and 2018. Future drilling will balance the geographic distribution of monsoon records, which are currently biased toward the Northern Hemisphere, and push the temporal range back to the Paleogene and Cretaceous. *Sources: Precipitation: Climate Prediction Center Merged Analysis of Precipitation 1979–2018; Population: Center for International Earth Science Information Network (CIESIN), Columbia University (2018)*

The Orbital Heartbeat of Climate Change

To decipher the causes, consequences, and interconnections of Earth climate and other environmental processes, it is essential to understand the temporal relationship of their signatures in the geologic record. The highest possible quality chronostratigraphy is key to understanding the timing of critical events. Periodic climate variations that arise from changes to Earth's orbit on timescales of tens to hundreds of thousands of years are exquisitely preserved in marine sediments. These orbital (Milankovitch) forcings alter the amount and distribution of solar energy reaching Earth in a predictable way, but the climatic response to these forcings is highly variable and nonlinear. Scientific ocean drilling was instrumental in identifying pervasive orbital signals in marine sediments worldwide and continues to facilitate and augment the construction of a highly resolved astronomical timescale for the past 66 million years.

Extensive new work is required to achieve a complete orbitally tuned Cenozoic and Cretaceous timescale that allows us to correlate global records of temperature, precipitation, and ice volume. The timescale prior to 40 million years ago requires firmer footing, as fundamental uncertainties in orbital solutions remain, and the Cretaceous is still a major work in progress that mostly lacks orbital control. Equally important to climate science is understanding how subtle shifts in Earth's orbit propagate through the Earth system and how changing boundary conditions in Earth's climate system have amplified or dampened the climatic response. Increased temporal and spatial resolutions are vital to be able to meaningfully investigate the timing of inter-ocean phenomena such as changing polar ice cover, tectonic processes, atmospheric and oceanic circulation, movement of species and nutrients, and carbon cycling at century to millennial resolutions. Future scientific ocean drilling requires high-quality sediment cores with significantly increased temporal resolution, as well as the use of big data analytics, to tease out inter-basin and latitudinal differences in the expression of astronomically paced climate cycles. These improved timescales are vital to understanding feedbacks in the Earth system, the pace at which tipping points are traversed, and the importance of large igneous provinces and bolide impacts as potential drivers of mass extinctions.





Predictable changes in Earth's orbit alter the amount and distribution of solar energy reaching Earth's atmosphere. Scientific ocean drilling has shown that these Milankovitch cycles (left panels), which operate on timescales between 100,000 and 400,000 years (eccentricity), 41,000 years (obliquity), and 19,000 and 23,000 years (precession), have a profound impact on Earth's climate and are captured in the physical, biological, and chemical composition of marine sediments. Marine sediments provide a fundamental tool for developing geochronology and the geologic timescale. The different colors of the $\delta^{13}C$ records in the right panel correspond to different scientific ocean drilling sites. EECO = Early Eocene Climatic Optimum. K/Pg = Cretaceous-Paleogene boundary. MECO = Middle Eocene Climatic Optimum. PETM = Paleocene-Eocene Thermal Maximum. *Source: Modified from Littler et al. (2019), https://doi.org/10.5670/oceanog.2019.122*

Aridity and past desertification. Scientific ocean drilling cores containing oceanic dust generated from the continents of Africa, Arabia, and Australia provide evidence of intervals of extreme droughts and expanding deserts over the last tens of millions of years. Multiple hypotheses have been developed for explaining these periods, including one that postulates an anti-correlation between the extent of, for example, the Sahara Desert and the African Monsoon during glacial and interglacial periods, respectively, and another that suggests they were the result of major changes in ocean circulation patterns. Future scientific ocean drilling offshore major continental land masses and along land-to-sea transects (including collecting sediment cores in lakes) are required to further test those hypotheses and to reveal the more detailed histories of aridification on land. These results will have direct consequences for understanding currently changing desertification patterns and the increasing number of wildfires, where the dynamics between desertification and monsoonal systems are likely to shift assuming a continued global warming trajectory for Earth.

TELECONNECTIONS IN THE CLIMATE SYSTEM

Other central features in Earth's climate system are natural climate oscillations arising from the exchange of heat and moisture, and other feedback processes, between the ocean and atmosphere on interannual, multidecadal, and orbital (20–400 kyr) timescales. This interplay between processes in the ocean and atmosphere are described as teleconnections in the climate system. A prominent example of a climate teleconnection is the El Niño-Southern Oscillation (ENSO). Improving our understanding of how the ocean and atmosphere interact is an a priori requirement for making decadal through centennial-scale climate predictions. Through collection of high-resolution marine paleoclimate archives from across the globe, scientific ocean drilling can provide high-fidelity records that document natural variability in the frequency and magnitude of these climate phenomena and establish how far-field processes (i.e., Asian monsoons and ENSO) are connected. There is also a need to establish whether this type of natural interannual to multidecadal climate oscillations originate from internal climate dynamics and feedback processes or are forced by changes in solar radiation, a question that is difficult to fully investigate using the relatively short instrumental time series of modern climate. Exploring the origins and establishing the teleconnections between high-frequency climate variability presents a particular challenge for future scientific ocean drilling. It requires acquiring high-resolution time series from the Arctic, to the equator, to the Southern Ocean and working closely with the **terrestrial and ice core drilling communities** to effectively integrate marine records with other paleoclimate archives.

THE ROLE OF POLAR ICE

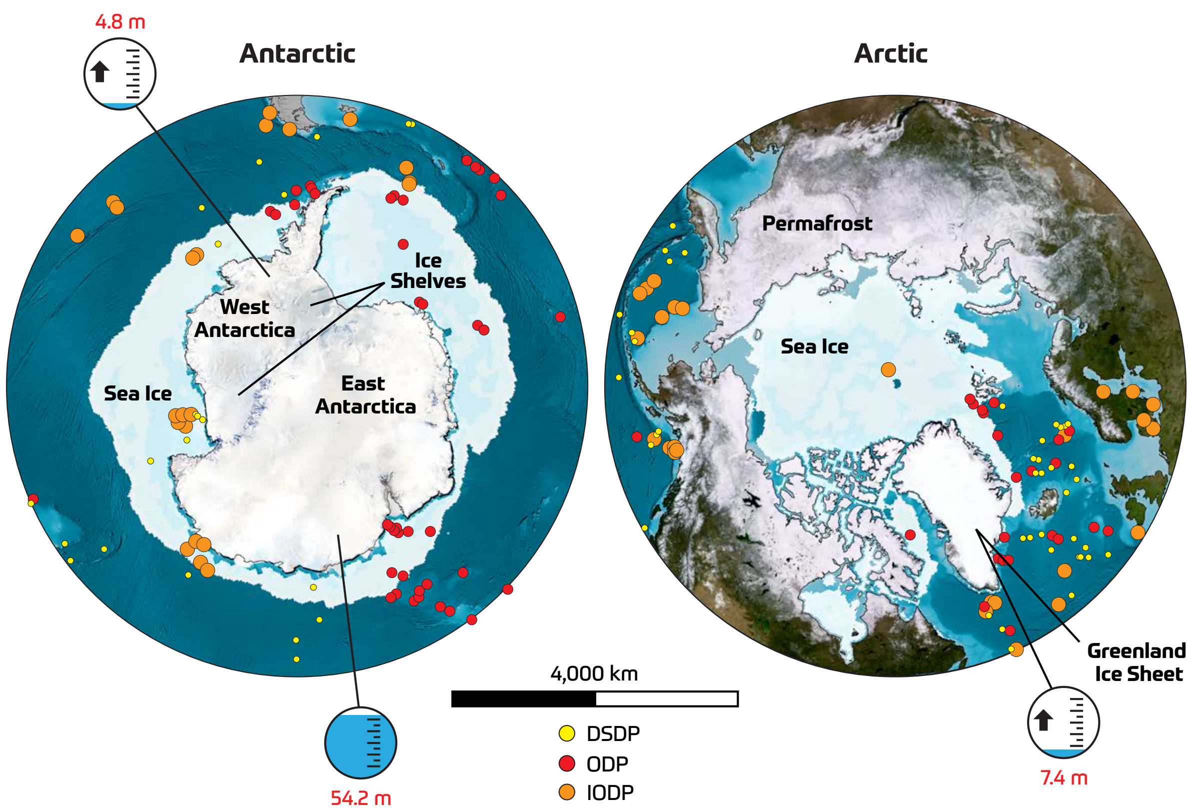
The cryosphere, a primary component of Earth's climate system, can change rapidly and over broad regions. The rapid modern melting of sea ice in the Arctic, and accelerated losses of glacial ice on Antarctica and Greenland, are trends that pose real concerns for society. Establishing the impact of these observed trends and elucidating the role of polar ice in Earth's climate system requires drilling beneath the polar oceans to establish the geologic history of the cryosphere.

Scientific ocean drilling can provide the basic data needed for a global synthesis of monsoon variations across tectonic, orbital, and millennial timescales.

High-latitude polar climate records. Scientific ocean drilling has provided the only Cenozoic marine climate record from the Arctic Ocean and, through multiple expeditions, has contributed considerable insights into the development of the Antarctic ice sheet. Yet, too few drilling records from high-latitude regions exist to fully document the geologic history of the cryosphere and ultimately evaluate its **feedbacks** within the climate system. For example, while we know that seasonal sea ice existed briefly in the Arctic as far back as the Cretaceous, we are unable to say when perennial sea ice first formed, what mechanisms allowed it to form, and how variable it has been. Other important questions include the extent and dynamics of the Greenland and Antarctic ice sheets during the long-term global cooling that occurred through the Neogene and across glacial and interglacial intervals of the Quaternary. On longer timescales, the extent of Antarctic ice sheets and bi-polar sea ice in warmer pre-Oligocene greenhouse climates, and the possible impact they had on other facets of the global climate system, still needs to be determined.

Polar amplification. The geologic history of the cryosphere must be better resolved if we are to understand past and future changes in the climate system. Enhanced poleward transport of heat, the increased absorption of solar radiation as snow and ice melt, and topographic changes associated with changing ice cover are thought to cause polar amplification of temperatures—a phenomenon whereby any change in the net solar radiation fueling the climate system produces a greater change in temperature near the poles than the planetary average. Studies of latitudinal temperature gradients between scientific ocean drilling boreholes document the magnitudes of polar amplification of temperature in the geologic past, and diverse records of sea surface and terrestrial temperatures reveal notably higher past polar temperatures, as exemplified by palm trees in Antarctica, breadfruit trees in Greenland, and alligators in the Arctic. However, the exact amplification processes are not well understood and numerical climate models still have trouble explaining how the poles could be warm enough to sustain these plants and animals through the polar winter. This suggests that we may be missing fundamental dynamics in the climate system that may affect our models of a future, possibly much warmer, Earth. What were the magnitudes and mechanisms driving polar amplification in the warmer and higher CO_2 climates of the past? Answering this question is imperative to understanding the implications of modern climate change and projecting the cascading effects of continued polar warming in our future climate system. To this end, scientific ocean drilling will reconstruct the geologic history of Earth's cryosphere, in particular, to constrain the magnitudes and effects of polar amplification.

Cryosphere feedbacks. The integration of polar records with existing and new climate archives from tropical and extratropical regions will allow us to assess feedbacks between the cryosphere and other components of the climate system. For example, an important, recently observed **feedback** in the Earth system concerns the weakening and broader meandering of the polar jet stream as the Arctic



Major components of Earth's cryosphere, with the bi-polar extent of sea ice shown from June 21, 2019. Past scientific ocean drilling sites located at latitudes greater than 55° illustrate both the ongoing efforts to unravel the evolution and dynamics of the cryosphere and some of the understudied regions around the Antarctic continent and within the Arctic Ocean that innovative drilling strategies, platforms, and tools now enable us to target. The circular thermostats show the average sea level rise that can be expected from the melting of these ice sheets. DSDP = Deep Sea Drilling Project. ODP = Ocean Drilling Program. IODP = Integrated Ocean Drilling Program and International Ocean Discovery Program. *Illustration by Matt O'Regan* warms, which alters weather and climate patterns across much of the Northern Hemisphere. Other feedbacks between Arctic and global climate include thawing of permafrost, accelerated erosion of polar coastlines, and the destabilization of gas hydrates that may all inject large amounts of greenhouse gases in the atmosphere, further acidifying ocean waters. What were the past magnitudes and rates of carbon release from these poorly constrained reservoirs? What influence did they have on local biologic systems and global climate processes? Answers to these questions remain locked in high-latitude marine sediments and are only obtainable through scientific drilling in polar oceans.

ICE SHEETS AND SEA LEVEL RISE

Changes in global sea level over the past 50 million years are largely the result of the waxing and waning of polar ice sheets. At present, around 10% of Earth's land area is covered by ice sheets, with the potential to raise global sea level by over 65 m should all ice melt. Scientific ocean drilling has provided the only firm control on global ice volume prior to the Last Glacial Maximum (around 20,000 to 26,000 years ago) by dating glacial advances across polar continental margins and through analyses of the geochemical composition of marine microfossils. Results from past drilling now underpin global sea level reconstructions for the past 100 million years. Future scientific ocean drilling will significantly improve the fidelity of ice sheet and sea level records to better delineate rates and magnitudes of sea level rise and the processes and events that influenced past global patterns of sea level change.

Understanding past global sea level change in Earth's climate system requires separation of regional tectonic and glacio-isostatic processes from global changes. Firm constraints on past sea levels and identifying regions of ice sheet melt that contributed to these sea level variations require a portfolio of globally distributed records of sea level change. Marine-based ice sheets are highly sensitive to the warming of both ocean and atmosphere. This fact, combined with uncertainties relating to polar amplification, ocean-ice sheet interactions, subglacial hydrology, and dynamic ice processes, lead to serious concerns that model-based projections of sea level rise are underestimated and thus call for greater efforts in **ground truthing future climate change**. We may be approaching, or have already crossed, the **tipping point** for ice sheet collapse in West Antarctica and many of the marine-terminating outlet glaciers draining the Greenland ice sheet. Scientific ocean drilling provides the only means of sampling the geologic record on continental margins that have major ice sheets, which will generate the critical data needed to build and constrain models for future projections. The need is pressing for scientific ocean drilling to deliver high-quality "ice proximal" records that document past times of ice sheet collapse, capture major changes in ocean and atmospheric circulation, and test and improve models that project future sea level rise.

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STRATEGIC OBJECTIVE 4 FEEDBACKS IN THE EARTH SYSTEM

Constraining the processes that regulate or destabilize the Earth system

SUMMARY

Feedbacks that amplify or regulate processes within the Earth system are pervasive, crucial to all parts of the system, and act on all timescales. Over long timescales, Earth system feedbacks have resulted in climate alternating between greenhouse and icehouse states, the evolution of vastly different biota during different geologic periods, and the repeated reconfiguring of continents. On shorter timescales, feedbacks between the atmosphere, ocean, and cryosphere have accelerated the growth and decay of ice sheets, a complex process accompanied by large changes in temperature, precipitation, sea level, and vegetation. On human timescales, changes in ocean circulation and resultant increases and decreases in heat storage in the deep ocean have caused rapid and sustained shifts in high-latitude temperatures and precipitation. Great strides have been made in identifying various feedbacks in the Earth system, but our knowledge of how these feedbacks operate, how they interact, the timescales over which they are stable, and the points at which feedback loops break down is limited. Scientific ocean drilling provides access to the long timescale records needed to investigate the many different feedbacks within the Earth system and the effects those feedbacks had on our planet's functioning.

TECTONICALLY DRIVEN FEEDBACKS

Over millions of years, tectonic activity continually changes the topography of Earth's surface, reconfiguring ocean basins and continents and uplifting mountain ranges. Tectonic processes are components of feedback loops and they also set the boundary conditions within which other feedbacks operate.

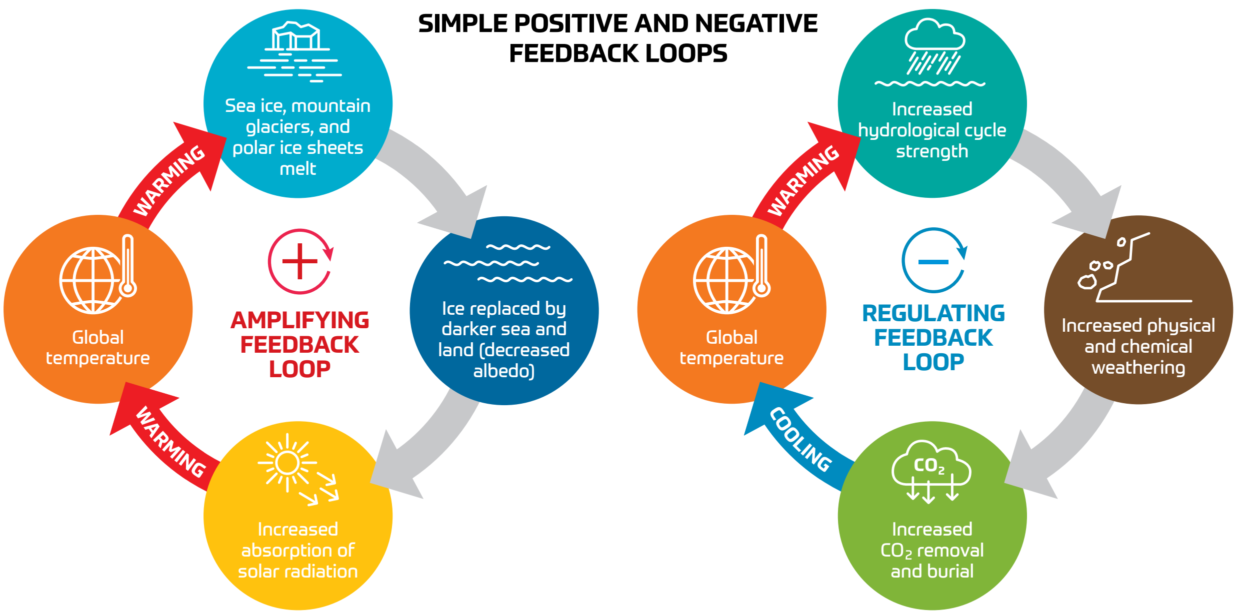
Mountain building, weathering, and atmospheric CO_2. The silicate rock weathering hypothesis posits that over million- to hundreds of million-year timescales, there is a negative feedback between the tectonic uplift of mountains and the amount of CO_2 in Earth's atmosphere. Tectonic uplift of mountains causes "relief rainfall" that increases mechanical erosion on steeper slopes and enhances chemical weathering rates. The amplified chemical weathering consumes more atmospheric CO_2, and as a result, causes global cooling. As cooling increases glaciation, it leads to enhanced erosion and further isostatic uplift. Scientific ocean drilling will test the hypothesis that this slow negative feedback regulated atmospheric CO_2 in the past in order to predict whether the Earth system can modulate the current rapid, massive injection of carbon by humans and over what timescale.

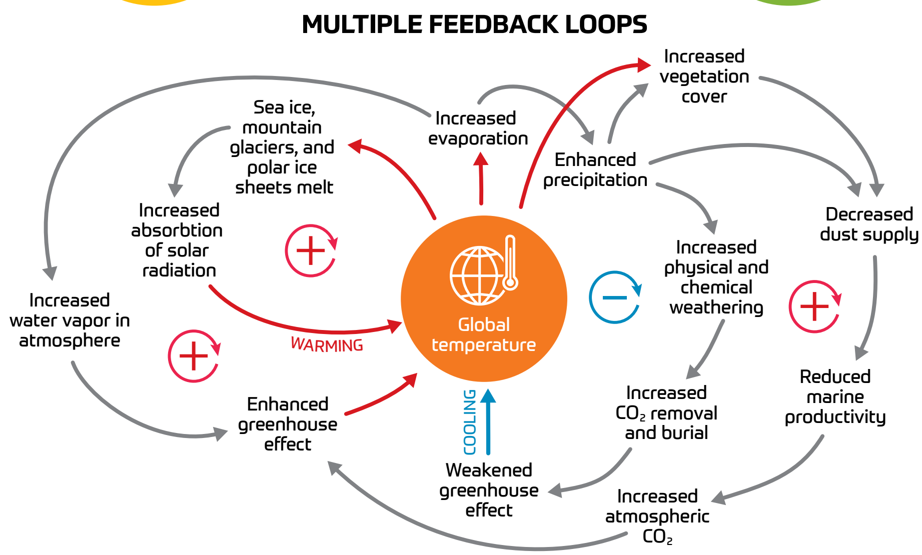
Monsoon systems. Characterized by strong seasonality in wind and rainfall patterns, monsoons are a major component of the climate system and central to the hydrological cycle. Scientific ocean drilling has shown that although insolation—the amount of solar radiation received on a given surface in a given time period—is the primary driver of monsoon systems, tectonic features of Earth's surface are responsible for large regional differences among them. Future scientific ocean drilling needs to address the fundamental unknowns in this complex nested feedback system that includes tectonic uplift, the timing of monsoonal initiation, atmospheric greenhouse gas concentrations, the cryosphere, and ocean circulation. By significantly extending both the spatial and temporal coverage of high-resolution monsoon records around the world and continuing to develop new proxies to distinguish global and regional components in the monsoon system, we will be able to reveal the feedback sub-loops that together drive monsoon variations.

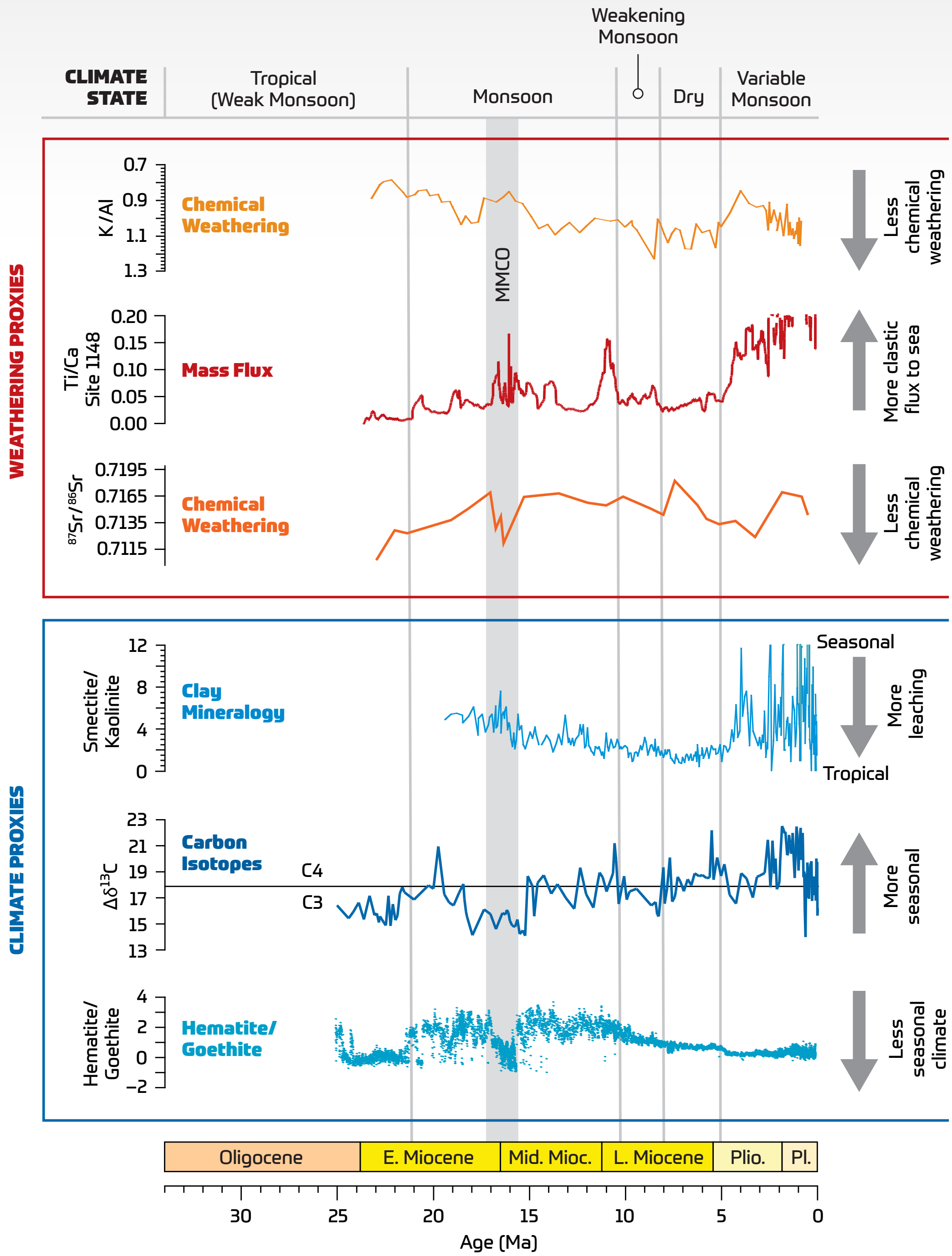
Gateways and sills. Geodynamic processes, including **tectonics and plume-related magmatism**, control the occurrence and character of gateways that connect the ocean basins (e.g., Drake Passage, Tasman Gateway, Fram Strait), as well as variations in the water depths of major

Definition of an Earth System Feedback

A feedback is a mechanism by which the end products of a process influence the ongoing operation of that process. A perturbation to the Earth system can lead to positive and/or negative feedbacks, as illustrated in the top panels. Negative feedbacks (–) help regulate the Earth system and maintain its equilibrium. For example, negative feedbacks between Earth's rock cycle (driven primarily by plate tectonics) and global biogeochemical cycles (especially for carbon, hydrogen, nitrogen, and sulfur) result in a relatively stable global climate over long timescales. In contrast, positive feedbacks (+) in the Earth system amplify the responses of processes, possibly leading to runaway behavior. For example, climate warming resulting from increasing atmospheric greenhouse gas concentrations causes sea ice to melt, decreasing surface albedo. The dark ocean waters absorb more solar radiation, resulting in more sea ice melting and enhanced ocean warming. Positive feedbacks that lead to runaway behavior are particularly important in the Earth system because they can drive the system past a **tipping point**, resulting in a dramatic, often irreversible shift in the system. One perturbation can also lead to multiple loops, some positive and some negative, as in the example at the bottom of a subset of feedbacks that influence global temperatures. The net effect of such networks of interrelated processes depends on the relative strength of the different feedback sub-loops, the timescales over which they operate, and how they interact. *Illustration by Rosalind Coggon*







Robust records of both past weathering and climate are necessary to investigate the temporal relationships between weathering and climate and, hence, the feedbacks between tectonic and climate processes. A range of complementary proxies allow us to reconstruct such records from drill cores, as illustrated here with a compilation of some of the more robust erosion and weathering proxies spanning 25 million years at Ocean Drilling Program (ODP) Sites 1146 and 1148 in the South China Sea. The upper three panels are proxies for weathering: (top) chemical weathering (K/Al), (middle) mass flux (Ti/Ca) from ODP Site 1148, and (bottom) chemical weathering (Sr isotopes) from ODP Site 1148. The lower three panels are proxies for changing climate. (top) Clay mineralogy (smectite/kaolinite), (middle) the difference in isotopic composition of atmospheric and terrestrial biomass carbon from ODP Site 1148, which reflects shifts between C4 grassland and C3 woodland flora in the continental flood plain, and (bottom) the chemical weathering index (C_{RAT}) proxy tracking the relative influence of chemical weathering versus physical erosion. MMCO = Middle Miocene Climatic Optimum. *Modified from Figure 8 in Clift et al. (2014), https://doi.org/10.1016/j.earscirev.2014.01.002* bathymetric features such as sills (e.g., Greenland-Scotland Ridge, Strait of Gibraltar, Isthmus of Panama, Bosporus). The tectonic evolution of oceanic gateways and sills therefore modifies large-scale ocean circulation, which is a component of multiple climate feedback loops. Targeted drilling will allow us to reconstruct the timing of the opening and closing of gateways and changes to ocean circulation patterns to determine the influence gateways have on climate feedbacks across critical time periods in Earth's history. For example, it is still unclear whether large-scale reorganization of ocean circulation that resulted from the opening of the Drake Passage preceded or followed the expansion of glacial ice on Antarctica due to climate feedbacks during the Eocene-Oligocene.

CRYOSPHERE-DRIVEN FEEDBACKS

Ice core records have documented decreases in atmospheric CO_2 and CH_4 concentrations during glacial intervals when the cryosphere expands and increases during interglacial intervals when the cryosphere retracts. The feedbacks responsible for driving these **cycles**, and the longer-term interplay between the cryosphere and climate system, remain widely debated. Scientific ocean drilling has made major advances in establishing when ice sheets and sea ice nucleated and has provided evidence that changes in Earth's orbit drive a major feedback between insolation and cryosphere extent. Future scientific ocean drilling in polar regions will allow us to better define the development and persistence of the cryosphere and unravel the many feedbacks between the cryosphere and other components of the **climate system**.

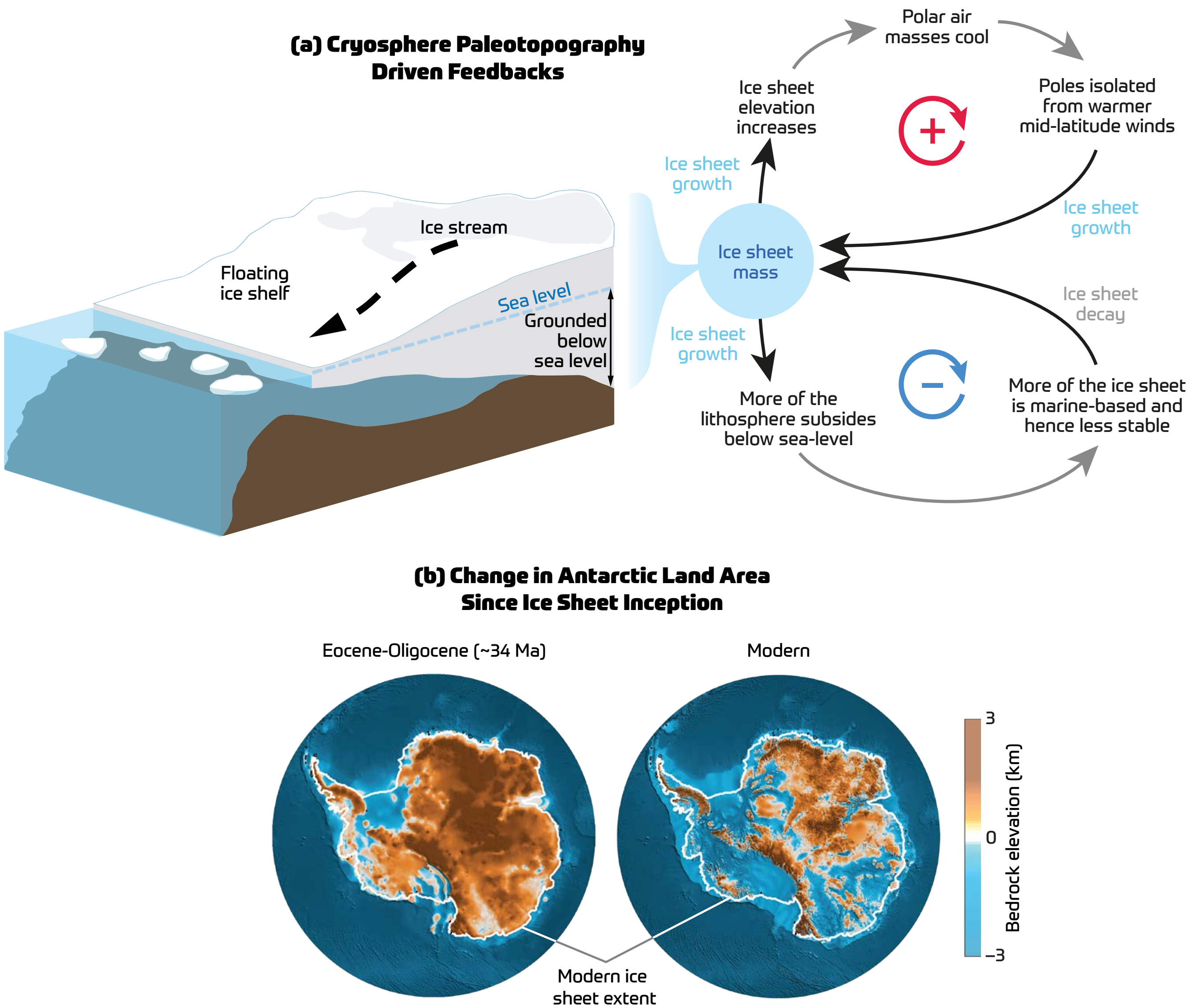
Carbon burial during cryosphere expansion. Scientific ocean drilling allows us to test hypotheses that address feedbacks responsible for enhancing carbon storage in seawater and marine sediments during periods of cryosphere expansion. Examples of how carbon storage can be enhanced include reductions to the vigor of deepwater circulation, increased nutrient delivery that can fuel the **biological pump**, and the growth of sea ice that limits air-sea gas exchange. **Land-to-sea** transects drilled across Arctic shelves can test whether carbon sequestration and release from terrestrial and submarine permafrost also play a measurable role in climate feedbacks responsible for the waxing and waning of ice sheets.

Volcanic outgassing during deglaciation. It has been theorized that stress relaxation in the mantle resulting from deglaciation enhances volcanic outgassing from deep Earth magmatic sources. This outgassing increases atmospheric greenhouse gases concentrations, accelerating warming and melting more ice. Scientific ocean drilling can test whether volcanic outgassing drives a positive climate feedback by documenting the frequency of volcanic ash layers in sediments deposited at time intervals characterized by the growth or decay of the cryosphere.

Scientific ocean drilling allows us to test hypotheses that address feedbacks responsible for enhancing carbon storage in seawater and marine sediments during periods of cryosphere expansion.

Ice sheet grounding and stability. Our ability to reproduce the dynamic behavior of ice sheets in **climate models** and examine how ice sheets interact with the rest of Earth's climate system requires detailed knowledge of their paleotopography, including surface elevation and areal extent and the elevation of their underlying bedrock. As ice sheets grow, they cool polar air masses, providing a positive atmospheric feedback for ice sheet growth by isolating the poles and preventing intrusion of warmer mid-latitude winds. However, ice sheet growth also introduces a negative feedback to the system. The growing ice load slowly depresses the underlying lithosphere, causing the ice sheet to become more marine-based as the land subsides and ice sheet grounding lines fall below sea level. This decreases the overall stability of the ice sheet, as marine-based components have a lower frictional coupling to the underlying substrate and are highly sensitive to oceanic and atmospheric warming. Glacial erosion along with lithospheric subsidence is suggested to have resulted in the current grounding of large portions of the Greenland and Antarctic ice sheets and most of their outlet glaciers and ice streams below sea level.

Scientific ocean drilling can test the strength of these competing cryosphere-driven feedbacks by reconstructing the paleotopography of the Antarctic continental shelf areas and comparing it to the timing of the waxing and waning of the Antarctic ice sheet through the Paleogene and Neogene. Scientific ocean drilling can also improve constraints on the size of the Greenland ice sheet through the Miocene and Quaternary. This information can help resolve the nature and strength of feedbacks between atmospheric circulation, surface air temperatures, and sea ice dynamics during this time. Furthermore, documenting how Quaternary glacial activity reshaped the Arctic's shallow continental shelves is critical for reconstructing the development and influence of the shallow seaways that are major conduits for inflowing Atlantic and Pacific waters into the Arctic.



(a) Changes in the paleotopography of both the upper and lower surfaces of ice sheets, as a result of changes in ice sheet mass, can result in both amplifying and regulatory feedbacks. (b) Comparison between modern and reconstructed (~34 million years ago) bedrock elevation beneath the Antarctic ice sheet, illustrating how lithospheric loading by the ice sheet, tectonic processes, and glacial erosion have resulted in a 25% reduction in the land area located above sea level since the Eocene-Oligocene. Scientific ocean drilling results are used to reconstruct paleotopography, or bedrock elevation, which is a critical factor in modeling the nucleation and dynamics of ice sheets. *Sources: (a) Original illustration by Matt O'Regan and Rosalind Coggon. (b) Paleotopography: Paxman et al. (2019), https://doi.org/10.1016/j.palaeo.2019.109346; Modern bedrock elevation: Fretwell et al. (2013), https://doi.org/10.5194/tc-7-375-2013*

MARINE GAS HYDRATES AND CARBON CYCLE FEEDBACKS

Gas hydrate is an ice-like substance, where low-molecular-weight gases (primarily methane, but also CO_2, H_2S) are trapped within a frozen lattice of water molecules. It is estimated that gas hydrates account for 15%–50% of Earth's total mobile carbon pool, and they appear to exist in continental shelf and slope sediments around the world. Previous research suggests that gas hydrates may be extremely sensitive to changes in ocean pressure and temperature and may destabilize through significant drops in sea level or warming of intermediate waters. It has also been suggested that most of the methane released in a warming ocean would be oxidized to dissolved inorganic carbon by microbes in the form of CO_2 in near-seafloor sediments and/or in the water column. By loading intermediate waters with CO_2 that is later upwelled and ventilated to the atmosphere, hydrate destabilization could play a role as an amplifying feedback in **Earth's climate system**. Scientific ocean drilling provides opportunities to better understand the origin and quantify the distribution of methane in global hydrate reservoirs. It can provide new information about how gas hydrates respond to environmental change and how they fit into the **global cycling of carbon**. Scientific ocean drilling can also help elucidate the role gas hydrates may play in initiating instability on the continental slopes with the potential for **landslide hazards**.

BIOLOGICALLY DRIVEN FEEDBACKS

Feedbacks within Earth's biosphere, and between the biosphere and other components of the Earth system, have driven evolution and extinction events through Earth's history. They have also influenced **ocean health** and our planet's **habitability** and **climate**. Our knowledge of the mechanisms that regulate those feedbacks is mostly incomplete. For example, it is thought that the evolution and rise to dominance of larger-celled phytoplankton drove the Mesozoic marine revolution. At that time, many invertebrate groups took on increasingly complex defenses against predation. It is posited that the arrival of larger calcareous nannoplankton and diatoms facilitated a more efficient transfer of energy from primary producers to higher trophic levels, causing diversification of predators and thus a more complex food web with larger energy flows. These changes to the ocean ecosystem may also have led to increased removal of both organic and inorganic carbon from the surface ocean to the seafloor—via the so-called "biological and alkalinity pumps"—where they became sequestered in sediments. It has been hypothesized that this improved capacity of plankton to sequester carbon in the ocean fundamentally changed the functioning of the **carbon cycle**, and that more efficient removal of atmospheric CO_2 increased the ocean ecosystem's resilience to **severe acidification events**. The increased plankton capacity may explain why the numerous large igneous province emplacements since the Jurassic did not cause mass extinctions like those in the Permo-Triassic or Triassic-Jurassic, which occurred before the rise of pelagic calcifiers (i.e., planktic foraminifera).

Scientific ocean drilling can provide access to well-preserved microfossils in globally dispersed cores to map out evolutionary pathways in various marine environments and ecosystems to test these hypotheses. It will also allow us to further reconstruct ancient changes in both the biological and alkalinity pumps across major climatic events and evaluate how climatic or environmental changes cause shifts in the structure of ecosystems that could lead to other feedbacks. Understanding the role plankton ecology plays in buffering surface ocean pH and in carbon sequestration is of critical importance as we seek to determine the future response of the marine biosphere to ongoing anthropogenic changes.

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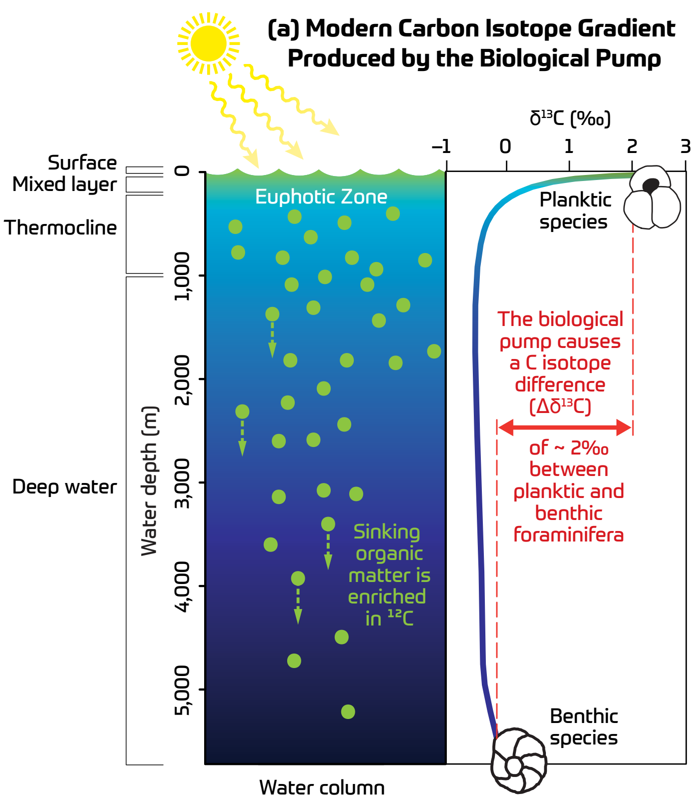
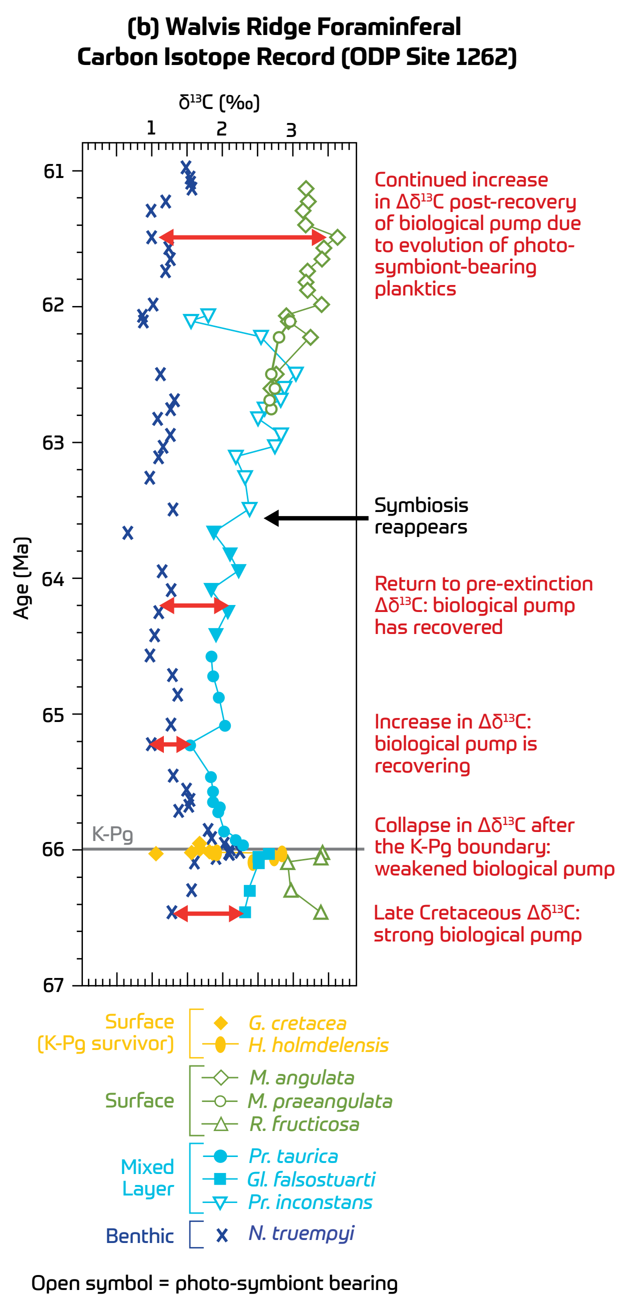
TERRESTRIAL TO MARINE FEEDBACKS

The terrestrial biosphere plays a major role in Earth system functioning and feedbacks, and there are suggestive correlations between changes in the terrestrial and marine biospheres. The rise of angiosperms may have increased terrigenous nutrient flux to the ocean that spurred the evolution of larger marine phytoplankton. Feedbacks between terrestrial grasslands and marine ecosystems may have influenced the rapid rise in diatom diversity during the last 40 million years. Enhanced productivity due to dust fertilization during relatively drier Pleistocene glacial intervals has been estimated to account for half of the 80 ppm changes in atmospheric CO_2 during these times. Nutrient flux thus may be an important feedback in the climate system. However, we currently have a limited understanding about how land vegetation may have controlled long-term trends in nutrient fluxes and how it may have affected **global climate** and **ocean health**.

To understand the feedbacks between terrestrial landscapes and processes and marine productivity and carbon burial requires collecting high-quality marine sediments that contain details of terrigenous nutrient flux, marine primary productivity, and terrestrial vegetation in climatologically sensitive regions and over the last 100 million years. Core materials provided by scientific ocean drilling will allow us to establish how marine productivity and carbon sequestration vary at different nutrient levels. We will be able to tease out the role atmospheric CO_2 plays in regulating marine productivity through alteration of





Export production, the removal of organic matter from the euphotic zone to the deep sea, is primarily driven by the biological pump, in which organic matter such as fecal pellets sink via biological processes combined with gravity. Photosynthesis favors ^{12}C over ^{13}C, enriching organic matter in ^{12}C and resulting in lower $\delta^{13}C$ values. Thus, the functioning of the biological pump results in a carbon isotope gradient from ^{13}C-enriched surface waters to ^{13}C-depleted bottom waters, as recorded by the carbon isotope difference between planktic and benthic foraminifera ($\Delta\delta^{13}C$) (a). Hence, foraminifera can be used to reconstruct past changes in the biological pump, as illustrated by a reduction in $\Delta\delta^{13}C$ at the Cretaceous-Paleogene (K-Pg) boundary in Ocean Drilling Program (ODP) Site 1262 cores. The reduction in $\Delta\delta^{13}C$ indicates a decline in strength of the biological pump (b). Development of more detailed records of past changes in the biological pump will allow us to investigate the feedbacks between the climate system, the marine carbon cycle, and evolution and diversity. *Sources: (a) Original graphic by Chris Lowery and Rosalind Coggon. (b) Modified from Birch et al. (2016), https://doi.org/10.1130/G37581.1* precipitation patterns and vegetation cover, which in turns modifies weathering rates and nutrient fluxes into the ocean. Purposely designed **land-to-sea** transects will permit us to integrate marine records of ocean nutrient flux, plankton ecology, and carbon burial collected through scientific ocean drilling with vegetation and climatological records from hinterland regions collected through continental drilling efforts.

POTENTIAL MICROBIAL SUBSEAFLOOR FEEDBACKS

Feedbacks between subseafloor microbial life and other Earth system components are largely unknown. Scientific ocean drilling provides the means to explore the extent to which microbial life in the sediments and underlying igneous crust affects oceanic conditions and tectonic processes via metabolic reactions. It also provides the tools needed to examine biological mediation of hydrothermal alteration of the substrate and in turn how ocean conditions and tectonic processes affect **habitability** beneath the seafloor.

Microbial effects on lithospheric permeability and rheology. Previous scientific ocean drilling has shown that tectonic and magmatic processes affect the nature of permeable pathways within the oceanic lithosphere and hence subsurface fluid flow. These processes seem critical to sustaining a deep microbial biosphere, but we don't know to what extent the biosphere might, in turn, influence tectonic and magmatic processes. It has been suggested that biologically moderated mineral precipitation reduces the porosity and permeability of the upper oceanic crust. This process is potentially an important feedback between the biosphere and **crustal structure** because the permeability of the crust controls where hydrothermal fluid and heat exchange occurs along mid-ocean ridges, which in turn may affect how shallow melts are intruded into the upper crust.

Similarly, serpentinization reactions associated with microbial communities could significantly affect the rheology of the lower crustal or mantle rocks in which they occur, in turn influencing the deformational behavior and **hazard-generating** potential of oceanic lithosphere when it is consumed in **subduction zones**. Investigation of these potential feedbacks between the deep biosphere and the **life cycle of the oceanic lithosphere** relies on scientific ocean drilling to recover samples of lithosphere-hosted microbial communities to enable assessment of how they modify the rocks they inhabit.

Deep Earth oxidation state. Subduction of microbially altered sediments and rock may also result in feedbacks between the subsurface biosphere and Earth's interior. **Subseafloor life** significantly influences Earth's surface oxidation and ocean and atmosphere composition, but the rates at which this happens, and how those rates have changed over time, are unknown. There is a suggestion that the redox state of subducted sediment influences the extent of mantle oxidation, in turn affecting magmatic evolution, mineral assemblages, gas speciation in volcanic systems, and the long-term evolution of Earth's atmosphere. Evaluation of the feedbacks between the ocean and the atmosphere and biosphere ecology requires direct sampling by scientific ocean drilling. These records of past ocean conditions and contemporaneous biosphere structure can be deciphered through decoding of sediment chemistry in combination with microfossils, DNA, and other biomarkers.

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STRATEGIC OBJECTIVE 5 TIPPING POINTS IN EARTH'S HISTORY

Using Earth's geologic past to illuminate future environmental change

SUMMARY

Parts of the Earth system, particularly ice sheets, ecosystems, and ocean circulation, do not respond linearly to external forcings. Changes may be gradual before a critical threshold is reached—a "tipping point"—beyond which the system changes rapidly and often irreversibly into a new state. Because of the interconnected nature of the Earth system, when a tipping point is crossed in one part, it could trigger a cascade of tipping points being crossed elsewhere in the system. Scientific ocean drilling can recover sediment and rock records in multiple tectonic settings, across all ocean basins, and from shallow continental shelf areas to the deepest subseafloor environments. These records can elucidate the environmental conditions when tipping points were crossed, the rates at which the Earth system built up to tipping points, how long it took for the system to attain a new stable state, and how the new state differed from the previous one. Lessons learned from the geological past can help us understand why certain Earth system components have tipping points and not others, how exceeding tipping points affects ecosystem function, and what drives species to extinction. Identifying tipping points before Earth exceeds them will provide the information society needs to decide how to address today's changing climate.

TIPPING POINTS IN EARTH'S CLIMATE SYSTEM

The Earth system is in the midst of a significant transition. Anthropogenic greenhouse gas emissions are driving global warming, which is destabilizing ice sheets, raising global sea level, changing precipitation patterns, reducing ocean oxygen concentrations, and causing the displacement of both terrestrial and marine ecosystems. What will happen if the marine-based West Antarctic Ice Sheet enters into a state of irreversible retreat or if there is widespread thawing of Arctic permafrost? Will Earth cross a tipping point and transition to a new equilibrium state? What might this new state look like?

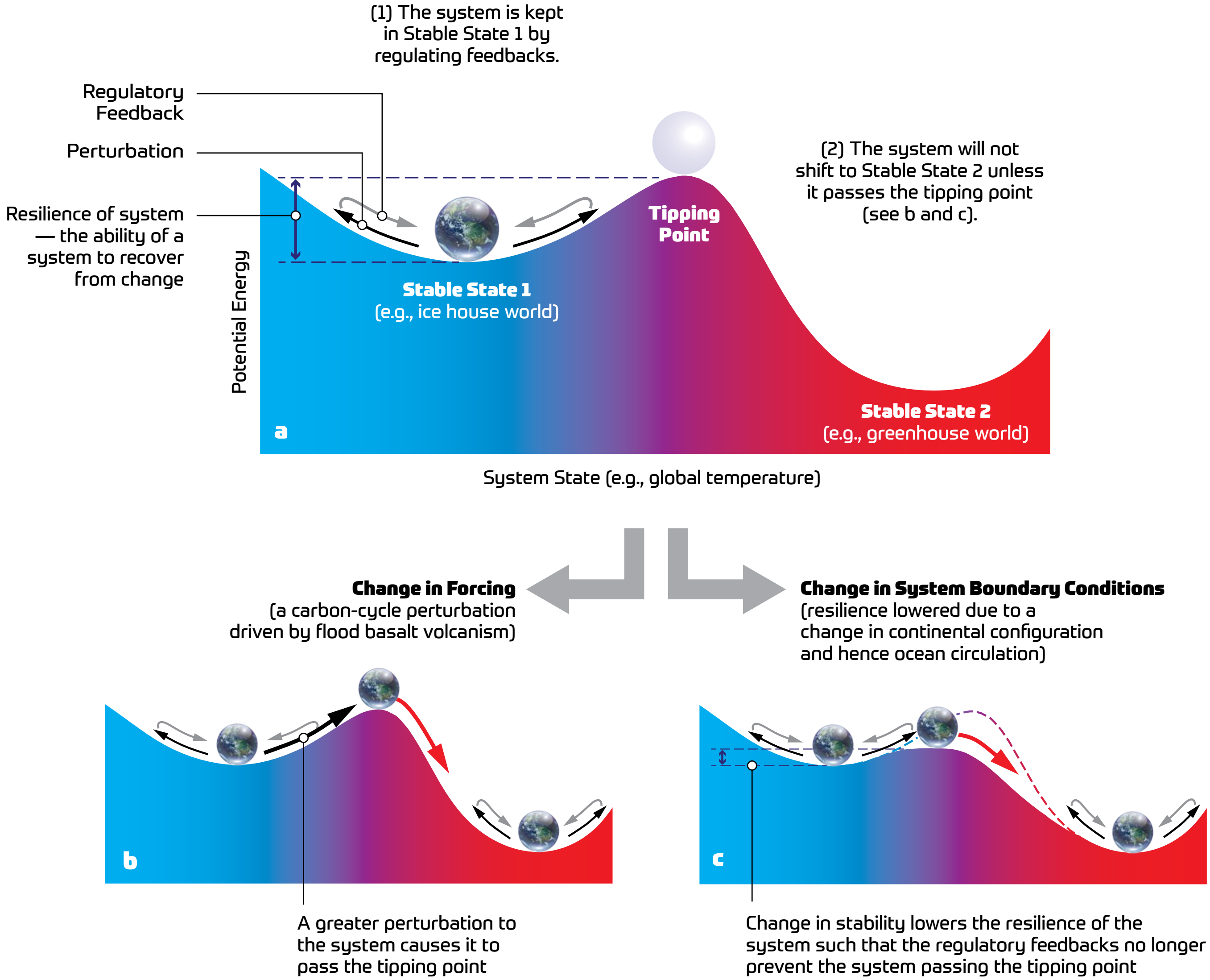
For many components of **Earth's climate system**, modern observational data sets cover too short a time period to answer these questions. Marine sediments contain the longest, best-preserved, continuous, high-resolution, in situ records of climate and environmental changes, making scientific ocean drilling ideally suited for identifying Earth conditions when tipping points were exceeded in the geologic past and investigating the consequences of exceeding them. Indicators that key tipping points may have been crossed in the past include transitions into and out of glacial intervals, far-reaching ecosystem changes, shifts in precipitation patterns and aridity, and sea level changes. When some tipping points are crossed—for example, as a result of ocean acidification and/or oxygen depletion—the marine sedimentary record provides evidence of rapid, large-scale system changes to the biosphere, including mass extinctions. In order to combine knowledge of Earth's past tipping point behavior into **models of future climate change**, we need to understand how the boundary conditions of the Earth system have changed with time, and how they affect its stability.

DRIVERS OF TIPPING POINT BEHAVIOR

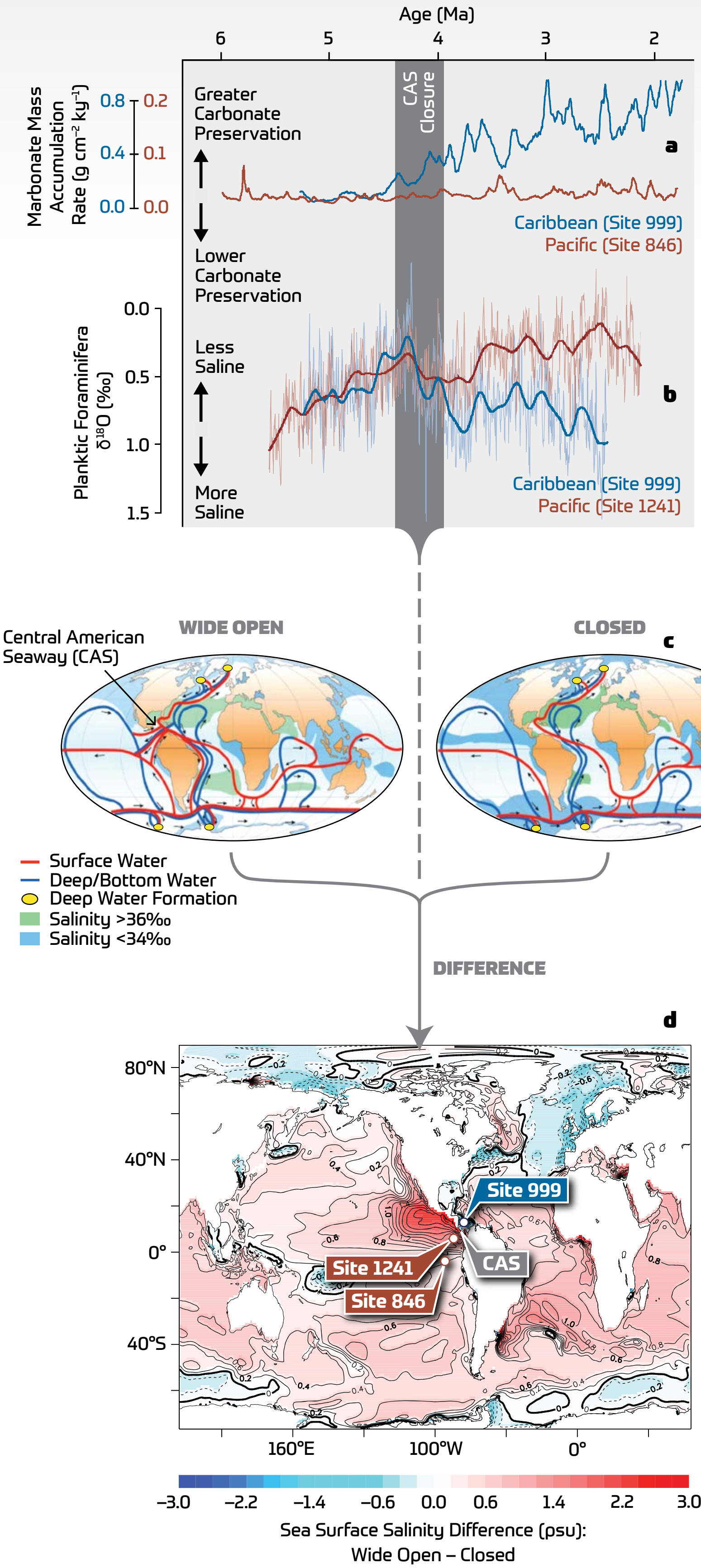
Components of the Earth system may exceed tipping points as a result of forcing by internal amplifying feedbacks or external drivers. A tipping point may also be exceeded if changes lower the system's resilience—its ability to recover from perturbations. Drivers of threshold behavior include **orbitally forced changes in insolation**, **atmospheric CO_2 concentrations**, tectonic reconfiguration of the ocean basins, and global increases in volcanic activity. Scientific ocean drilling provides access to high-resolution records of a wide range of Earth system processes that allow us to reconstruct the detailed event chronologies required to decipher which external forcings, geological cycles, or feedback mechanisms drove the Earth system to exceed tipping points in the geological past.

Changes in ocean basin configuration. Thermohaline ocean circulation is responsible for distributing heat, nutrients, salt, and carbon globally. Changes to this global circulation as tectonic gateways slowly open and close can thus alter regional and global climate. Deep ocean sediment records collected by scientific ocean drilling suggest that changes in **ocean basin configuration** were the start of a sequence of events that led to the development of continental-scale ice sheets over most of Antarctica near the Eocene-Oligocene transition around 34 million years ago. As global ocean circulation shifted, species turnover in marine plankton groups followed, fundamentally altering the **carbon cycle** and marine food webs.

Despite progress in our understanding, the connection between the opening of Drake Passage and the timing of the initiation of Antarctic glaciation at the Eocene-Oligocene transition remains controversial. Similarly, the relationship between the closing of gateways such as the Central American Seaway in the Middle Miocene, which has been hypothesized to also have affected ocean circulation patterns and global climate, is still debated. A new focus on latitudinal and longitudinal transects that target



Stability landscapes in which valleys represent stable states and the peaks between them represent tipping points. Regulating feedbacks that prevent perturbations from pushing the system beyond a tipping point keep the system in a stable state (a). In the climate system, changes in insolation are offset by changes in precipitation and carbon burial. The tipping point may be crossed if the system is perturbed even more, for example, it is subject to greater forcing as a result of internal amplifying feedbacks or an external driver (b), or if gradual changes in system parameters lead to a change in the stability landscape that lowers its resilience to perturbations (c). *Illustration by Rosalind Coggon*



specific time intervals—in locations proximal to ancient oceanic gateways and sills—will enable us to reconstruct latitudinal temperature gradients, map deepwater formation areas, and determine when ice sheets developed and retreated from continental margins.

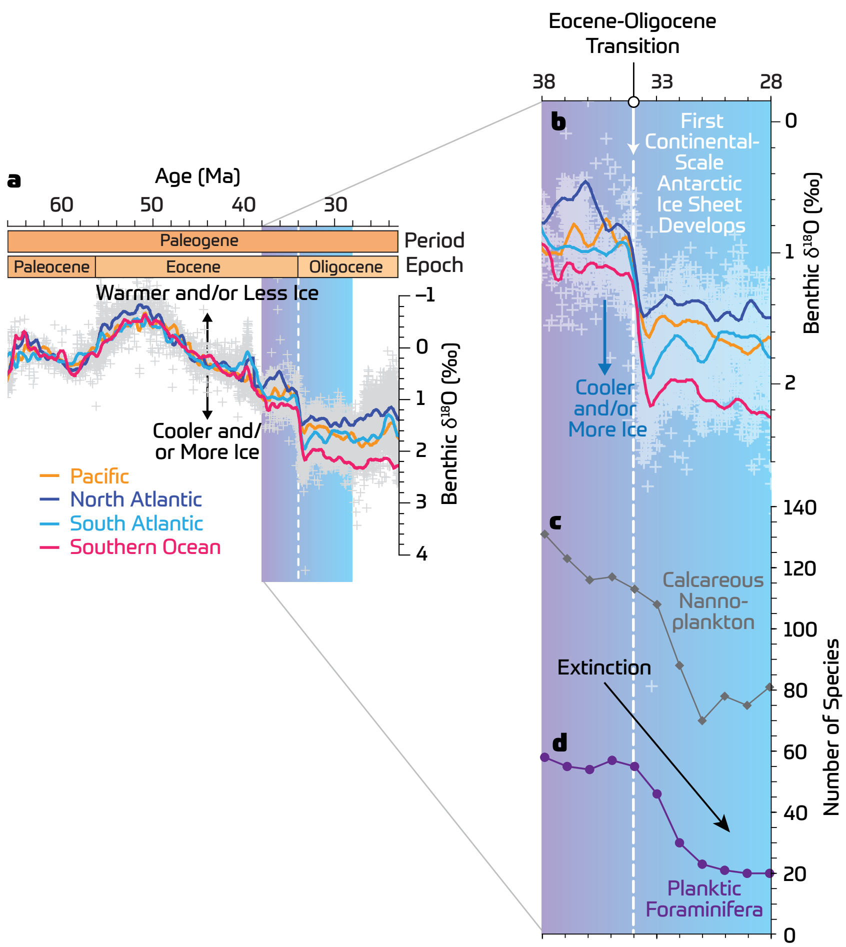
Increases in volcanic activity. The emplacement of **large igneous provinces** (LIPs) has been hypothesized to lead to tipping points being crossed in a number of Earth system components. Outgassing from such extensive volcanism increases atmospheric CO_2 and leads to global warming. The same volcanism produces aerosols that can instead result in global cooling. It also injects extra nutrients into the ocean, increasing marine primary production, which is thought to draw down dissolved oxygen when the plankton die off, resulting in the formation of large dead zones. This volcanism may also lead to significant **metal pollution** when mantle-derived metals dissolve in high concentrations in seawater at levels potentially lethal for many marine species. While it has been suggested that LIP volcanism results in mass extinctions, detailed chronologies of these events and their environmental consequences remain unresolved. Consequently, questions remain as to which LIP-related mechanism, or combination of mechanisms, caused ecosystem tipping points to be crossed.

Drilling records indicate a tectonic-gateway-driven tipping point in ocean circulation due to closure of the Central American Seaway (CAS). The divergence of carbonate preservation records (a) between Ocean Drilling Program sites in the Caribbean Sea and the Pacific Ocean indicate a separation of deep water masses around 4.4 million years ago, while records of sea surface salinity (b) indicate a partitioning of surface waters between the Caribbean and the Pacific a few hundred thousand years later. Together, these records indicate the CAS closed gradually. They are consistent with the modeled effects of closure of a wide open CAS on global ocean circulation (c) and sea surface salinity (d). *Sources: (a and b) modified from O'Dea et al. (2016), https://doi.org/10.1126/sciadv.1600883, which is based on data from (a) Haug and Tiedemann (1998), https://doi.org/10.1038/31447 and (b) Sarnthein (2013), https://doi.org/10.1016/B978-0-444-53643-3.00129-1. (c and d) from figures in Sentman et al. (2018), https://doi.org/10.1029/2018PA003364*

SCALES AND RATES OF TIPPING POINTS

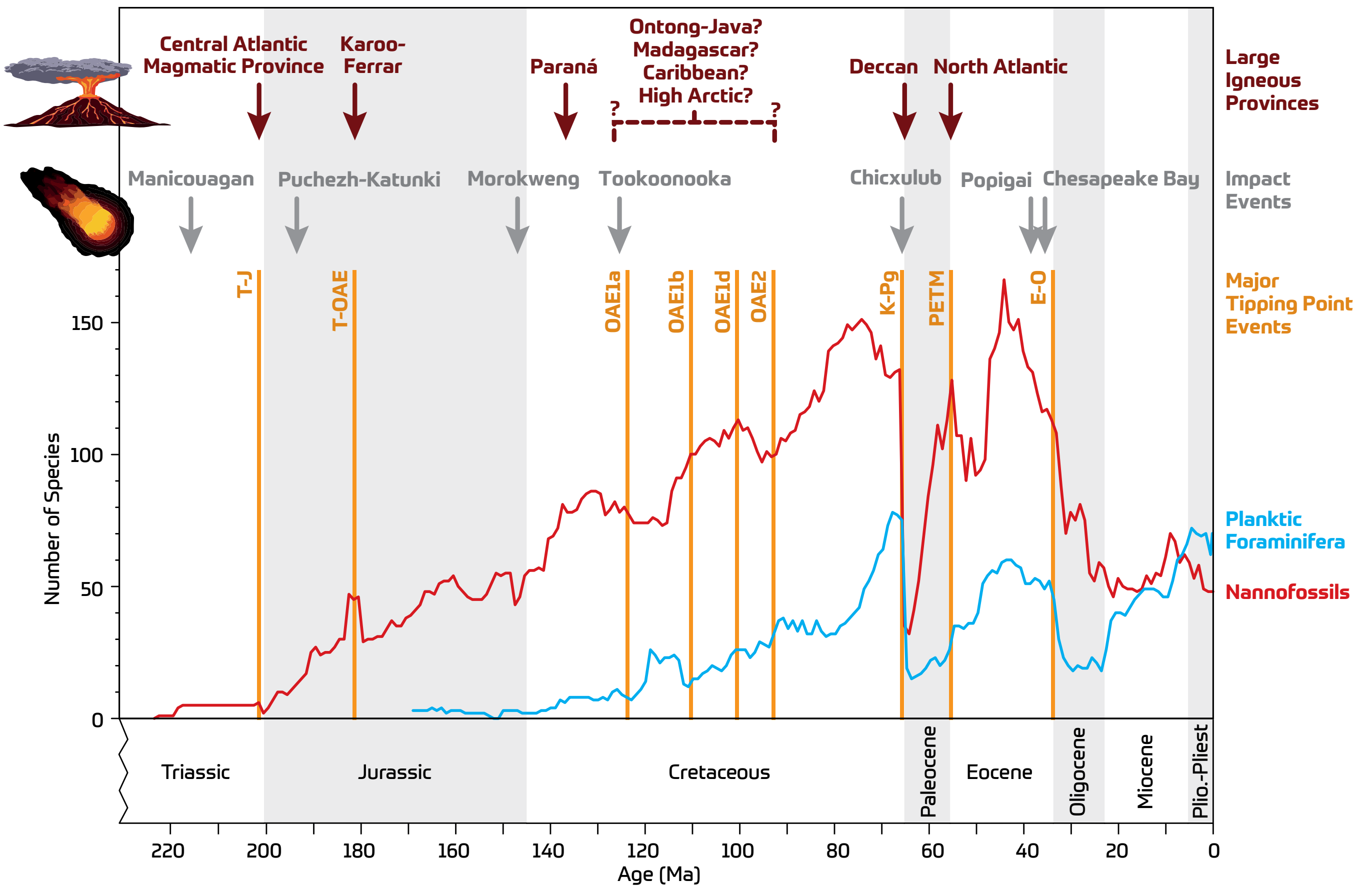
Tipping points in the Earth system can be reached over a range of spatial and temporal scales. Exceeding tipping points may result in global or regional changes. Changes may occur in a geologic instant or over millennia to millions of years, and they may comprise a single event or multiple "stepped" changes in system state. The marine sedimentary record contains key information on the rate, spatial extent, and nature of the changes to the Earth system as it approached and crossed tipping points in the past. Such knowledge is required to evaluate how quickly components of the Earth system may be reaching tipping points in response to the vast modern-day inputs of atmospheric CO_2 and whether the tipping points are being reached regionally or globally.

Stepped tipping points. Scientific ocean drilling has shown that the Cretaceous-Cenozoic record of Earth's temperature and ice sheet history includes a long progression of crossing tipping points. Our modern icehouse world, characterized by bi-polar ice sheets, developed by crossing several major tipping points that cooled our polar regions. These cooling events thrust Earth's climate and ocean into a new steady state. It is hypothesized that these cooling events were not single global "events" but rather shifts in a number of local parameters (paced by orbital forcings) that, when combined, resulted in major global change. There is growing consensus that the Eocene-Oligocene transition is not a single tipping point, but rather a stepped tipping point toward colder conditions with more ice cover. Future scientific ocean drilling is needed to establish how multiple smaller events on decadal to centennial timescales can combine to create stepped tipping points that result in larger Earth system events. To be successful in this effort, scientific ocean drilling must improve the global coverage of past key climate change intervals and collect cores at increasingly higher temporal resolutions that do not obscure any decadal- to century-scale system behaviors. Future **drilling technology** developments are needed that will enhance core recovery and that along with targeting high-accumulation-rate sediments, will improve the temporal resolution of our records. These improvements



Scientific ocean drilling cores have revealed the details of a stepped global tipping point event at the Eocene-Oligocene boundary. (a) The oxygen isotopic composition ($\delta^{18}O$) of benthic foraminifera reveals a general cooling trend through the late Eocene. (a and b) A major positive oxygen isotope shift at the Eocene-Oligocene transition indicates more abrupt cooling and ice sheet growth, due to tipping point behavior. The Eocene-Oligocene transition resulted in major changes in the global ocean. The carbonate compensation depth deepened by about a kilometer and North Atlantic Deep Water began to form, marking a major reorganization of ocean circulation as reflected in the divergence of benthic foraminiferal $\delta^{18}O$ values of the different ocean basins. These changes resulted in a severe and protracted loss of species in groups that had evolved in a fundamentally different greenhouse ocean, including (c) calcareous nannoplankton and (d) planktic foraminifera. *Sources: (a and b) Cramer et al. (2009), https://doi.org/10.1029/2008PA001683. (c and d) Lowery et al. (2020), https://doi.org/10.1146/annurev-earth-081619-052818* will allow us to carry out robust land-to-sea or ocean-to-ocean comparisons to look for leads and lags—critical input for modeling the sequencing and chronology of tipping point behavior.

Global vs. regional tipping points. Previous scientific ocean drilling has shown that organic-rich layers deposited in the Mediterranean represent short (~5,000–6,000 years) anoxic events driven by variations in Earth's orbit. These events appear to be confined to this regional enclosed inner sea. They are hypothesized to have been caused by changes in regional rainfall patterns in northern Africa, with phases of intensified precipitation leading to a freshening and stratification in the Mediterranean Sea. At the other end of the spectrum, Cretaceous **oceanic anoxic events** lasted hundreds of thousands of years may represent global perturbations of the **carbon cycle** due to excess burial of organic carbon. It is thought that increased productivity resulting from the emplacement of large igneous provinces drove global ocean anoxic events. In both cases, environmental changes must have caused rapid changes to the marine ecosystems, yet they occurred over markedly dif-



High-resolution scientific ocean drilling records of past Earth conditions and biodiversity allow us to identify the drivers of past tipping points in the Earth system, determine the consequences of exceeding tipping points, and investigate times when ecosystems were resilient to change. Species-level diversity of calcareous nannoplankton (red) and planktic foraminifera (blue) over the last 230 million years reveal extinction or radiation associated with major tipping points (orange lines). Over this interval there were seven impact events that produced craters >50 km in diameter (gray arrows), of which only Chicxulub is associated with a tipping point in the climate system and marine ecosystem. To better understand the role of large igneous provinces (brown arrows) in driving tipping point behavior, the timing and duration of these events (e.g., in the Cretaceous) and their environmental consequences need to be further constrained.

Note that the diversity data are presented in 1 million year bins, though it masks the complete extent of some extinction events, especially the K-Pg, in which 90% of both planktic foraminifera and calcareous nannoplankton species disappeared. T-J = Triassic-Jurassic boundary. T-OAE = Toarcian ocean anoxic event. OAE = Oceanic anoxic event. K-Pg = Cretaceous-Paleogene boundary. PETM = Paleocene-Eocene Thermal Maximum. E-O = Eocene-Oligocene boundary. *Sources: Modified from Lowery et al. (2020), https://doi.org/10.1146/annurev-earth-081619-052818; Impact event ages after Schmieder and Kring (2020), https://doi.org/10.1089/ast.2019.2085; LIP event ages after Clapham and Renne (2019), https://doi.org/10.1146/annurev-earth-053018-060136.*

ferent spatial and temporal scales. The fundamental differences between both events, in particular how and how fast tipping points were reached and over what temporal scales, remain unresolved. Scientific ocean drilling will focus on key time periods and locations around the world to reveal the differences in environmental conditions that lead to vastly different scales of Earth system response.

RESILIENCE TO CHANGE

Studies of tipping points in Earth history tend to focus on times when the system actually "tipped" and entered a new state as a result of internal or external drivers. However, periods of stability, such as the Late Cretaceous or middle Paleocene in which the system remained steady—despite the presence of drivers that might be expected to cause global changes—are equally important for constraining the sensitivity of the Earth system to tipping point behavior. To better understand tipping points, we need to recover records from stable geologic intervals when Earth system components did not reach tipping points. This critical information will help establish the conditions that makes system components resilient to threshold behaviors.

CONSEQUENCES AND RECOVERY

The most important downstream consequences of exceeding tipping points are typically found in the **biosphere**, which is well preserved in deep-sea sediments. Rapid changes to the ocean, atmosphere, and climate have driven both extinction and radiation over the past 200 million years. Together with macroevolutionary processes, they have shaped the **history of life**. An asteroid impact at the Cretaceous-Paleogene (K-Pg) boundary around 66 million years ago resulted in years of global darkness. Primary production declined, which led to marine food webs crossing a tipping point that resulted in the extinction of an estimated 75% of marine species, one of the most dramatic mass extinction events in Earth history. Biodiversity remained diminished for 10 million years after this global catastrophe. Recovery intervals following several Cretaceous ocean anoxic events and the Eocene-Oligocene transition also lasted approximately 10 million years.

The debate as to whether we are living through a human-caused "sixth extinction" typically focuses on whether species loss in the biosphere has already passed a tipping point that makes collapse inevitable or whether ecosystems are resilient. Through scientific ocean drilling we will leverage both the temporal and taxonomic resolution provided by fossilized plankton, benthic microorganisms, biomarkers, and other indicators to determine the response of ecologically sensitive groups to rapid environmental change, providing a perspective on our modern marine biosphere and what we might expect for the future as our climate warms.

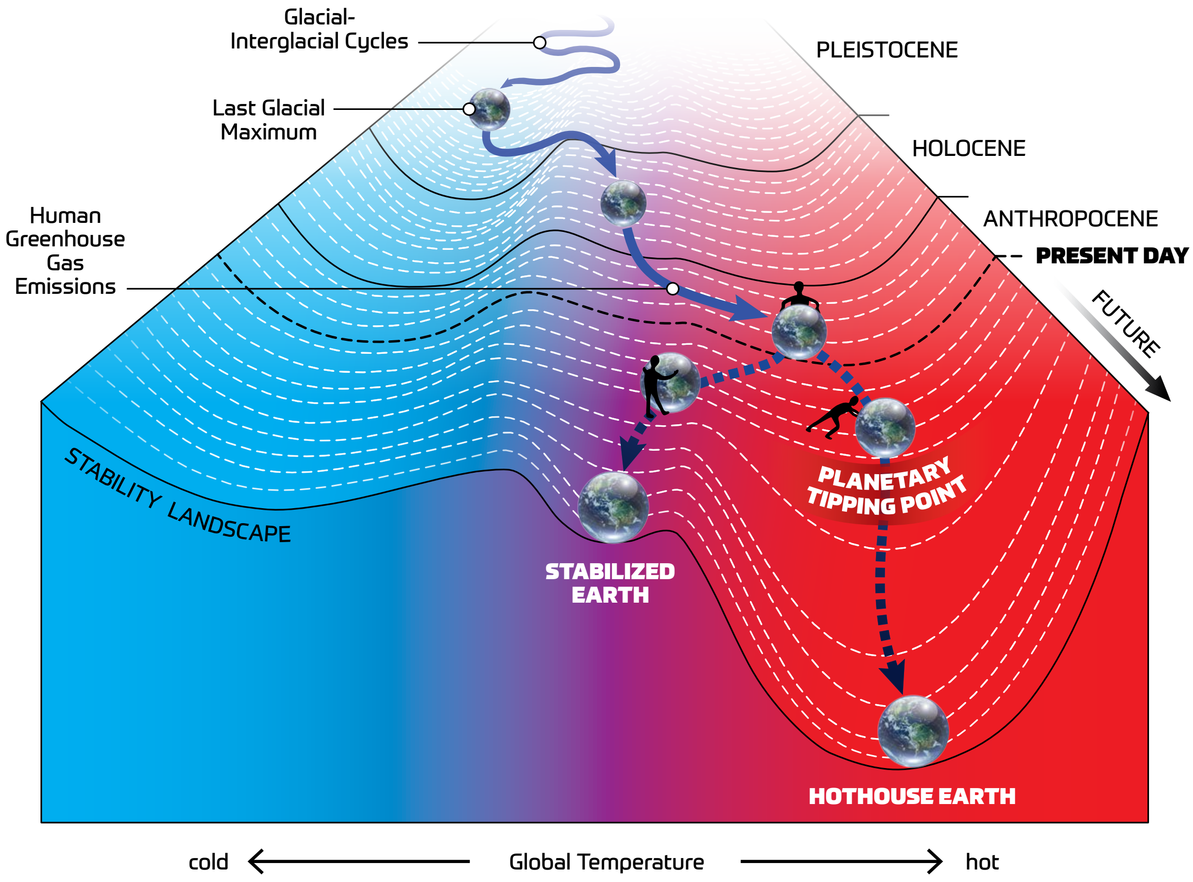
Speciation and radiation during recovery. Aspects of recovery following extinction events—such as speciation and radiation—operate on much shorter timescales. Scientific ocean drilling can help determine the rates of speciation and radiation during recovery, how and why the rates vary geographically, and how recovery affects the greater Earth system (including carbon cycling and **primary production**). This knowledge can lead to a better understanding of the long-term consequences of human-

Marine Biome Recoveries Following Major Perturbations

There have been five major mass extinctions over the last 500 million years of Earth history, and we are living through a sixth today. Key questions are: how do life and ocean health recover from negative anthropogenic pressures and how long do the effects persist? The Cretaceous-Paleogene (K-Pg) mass extinction provides a useful analogue, as the **meteorite impact** caused one of the few major changes in Earth system state that happened faster than modern climate change. Scientific ocean drilling results have shown that the ocean was habitable (again) very soon after the Chicxulub impact, that aerosols and CO_2 were important climate effects that pulled in opposite directions, and that the eruptions of massive flood basalts of the Deccan Traps earlier and later than the impact did not significantly affect the extinction rate. Despite the short duration of these environmental impacts, it is surprising that ecosystem function, in the form of the **biological pump**, did not recover for at least 1.8 million years. The causes for this long recovery period are not yet understood, but are likely related to disrupted marine food web interactions and temporary successions of dominance by cyanobacteria and smaller-sized phytoplankton such as algae. Investigations of geographically dispersed sediment cores containing high-fidelity records of fossils and biomarkers can test these working hypotheses. The results will significantly advance understanding of marine food web functioning and the global carbon cycle, with extensions to the modern global ocean while it undergoes similar changes.

Transitioning Toward an Ice-Free Planet

Although Earth has been free of permanent ice for an estimated 85% of its history, humankind has not lived through a transition to a significantly different cryosphere state. This transition to a new state could take place over many thousands of years, or Earth could be free of summer sea ice within decades and free of marine-based ice sheets in centuries. As depicted in the figure, Earth has now reached the fork in the road in the stability landscape. The Earth system can take two possible paths in the future (dotted lines). Currently, Earth is on a "hothouse" path driven by human emissions of greenhouse gases. If Earth exceeds the planetary tipping point, it will follow an irreversible path to a hothouse state. The alternative path leads to a Stabilized Earth, where human stewardship of the environment will allow the Earth system to maintain a quasi-stable state. Scientific ocean drilling provides the globally distributed samples needed to determine changes in climate system parameters—such as atmospheric CO_2 levels and the amount of ice loss—that caused the cryosphere to tip to new states in the past. Records that accurately characterize Earth's past transitions to ice-free conditions provide the ground truth data needed for calibrating and testing climate models. Marine sedimentary records are essential for understanding where Earth is today on the stability path, whether we are closer to the planetary tipping point than the figure depicts, and how much time humankind still has to take steps to prevent Earth from hurtling toward a hothouse world. *Illustration by Rosalind Coggon and Geo Prose, inspired by Figure 2 in Steffen et al. (2018), https://doi.org/10.1073/pnas.1810141115*



induced climate change given our current CO_2 scenario. In addition, determining the specific thresholds crossed that led to extinctions and the controls on species survivorship will help determine the vulnerability of current marine organisms to various Earth system tipping points. This new research frontier can be investigated using the very high temporal and taxonomic resolution offered by the microfossils in scientific ocean drilling sediment cores.

Scientific ocean drilling provides the globally distributed samples needed to determine changes in climate system parameters—such as atmospheric CO_2 levels and the amount of ice loss—that caused the cryosphere to tip to new states in the past.

Ocean-basin-scale biodiversity. There remains a significant need for an integrated ocean-basin-scale biodiversity **database** to determine global timescales and patterns of ecosystem change. Organic-walled and siliceous plankton currently lag behind the calcareous plankton in terms of the fidelity of their species-level biodiversity, particularly before the Eocene. Benthic microorganisms are even more diverse than their planktonic counterparts and provide a perspective on the deep sea, which is a fundamentally different environment than the upper water column. Similar global diversity compilations of benthic microorganisms will greatly improve our understanding of the marine biosphere and its long-term evolution, resilience, and adaption potential—in particular through and following tipping point events.

Most marine plankton in the modern ocean do not leave fossils behind, while the macrofossils of larger organisms are normally too large to be recovered in cores. Biomarkers, paleo-DNA, and fish teeth/bones represent exciting new opportunities to understand these end members of the marine ecosystem. Improved archiving of fossil occurrence and abundance data sets in community-built databases will significantly increase our ability to reconstruct marine biodiversity, evaluate ecosystem resilience to environmental change, determine the ways in which ecosystems evolve as they get closer to tipping points that trigger extinction, and reconstruct the geographic and temporal variability of extinction and recovery in the ocean.

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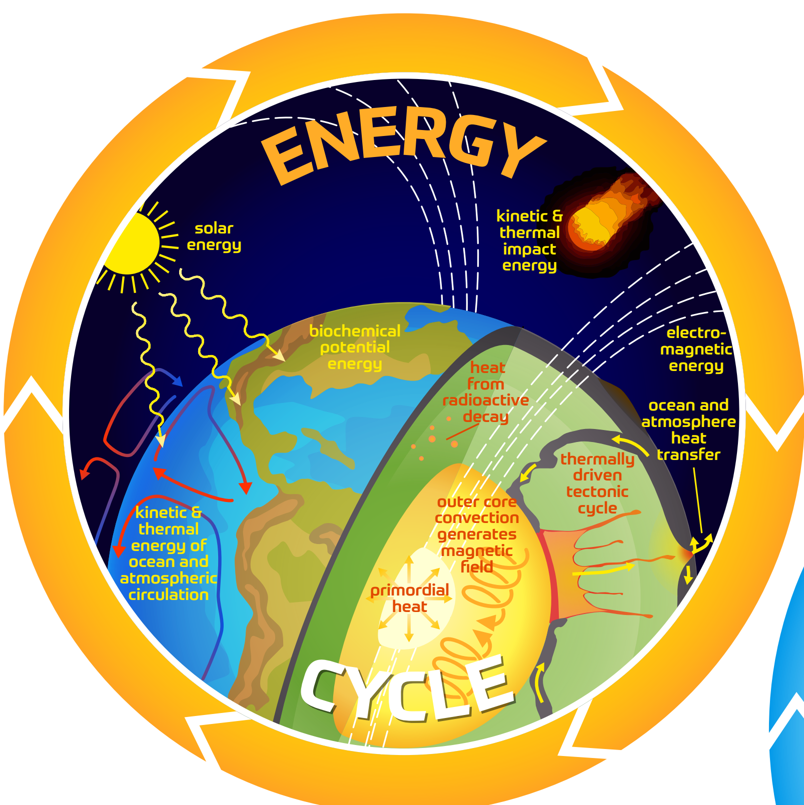
STRATEGIC OBJECTIVE 6 GLOBAL CYCLES OF ENERGY AND MATTER

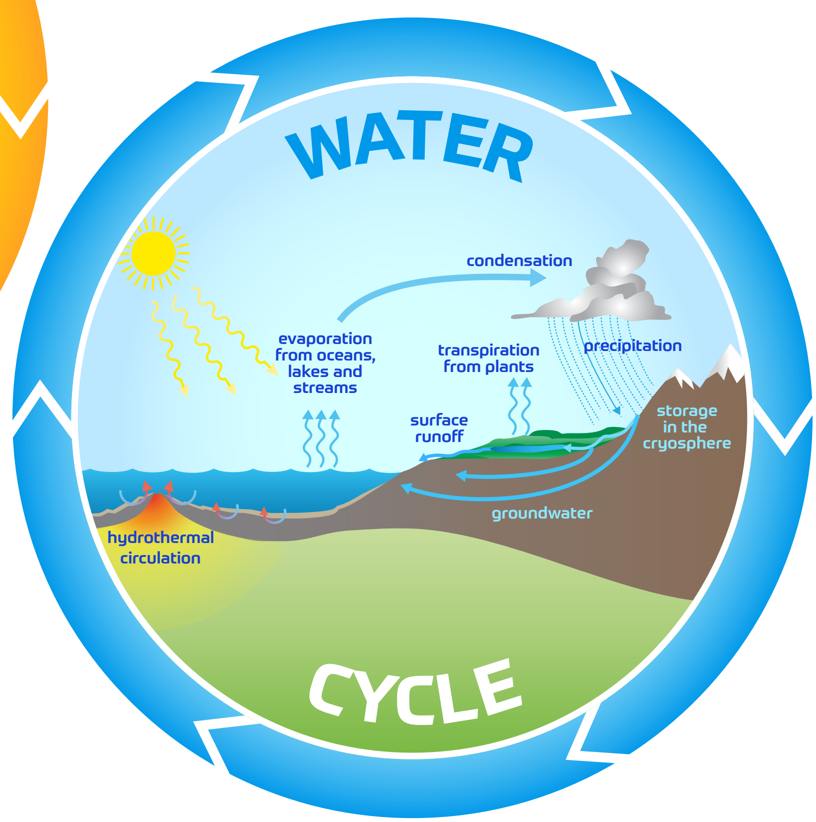
Determining the role, mechanisms, and magnitudes of Earth system cycles

SUMMARY

Energy and matter use multiple pathways to cycle among Earth system reservoirs. Such cycles are responsible for the continuous sculpting of our planet's surface, opening new ocean basins, building mountains, and eroding continents. They also drive the chemical evolution of our atmosphere and ocean, control the physical and chemical conditions that allow life to develop and evolve, regulate the recovery from major perturbations in Earth's climate, generate natural hazards that threaten communities globally, and contribute to the accumulation of key resources, including fresh water and critical metals. Scientific ocean drilling supplies important details and critical missing information about the rates and magnitudes of energy, chemical, nutrient, and fluid transfers among Earth's rocks, ocean, atmosphere, and life. These data can reveal how global cycles control Earth's evolution over a wide range of spatial and temporal scales.



On this and the facing page, simplified cartoons depict the different Earth system cycles covered in this chapter—energy, water, carbon, and metal. *Illustrations by Rosalind Coggon*

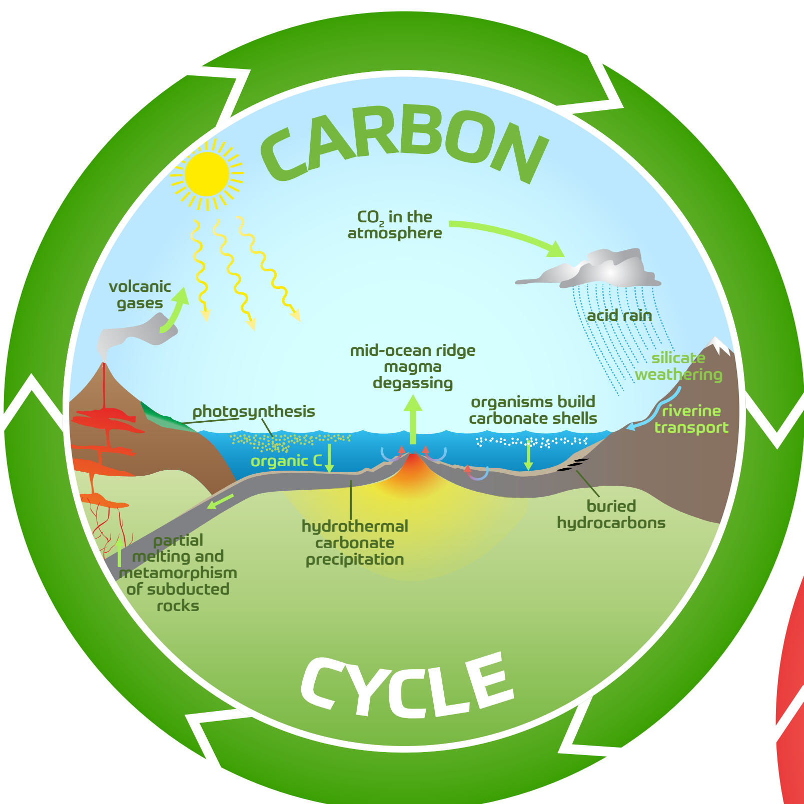


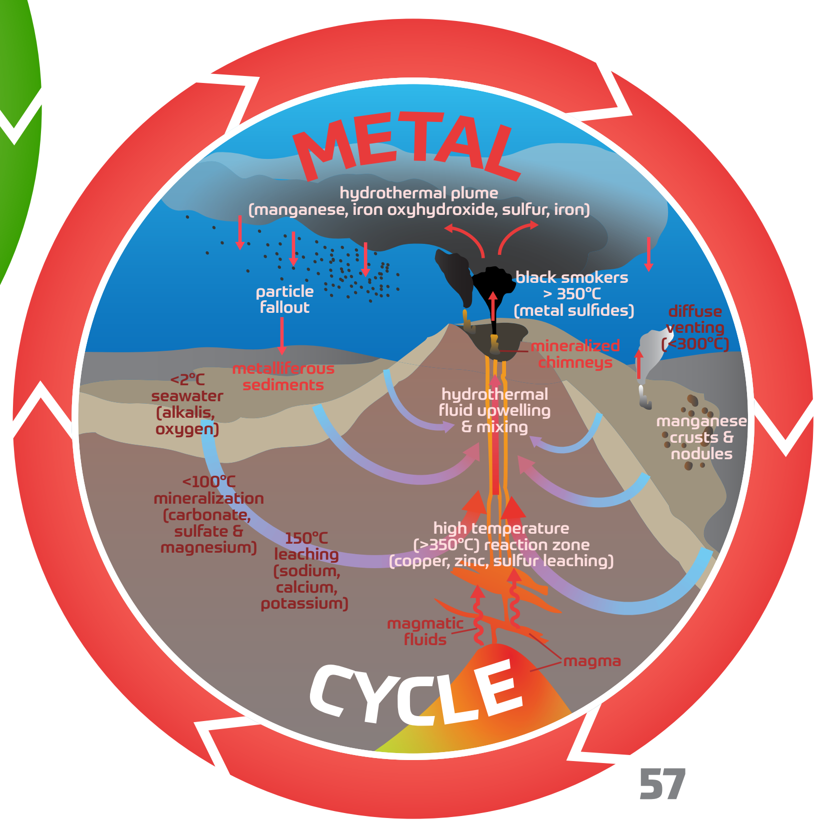
EARTH AS A SYSTEM OF INTERCONNECTED RESERVOIRS

The continuous cycling of energy and matter among reservoirs—large natural storage places—in the core and mantle, the oceanic and continental crust, the ocean, the atmosphere, and the biosphere drive Earth's long-term evolution. These cycles operate over a wide range of spatial and temporal scales and are driven by feedbacks that regulate or amplify Earth system processes, maintaining equilibrium or pushing Earth past a **tipping point** into a new stable state.

The energy that cycles through the system includes thermal (primordial and radioactive) energy from a cooling Earth, solar energy, energy derived from (bio)chemical reactions, and the electromagnetic energy that protects Earth and life from radiation. Heat from Earth's interior and the Sun drives convection within Earth, and the ocean and atmosphere, respectively. Convection creates Earth's magnetic field, drives **plate tectonics**, sustains **life** in the deepest realms of the oceanic crust and sediments, and impacts **Earth's climate system**.

The water cycle, the carbon cycle, the rock/element/metal cycle, and cycles of volatiles such as sulfur, nitrogen, phosphorous, and oxygen are fundamental matter cycles operating within Earth. Water transports heat and solutes, impacts rock deformation and chemical reactions governing alteration, and is essential for life. Carbon is a basic component of life, and its cycling affects atmospheric carbon dioxide and methane concentrations, ultimately affecting **Earth's climate system**. Element cycles exist from nanometer scales, with elemental exchange occurring between minerals, organisms, and the environments in which they exist, to plate tectonic scales, with element exchanges between oceanic crust and ocean water and **element recycling back into Earth's mantle at subduction zones**. Volatile cycles determine the capacity of the atmosphere to protect Earth and life from harmful incom-





ing cosmic radiation, are vital components of the **microbial biome and of human life**, and impact mineral resources and **geohazards**.

These complex interconnections among Earth's reservoirs remain poorly understood. Scientific ocean drilling allows us to access to the subseafloor to conduct in situ monitoring and experiments to characterize the pathways, rates, and magnitude of exchange between reservoirs. Such investigations are important for resolving how **subseafloor life** impacts the cycling of energy and matter in the oceanic crust and in **Earth's upper mantle** and for deciphering the role the solid Earth cycle plays in regulating ocean biogeochemistry. Scientific ocean drilling also helps to map the relative importance of the major controls (tectonics, weathering, life, and atmosphere-ocean interactions) on matter and energy cycles and their impact on ocean productivity, oxygenation, marine life and evolution, and ocean acidification and health. Through scientific ocean drilling we can improve our understanding of the interrelationships among tectonics and volcanism, climate, the hydrologic and biogeochemical cycles, and life.

ENERGY CYCLING

Ever since Earth condensed from a cloud of gas and rocks 4.6 billion years ago, its continents, ocean, biosphere, and atmosphere have continuously evolved. The transfer and feedback of energy through the interconnected Earth system is the fundamental driver for change at all spatial and temporal scales.

Scientific ocean drilling allows us to access to the subseafloor to conduct in situ monitoring and experiments to characterize the pathways, rates, and magnitude of exchange between reservoirs.

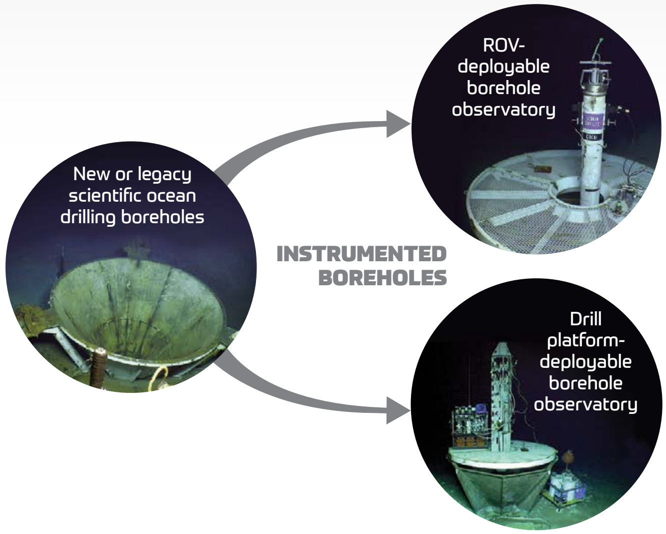
Energy transfers from the deep Earth. Energy is transferred among Earth's many reservoirs through a variety of pathways over many different temporal and spatial scales. Scientific ocean drilling allows us to investigate many of these pathways, from thermal convection within Earth's core that drives global-scale variations in the geomagnetic field to the production of biomass within the oceanic crust. Drilling allows us to track subtle changes in the orientation and magnitude of Earth's magnetic field. With this information, we can map the behavior of the geodynamo over thousands to millions of years, the geodynamic behavior of the mantle, and upwelling of thermochemical mantle plumes. Through scientific ocean drilling, we will gain a better understanding of the dynamics of heat conduction in oceanic lithosphere and the role fluids, faults, microbial alteration, and metamorphic processes play in the transport of heat and elements from the mantle through oceanic lithosphere into the ocean. This will provide insights into the possibility of long-term energy storage in the subseafloor due to the production of biomass through attendant microbial communities.

Planetary cooling processes. At the longest timescales, thermal convection in Earth's interior is manifested at the surface through the production, motion, and destruction of tectonic plates over hundreds of millions of years. Only through recovery of **globally representative sections of oceanic crust** and in situ monitoring of subseafloor conditions can we determine how planetary cooling drives plate tectonics and how it affects the architecture of our planet and the long-term geochemical evolution of its crustal, mantle, and ocean reservoirs.

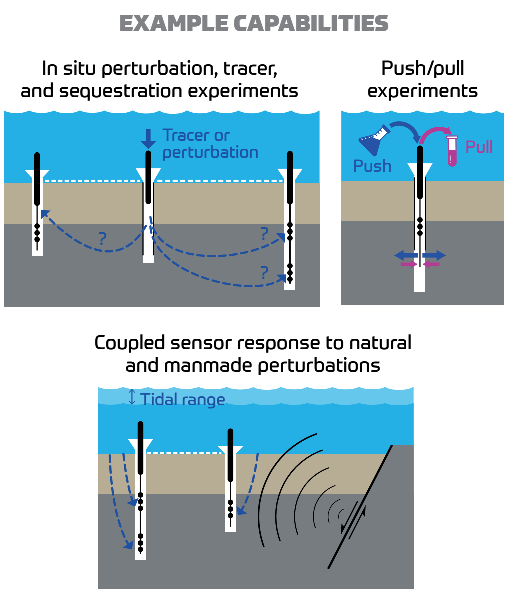
MATTER CYCLING: WATER

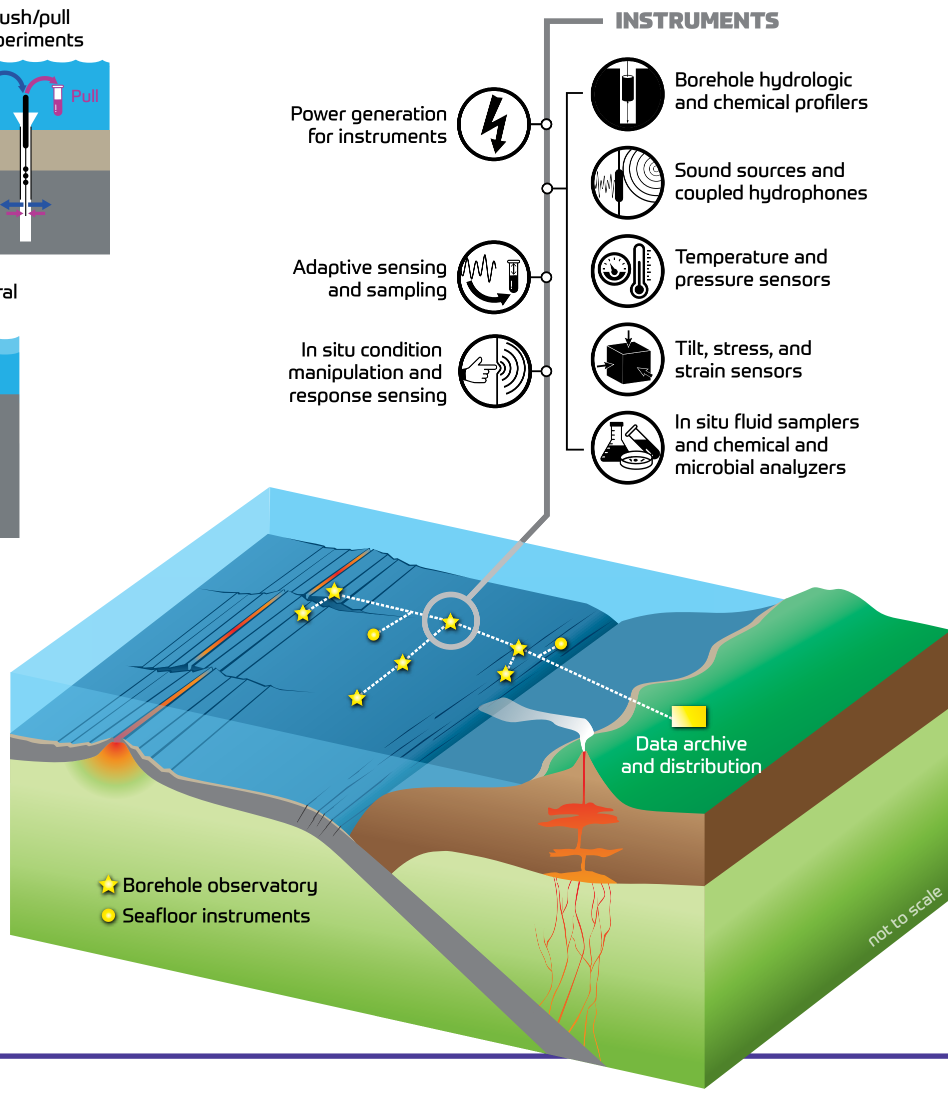
Water transports heat and dissolved elements, making it integral to the functioning of our planet and a requirement for all terrestrial life. Seawater circulation through the oceanic lithosphere facilitates heat loss from Earth's interior. Fluid-rock reactions affect the melting behavior of mantle source materials and with that the initial composition of tectonic plates. Water also has an impact on rock deformation and the chemical reactions governing hydrothermal and seawater alteration of oceanic crust. Ocean currents redistribute heat, carbon, and nutrients globally, with consequences for Earth's climate. We have limited understanding of what pathways in the hydrological cycle influence **global climate change**, how ocean circulation modulates **climate sensitivity**, and how the hydrological cycle would behave in a warmer world. By collecting detailed sedimentary records globally across key Cenozoic climate transitions, we can assess the influx of fluvial and eolian sediments and other water cycle-related proxies to establish the long-term history of the hydrological cycle.

In Situ Investigations of Subseafloor Hydrogeology and Biogeochemical Cycling



The flux of dissolved elements associated with hydrothermal flow that cools the oceanic crust and the processes and timing associated with this exchange are poorly constrained. Experiments that utilize boreholes—after a drilling expedition is over—have begun to examine the exchange of elements between circulating seawater and the host rock and the resultant fluxes between these two reservoirs. Exchange processes can be abiotic or biotic, the latter influenced by endemic subseafloor microbial communities. Future studies using instrumented boreholes will expand our understanding of exchange processes through novel adaptive sampling, sensors, and experiments within one or multiple boreholes connected for real-time sensor data return and instrument adjustment.





Schematic of a cabled array of borehole observatories and seafloor instruments that provide the capability to monitor in situ hydrogeologic and biogeochemical conditions and conduct in situ experiments. Photos: (left) DSDP Hole 395A. (right top) IODP Hole U1383C, a CORK instrumented with two packages. (right bottom) IODP Hole U1383B, instrumented with a CORK-Lite. *Original illustration by Rosalind Coggon, Geoff Wheat, and Geo Prose*

Hydrothermal fluid flow. Previous scientific ocean drilling efforts have revealed that oceanic crust hydrogeology is highly heterogeneous. Heat from cooling ocean lithosphere drives hydrothermal fluid flow through the mid-ocean ridges and across their flanks, and the accompanying fluid-rock chemical exchanges facilitate the long-term geochemical evolution of the mantle, crust, and ocean over millions of years. This fluid flow and chemical interaction are now also understood to deliver energy and nutrients to **microbial communities** that subsist within oceanic crust. Subsequent temperature- and pressure-regulated dehydration reactions during subduction of mature and hydrated oceanic crust can release fluids from the downgoing slab, while compaction and biogeochemical processes in the overlying sediments may alter subsurface pressure gradients and drive fluid flow. Scientific ocean drilling at sites of **increasing crustal age** will allow us to test models for subseafloor fluid circulation and other hydrogeological processes through the integration of core and pore fluid analyses; downhole logging data; measurements from in situ borehole hydrological experiments; and measurements of fluid pressure, temperature, dissolved element concentration, and DNA/RNA from borehole observatories.

Freshwater aquifers. Scientific ocean drilling allows us to explore interactions between the submarine hydrogeologic cycle and continental groundwater systems, including subterranean estuaries where fresh water and salt water mix. Freshwater aquifers that extend seaward beneath continental shelves—a relic of past glaciation when freshwater flow extended seaward—constitute a crucial nonrenewable resource. Similar freshwater lenses occur beneath atolls, other oceanic islands, and along continental slopes where they may be the only source of drinking water available to local communities. In some coastal systems, fresh water constantly discharges and seeps upward, but we do not know whether such discharges cause instability in the flanks of volcanic islands, change the composition of microbial communities, and pose threats to coastal communities by destabilizing continental or insular slopes with a potential to cause submarine landslides. Coastal freshwater reservoirs can be best investigated through **land-to-sea drilling** to produce detailed profiles of porewater chemistry and petrographic and isotopic analyses of diagenetic minerals and to map out how freshwater lenses may be affected by unwanted seawater influxes and/or contaminants.

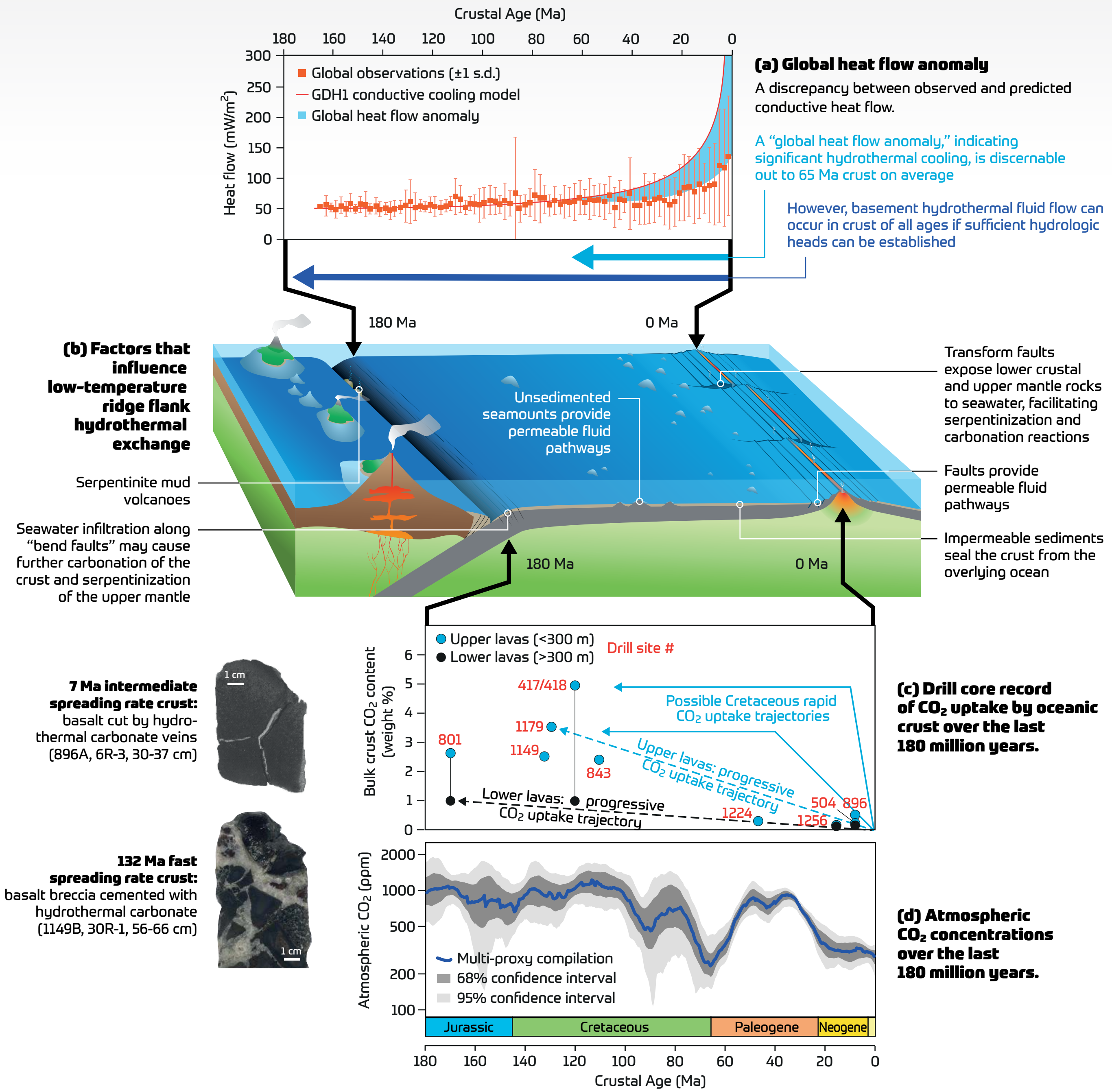
Evaporation effects. Evaporation of seawater can play a key role in global geochemical cycles. Evaporation within restricted ocean basins can lead to the deposition of evaporites—sedimentary rocks rich in a variety of salts. Such deposits record the history of hypersaline fluid flow within a basin and can constitute a major sink for elements such as sodium, chlorine, and sulfur. Scientific ocean drilling can recover sections through evaporite deposits to illuminate the nature and consequences of cutting off these basins from the world ocean and how these changes affected climate, tectonic, and hydrologic **feedbacks**. The mineralogical records from the recovered evaporites will assist in deciphering temporal and spatial changes in ocean chemistry and in quantifying the contribution of brine-rock interactions to global cycles of key elements such as sulfur.

MATTER CYCLING: CARBON

The ocean contains 60 times as much carbon as the atmosphere. The ocean reservoir is critical not only because of its size but also because of the long timescales at which carbon is exchanged across the ocean-atmosphere boundary. The **oceanic crust and upper mantle** are also significant carbon reservoirs. The amount of carbon stored within them is poorly understood because of uncertainties in the extent and duration of hydrothermal calcium carbonate precipitation in oceanic crust, the global role of ultramafic rock serpentinization in CO_2 uptake, and the utilization of the various forms of carbon compounds by microbial communities. The fate of carbon stored in mature oceanic lithosphere during subduction is also unknown because carbon may be transferred along volatile pathways that are currently poorly quantified. For example, we do not know what proportion of the crustal carbon budget is recycled into the mantle, degassed back to the atmosphere via back-arc volcanism or otherwise returned to the surface via fluid flow in the forearc. Scientific ocean drilling allows us to investigate diverse tectonic environments spanning the **oceanic life cycle of tectonic plates** to quantify the role oceanic crust and carbonate sedimentation play in the long-term global carbon cycle.

Cenozoic CO_2 decrease. During the last ~50 million years, long-term decreases in atmospheric CO_2 have coincided with substantial and sustained climate cooling—except for the unprecedented temperature increase since the Industrial Revolution. The reason for this coupled trend has been debated for decades and has been hypothe-

Quantifying the role of mid-ocean ridge spreading in controlling atmospheric CO_2



Scientific ocean drilling is required to quantify the role of natural CO_2 sequestration in oceanic crust as a result of hydrothermal exchange between the crust and overlying ocean in the long-term global carbon cycle. The role mid-ocean ridge spreading plays in controlling past atmospheric CO_2, and hence climate, remains controversial because of uncertainties regarding the rate, extent, and duration of hydrothermal carbonate precipitation. (a) A global heat flow anomaly indicates that hydrothermal circulation persists across the ridge flanks for ~65 million years on average[1], but fluid circulation can occur at all crustal ages given sufficient hydrologic head and permeability, which are influenced by factors such as local basement cover, topography, stratigraphy, and structure (b)[2]. (c) The higher bulk CO_2 contents of cored Cretaceous and Jurassic lavas compared to younger lavas is consistent with either progressive CO_2 uptake by the crust (dashed arrows) or with the majority of uptake within 10–40 million years of crustal formation (solid arrows)[3]. (d) Global conditions during the Jurassic and Cretaceous, including higher atmospheric CO_2[4] and global temperature, may have enhanced hydrothermal carbonate precipitation. The lithospheric flux of carbon into subduction zones likely depends on the age of the plate, its pathway across Earth's surface, its sedimentation and hydrological history, and the physical and chemical conditions of the overlying ocean. To quantify the role of hydrothermal circulation in the long-term global carbon cycle requires acquiring intermediate age oceanic crust.

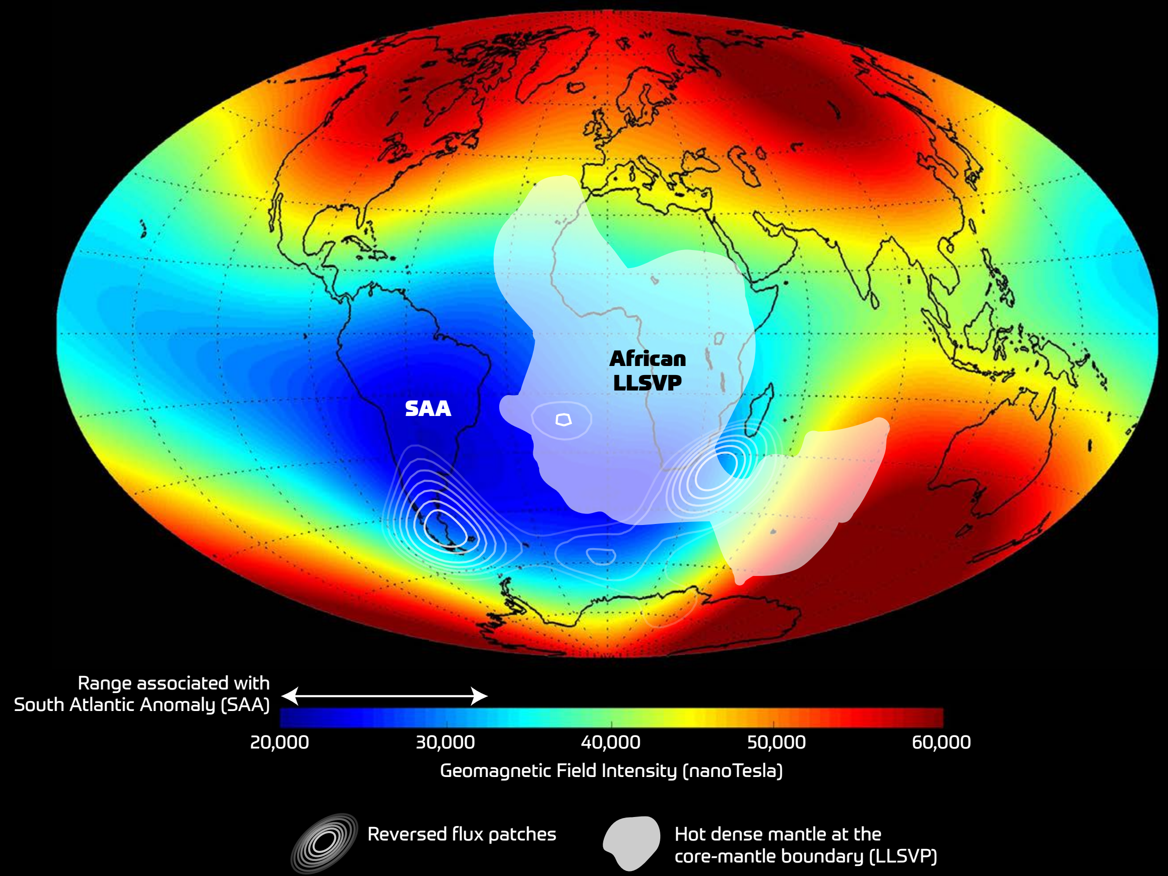
Original figure compiled by Rosalind Coggon. [1]Modified from Stein and Stein (1994), https://doi.org/10.1029/93JB02222. [2]Illustration by Rosalind Coggon and Geo Prose. [3]Modified from Alt and Teagle (1999), https://doi.org/10.1016/S0016-7037(99)00123-4; core photographs from Alt et al. (1993), https://doi.org/10.2973/odp.proc.ir.148.1993, and Plank et al. (2000), https://doi.org/10.2973/odp.proc.ir.185.2000). [4]Modified from Foster et al., 2017, https://doi.org/10.1038/ncomms14845).

DECODING MAGNETIC FIELD VARIATIONS

Convection in the liquid-metal outer core gives rise to Earth's geodynamo and sustains our planet's strong magnetic field. The geomagnetic field shields Earth from damaging cosmic radiation and therefore preserves planetary habitability. Marine sediments and the underlying volcanic rocks record geohistorical variations in the magnetic field. Scientific ocean drilling provides magneto-stratigraphic records that—when incorporated in a global database—are an invaluable tool for constraining the timing and rates of a wide range of Earth cycles over millions of years. The cores provide critical data for establishing a common paleomagnetic reference frame, allowing the movement of Earth's tectonic plates and upwelling mantle plumes to be mapped through time.

Rock magnetic studies of seafloor core samples allow us to gain fundamental knowledge about the source of magnetic anomalies preserved in the oceanic crust and about past paleointensities of Earth's magnetic field. Yet, the geomagnetic field and the geodynamo remain one of the least understood planetary phenomena, as the nature of the magnetic field is constantly changing, with long periods of small changes interspersed with major excursions or complete polarity "reversals." Scientific ocean drilling enables us to investigate the causes and consequences of this highly variable geodynamo behavior, across the world's ocean basins and over different timescales. Small irregular changes in the character of the magnetic field on short timescales are reflected in the "wandering" of the magnetic poles, which over the last decades have shown unexplained accelerations—with speeds up to 55 km/yr—that are theorized to result from turbulence or eddies in the outer core convection.

Another poorly understood behavior of the geodynamo concerns changes in the overall strength of the geomagnetic field. Current observations show a decline in strength over the last half century, with implications for how well life on Earth and our infrastructure will be protected from solar flares in the future. The lowest magnetic field intensities currently occur in the "South Atlantic Anomaly" and already are significantly affecting spacecraft and satellite orbits, exposing them to several minutes of damaging strong radiation. Current models suggest a possible link between the presence of this large low-intensity anomaly and the location of the large low shear wave velocity province (LLSVP) in the lower mantle beneath Africa. The occurrences of reversed flux patches that signal instability in Earth's geodynamo and are seen as a harbinger of a (near) future magnetic field reversal are also poorly understood. Scientific ocean drilling cores obtained from areas with high sedimentation rates (e.g., near continents) will provide long-term records with decadal to centurial resolutions that can assist us in ground truthing computer simulations of outer core turbulence. These sediment cores will also enable us to gain insight into similar future magnetic field variations and declines in overall field strength. *Credit: After Figure 82, https://directory.eoportal.org/web/eoportal/satellite-missions/s/swarm, ESA/DTU Space; and Tarduno (2018), https://doi.org/10.1073/pnas.1819025116*



sized to result from increased chemical weathering on the continents. When CO_2 reacts with rainwater, it forms carbonic acid, which then bonds with elements such as calcium or magnesium. In this way, large amounts of carbon are removed from the atmosphere and transferred to the ocean where it is stored in the deep subsurface reservoirs for millennia. The CO_2 removal from the atmosphere cools down Earth. This hypothesis is problematic because it is not clear what drives up chemical weathering rates while global temperatures have been dropping over timescales of millions of years. Scientific ocean drilling can help decipher whether increases in chemical weathering is a **feedback** and are coupled to increases in mechanical erosion due to orogenic uplift and increases in glacial erosion. Scientific ocean drilling can also help in the search of large negative atmospheric CO_2 **feedback loops** that balance out over timescales of millions of years and that could bring down the CO_2 concentrations over the course of the Cenozoic. Candidate processes include organic carbon burial in ocean sediments, inorganic precipitation of $CaCO_3$, precipitation of silicate minerals on the seafloor via clay authigenesis, dissolution of ocean crust basalt, deep biosphere uptake, sulfate reduction, and the subduction of carbonate-rich sediment and recycling and long-term storage into Earth's mantle. Scientific ocean drilling also is uniquely positioned to investigate whether decreasing ocean bottom water temperatures correlate with decreasing CO_2 storage in the oceanic crust.

Volcanism. One of the major inputs into the carbon surface system are volcanic eruptions that introduce mantle-derived CO_2 into Earth's atmosphere. It is still unknown how past eruptions in island arcs, volcanic islands, and large igneous provinces (LIPs) influenced the carbon cycle as a driver of short- and long-term climate change. Previous scientific ocean drilling has produced limited evidence for volcanic events as triggers for climate warming, but in many cases the timing is not well constrained and is asynchronous with other geological records, or the estimated volume of volcanic CO_2 production cannot explain the levels of increased global warmth. For example, it has been suggested that there may have been a volcanic trigger for abrupt warming 94 million years ago, but it remains unclear whether the magma production rate from Caribbean and/or Madagascar LIP submarine eruptions could have maintained this Cretaceous greenhouse for roughly 9 million years. This hypothesis is particularly problematic, as a lot of carbonate would be simultaneously buried, which would have drawn down atmospheric CO_2 and caused Earth to cool. In addition, ocean fertilization by submarine volcanism and the injection of large quantities of sulfate as aerosols also could cause cooling effects leading to "volcanic winters."

To decipher whether volcanic events triggered the Paleocene-Eocene Thermal Maximum, the Eocene Thermal Maximum 1, the Middle Eocene Climatic Optimum, and other global warming events requires scientific ocean drilling. Drilling is also needed to resolve discrepancies between the relative timing of these events and better estimate the volume of related CO_2 production. This exciting frontier for scientific ocean drilling can provide better insights in the forcing mechanisms for triggering and maintaining **past hot greenhouse climates**.

Scientific ocean drilling allows us to investigate diverse tectonic environments spanning the oceanic life cycle of tectonic plates to quantify the role oceanic crust and carbonate sedimentation play in the long-term global carbon cycle.

Methane hydrates. Hydrate destabilization could play an important role as a feedback in the **climate system**. Debates are ongoing about how much of the methane and CO_2 potentially could be released into the ocean and atmosphere. Scientific ocean drilling provides an opportunity to understand the distribution of hydrates, how they respond to environmental change, and how they fit into the global carbon cycle and climate system. This is another frontier in which scientific ocean drilling has great potential to link paleoceanography to methane hydrate formation and destruction, and the biosphere.

Microbial processes. The **deep biosphere** remains a large and mysterious carbon reservoir. Because it is one of the largest ecosystems on Earth, we now appreciate that it may drive subseafloor geochemical processes that affect ocean chemistry, the global carbon cycle, and the alteration of sediments and rocks. Deep subseafloor microbial cells principally fix carbon and nitrogen, but through volcanic processes they also cycle other volatiles such as sulfur, leading to the accumulation of massive sulfide deposits.

Oxidation can also be controlled by microbial action, causing significant pyrite formation on continental slopes during glacial lowstands and extensive redox reactions within basaltic crust. These processes provide crucial, bio-available elements for life and stimulate us to gain a fuller understanding of **microbial-driven cycles** in the subseafloor environments.

Sequestration. The sequestration of CO_2 in sediments and rocks **buffers climate** over geological timescales, while carbon also forms the engine of **all deep biosphere microbial life and life in general**. Subsurface carbon sequestration is an emerging opportunity for mitigating anthropogenic climate change. Similar to nature, humankind could possibly sequester CO_2 in the subseafloor in deep saline reservoirs on the continental shelf or in oceanic plateau basalts. The potential exists to actively pump carbon into spreading ridge flanks that cover vast expanses of the seafloor. Scientific ocean drilling will play an important role in exploring opportunities for submarine CO_2 sequestration, as these potential offshore carbon reservoirs require deep coring capabilities and improved drilling/logging technologies.

MATTER CYCLING: METALS

Fluid flow facilitates the cycling of metals between the lithosphere and ocean. Over millions of years, this cycling can lead to the formation of massive sulfides and ferromanganese nodules on the seafloor. Hydrothermal activity along mid-ocean ridges and other submarine volcanoes concentrates key metals in subseafloor ore deposits and provides useful analogues for understanding ancient deposits exposed on land that are important sources of traditional metals (Cu, Zn, Au) and critical metals (Co, Cr, V) used in green and advanced technologies. Subseafloor fluid flow may lead to the accumulation of potentially economic metal resources, while at other locations, no deposits form and seawater can have increased dissolved elemental concentrations. Scientific ocean drilling can help define the subseafloor locations and mechanisms and under which conditions metal resources are formed. It also has the potential to discover biogenic and non-biogenic mineral deposits that result from organic-mineral interactions.

Metal concentrations in sediments recovered by scientific ocean drilling can be used as tracers for geologic events. Mercury can be used to investigate **meteorite impacts** and **large volcanic eruptions**. Other metals can be used as proxies to help improve our understanding of the relationship between **global anoxic events** and the formation of large igneous provinces and the formation of natural resources (Mn, Co, Ni) in open ocean basins and more confined back-arc basins and marginal seas.

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STRATEGIC OBJECTIVE 7

NATURAL HAZARDS IMPACTING SOCIETY

Understanding natural hazards in the marine environment

SUMMARY

Earthquakes, landslides, tsunamis, volcanic eruptions, mega-floods, and other extreme natural events directly threaten communities, infrastructure, and the environment. Significant progress has been made in the investigation of such hazards through scientific ocean drilling, particularly in subduction zones. However, we remain largely uninformed about the subseafloor conditions that influence hazards; the mechanisms that control their recurrence, timing, and possible precursors; and how to assess their future likelihood. Scientific ocean drilling can help close knowledge gaps by installing subseafloor observatories to monitor in situ conditions before, during, and after hazardous events and by probing the stratigraphic record of prehistoric submarine and terrestrial hazardous events to understand processes and evaluate long-term magnitude-frequency correlations. Further advances in methodologies to interpret physical properties and processes from geological and geophysical records are also needed.

DETERMINING PHYSICAL CONTROLS OF GEOLOGIC HAZARDS

Scientific ocean drilling addresses questions about the physical controls on submarine geologic hazards through analyses of rock, sediment, and fluid samples. It also provides access to failure planes and slope failure deposits that are inaccessible by conventional gravity or piston coring. Analyses of rock and fluid samples provide information about the processes that can create geohazards. Fluid chemistry can inform us about reactions and changes in rock properties that are occurring at depths not reachable with current drilling capabilities. Collectively, these data about the present subsurface provide crucial in situ information for the physical models used to determine the risks from future earthquakes, landslides, and volcanic eruptions. Although marine geologists and geophysicists have made great strides in probing the physical properties, processes, and conditions controlling geologic hazards, scientific ocean drilling is poised to fill critical knowledge gaps.

Slip behavior. Recent study has shown unequivocally that faults and landslides slip in a wide variety of ways: while some apparently only slip gradually and steadily over time and others only fail suddenly and catastrophically, many others exhibit unstable slip behaviors over a wide range of magnitudes and durations. Questions such as whether material properties, physical conditions, or subsurface geometry of the failure plane control slip behavior, and how subsurface conditions and behavior may change through time, remain unresolved. By providing access to the subseafloor to permit long-term measurements of in situ conditions and to slip planes where rock and sediment samples can be collected, scientific ocean drilling can address how various slip behaviors influence hazard potential and how stress state and loading rate affect slip behavior. Understanding the **nature of slip processes**, for both earthquakes and landslides, is particularly important as it directly influences tsunami hazards.

Submarine explosive volcanism. Scientific ocean drilling can contribute to our understanding of the processes that control **submarine volcanic eruptions**. Characterizing the causal mechanisms of past volcanic eruption-related tsunamis can improve our understanding of the hazards associated with potential flank collapse, caldera formation, and pyroclastic flows from submarine volcanoes. Similarly, understanding whether and why some volcanic flank landslides fail in progressive stages and others catastrophically in a single event is important for assessing the potential for tsunamis and/or triggered large-volume eruptions in volcanic arcs. Drilling into volcanic deposits caused by mass wasting or the volcanic eruptions themselves will provide direct access to the products from a widespread group of largely understudied submarine volcanoes.

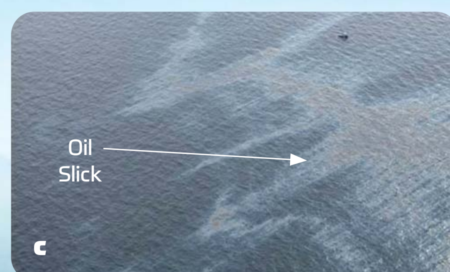
Marine Records of Natural Hazards

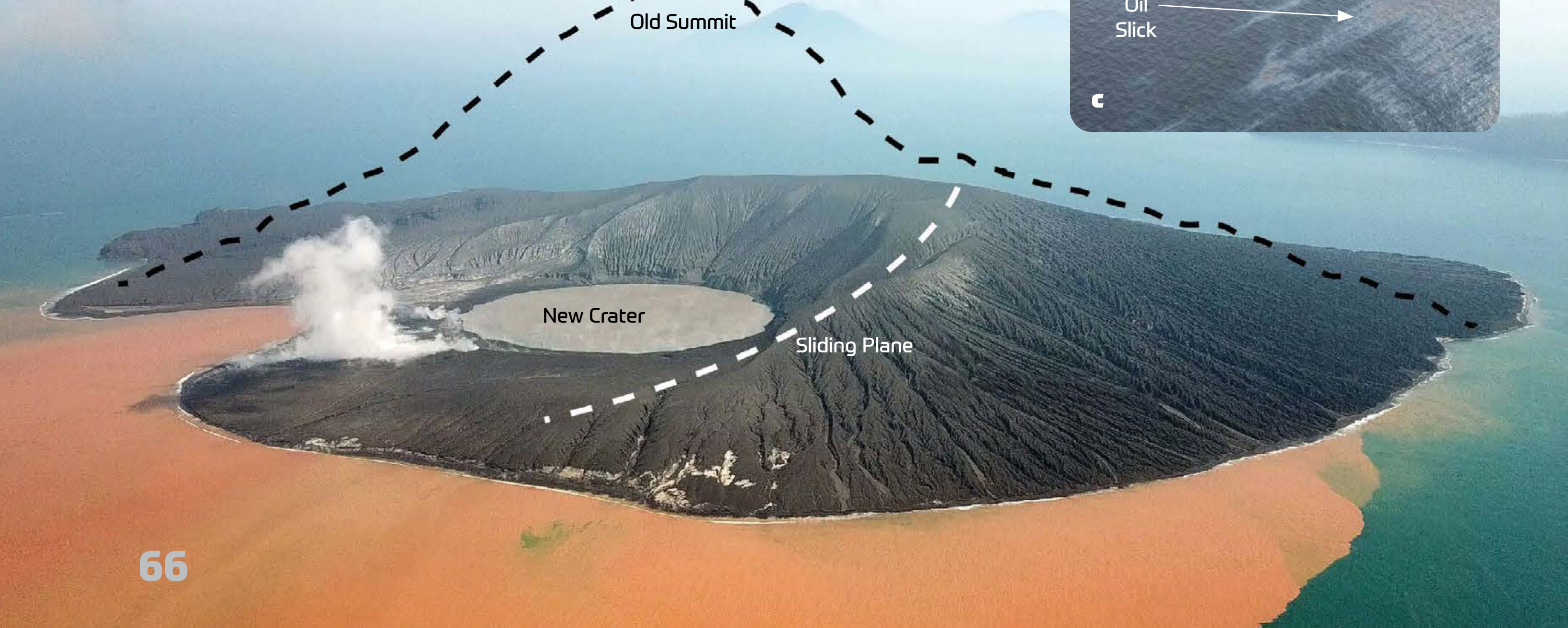
Large underwater earthquakes and the tsunamis they often generate have been responsible for some of the worst natural disasters of the early twenty-first century, taking hundreds of thousands of lives and forever altering coastal communities large and small. Recent events underscore how much we still have to learn about plate boundary faults. For example, the 2011 M_w 9.1 Tōhoku-oki (Japan) earthquake, and the effects of the earlier 869 CE Sanriku earthquake in the same area, have shocked the seismological community. Fault slip during the Tōhoku-oki earthquake was determined to be more than 50 m, extending from depth all the way to the trench, resulting in a much larger magnitude earthquake and tsunami than thought possible in this tectonic setting.

Volcanoes both above and below water also pose a variety of hazards. In 2018, the Anak Krakatau volcanic eruption (Indonesia) was accompanied by a tsunamigenic flank collapse, creating the deadliest eruption thus far in the twenty-first century. The human impact from the devastating 1883 Krakatoa predecessor eruption and tsunami was orders of magnitude larger. Although many volcanoes are hidden beneath the ocean, their eruptions can pose significant hazards. For instance, the unexpected 2010 South Sarigan Seamount eruption (Northern Mariana Islands) created a plume of ash extending 12 km into the atmosphere, intersecting airplane routes and disrupting ship and air traffic.

At active and passive tectonic margins, and in plate interiors and along volcanic flanks, submarine landslides pose hazards to offshore infrastructure, including seafloor telecommunication cables, drill rigs, and pipelines, and can generate tsunamis. Debris flows and turbidity currents triggered by earthquakes and typhoons repeatedly cause damage and major service disruptions to submarine communication cables worldwide. In 2006, 22 major cables broke following an earthquake off southern Taiwan. In 2004, a submarine landslide during Hurricane Ivan destroyed the Taylor Energy MC20A oil platform in the Gulf of Mexico, rupturing tens of oil wells and creating the longest duration oil spill in US history.

Scientific ocean drilling can fill gaps in our understanding of hazard processes through targeted investigations into the underlying properties, conditions, and physical mechanisms that control their occurrence. Drilling can also improve hazard assessments by helping to constrain the submarine location, magnitude, and frequency of past hazardous events. Focused studies can help us understand how changes in climate and sea level affect geologic systems, particularly those with potential landslide hazards. Through active monitoring, scientific ocean drilling can provide information on current subseafloor conditions and changes occurring near the hazard source. These data can be used to inform time-dependent hazard determinations and hazards forecasts.





(a) The town of Rikuzentakata on the northeast coast of Japan, three days after the 2011 tsunami reduced the town of 23,000 residents to rubble. *WorldView-2 satellite image by Robert Simmon, using data ©2011 DigitalGlobe.* (b) A drone image of the Anak Krakatau volcano two weeks after the flank collapsed. The volcano peak that had measured 320 m is missing. *Credit: Deutsches GeoForschungsZentrum (GFZ)* (c) Oil slick at the Taylor MC20 site. *Credit: US Coast Guard.*

Variations in slope stability. Uncertainties remain regarding the causes of large submarine landslides and their potential to generate devastating tsunamis, especially where the seafloor gently slopes. It is particularly important to determine whether the initiation points for these geohazards, which otherwise appear stable, are preconditioned for failure and/or are triggered by external events—for example, by methane release, earthquakes, or increased sediment supply. Previous scientific ocean drilling suggests earthquake shaking can strengthen and stabilize sediments through dewatering, making them less susceptible to landslides than similar units far from active margins that have not been shaken considerably. This strengthening effect, however, can be overwhelmed by high sedimentation rates on continental margins, making the conditions more unstable. Scientific ocean drilling can determine the primary controls on seafloor stability by providing more detailed characterization of multiple locations in the ocean basins. This information can be used to inform predictive models of sediment strength, potential methane dissociation, and slope stability.

Hazards triggering hazards. Extreme marine events often trigger other geohazards. Submarine earthquakes in subduction zones and along coastal strike-slip systems can trigger tsunamis, landslides, other earthquakes, and potentially even volcanic eruptions. Explosive phreatic volcanic eruptions in island arcs are not only destructive by themselves, they also often generate tsunamis and landslides and can be accompanied by large precursor and syn-volcanic earthquakes. Scientific ocean drilling will target areas in the ocean basins where we can start to establish and test these causal links among various hazards.

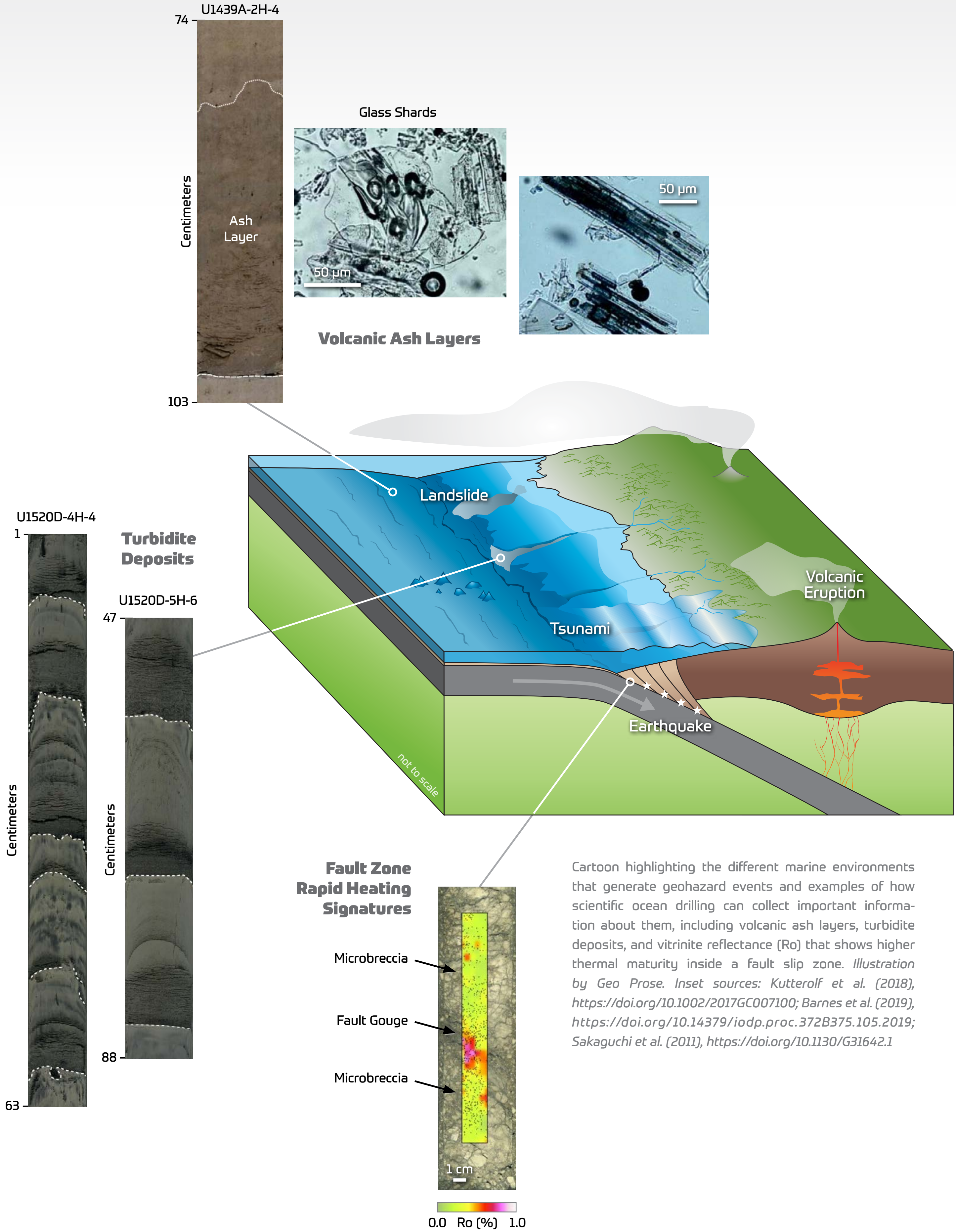
RAPID RESPONSE MEASUREMENTS OF HAZARDOUS EVENTS

Scientific ocean drilling can collect repeat measurements in the subseafloor to evaluate how stress state, pore pressure, temperature, and other hydrologic, mechanical, and chemical properties and conditions affect failure evolution at different stages in the cycles of hazardous events. Scientific ocean drilling can also change focus rapidly if there is an opportunity to capture measurements from hazard events that occur during the lifetime of this *2050 Science Framework*. Rapid response drilling following large, hazardous events will elucidate processes that occurred during the events and how the subsurface responded in the aftermath. For example, coring, logging, and borehole observatory measurements made through rapid response scientific ocean drilling after the 2011 M_w 9.1 Tōhoku-oki (Japan) earthquake permitted characterization of the fault's stress state during and immediately after the earthquake, the physical properties within and around the plate boundary fault zone at depth, and transient processes during the subsequent aftershock sequence. Given the importance of in situ and deep measurements, new technologies and operational strategies need to be developed so that time-sensitive observations and experiments can be conducted quickly after an event.

By providing access to the subseafloor to permit long-term measurements of in situ conditions and to slip planes where rock and sediment samples can be collected, scientific ocean drilling can address how various slip behaviors influence hazard potential and how stress state and loading rate affect slip behavior.

LEARNING FROM PAST HAZARD RECORDS

Increased knowledge of the magnitude and frequency of past events is important for quantitatively assessing future hazard potential. Submarine earthquakes and landslides, tsunamis, volcanic eruptions, hurricanes, and other extreme events all leave behind evidence in submarine rocks and sediments. Scientific ocean drilling provides the means to access this record and to go well beyond the short temporal record provided by shallow piston and long coring. Interpreting the history of past events—by establishing a detailed event stratigraphy over tens of thousands to millions of years—can be achieved through high-recovery and high-resolution core sampling. This strategy requires using a combination of conventional techniques (e.g., identifying and dating turbidites) and developing novel techniques to more robustly obtain a history of past events and to evaluate accurate timing and magnitudes.



Cartoon highlighting the different marine environments that generate geohazard events and examples of how scientific ocean drilling can collect important information about them, including volcanic ash layers, turbidite deposits, and vitrinite reflectance (Ro) that shows higher thermal maturity inside a fault slip zone. *Illustration by Geo Prose. Inset sources: Kutterolf et al. (2018), https://doi.org/10.1002/2017GC007100; Barnes et al. (2019), https://doi.org/10.14379/iodp.proc.372B375.105.2019; Sakaguchi et al. (2011), https://doi.org/10.1130/G31642.1*

Eruptive recurrence frequencies. Offshore sediments contain some of the longest and most complete histories of large-magnitude volcanic eruptions (VEI > 4; typically, VEI > 5 to 7). Volcanic ash that settles on the seafloor after an eruption punctuates the gradual deposition of sediments in marine environments and becomes incorporated in the sedimentary record. In contrast, ash records preserved onshore can be incomplete, as they are subject to erosion and other subaerial weathering processes.

An active database of ash layer observations in scientific ocean drilling cores provides the largest global compilation of eruptions in the geologic record. This database, which is continually updated, can be used to guide targeted investigations and further analyses, for example, to constrain the volume and recurrence of past eruptions. Such records also provide insights into the operative geochemical and background tectonic processes through characteristics that fingerprint the magma source and style of eruption. These well-dated ash falls provide important chronologies, especially in areas such as the Mediterranean, the western margin of the Americas, and near New Zealand and Japan, where radiocarbon chronologies are plagued with interfering carbon reservoir effects. Ash fall chronologies provide insights into hazards, but they also offer critical control on the timescales of global climate change and **feedbacks in the Earth system** during glacial/interglacial intervals in the Holocene and Pleistocene as well as deeper geologic times.

Sediment remobilization. Sedimentary sequences beneath the ocean remain largely undisturbed, but they can become remobilized during submarine landslides and debris flows and, particularly in nearshore settings, by tsunamis and tropical cyclones. The remobilized sediments, including those from land-derived mega-floods, eventually resettle in slope basins, trenches, and other submarine depressions. By analyzing sediments deposited in these environments, we can greatly extend the historical record of earthquakes and landslides. Comparisons of deposits collected at various global locations and settings can provide insight into how coastal zones respond to extreme weather, climate, and changing sea levels, as well as rapid geohazard events. Earthquake-triggered sediment remobilization also appears to drive significant organic carbon flux to the deep sea, with as yet unstudied consequences for those microbial communities residing at water depths deeper than 6 km in Earth's ocean trenches.

Ancient earthquake scars. Subseafloor sediments and rocks bear the scars of hazard events in other forms as well, such as thermal alteration and microscale deformation within fault rocks. Determining whether a particular fault—and particular rock units within it—hosted large, rapid slip events in the past, particularly at shallow depth, has direct implications for **earthquake and tsunami hazards**. Continued innovations in identifying and interpreting these signals for a wide range of geologic compositions and various conditions are needed.

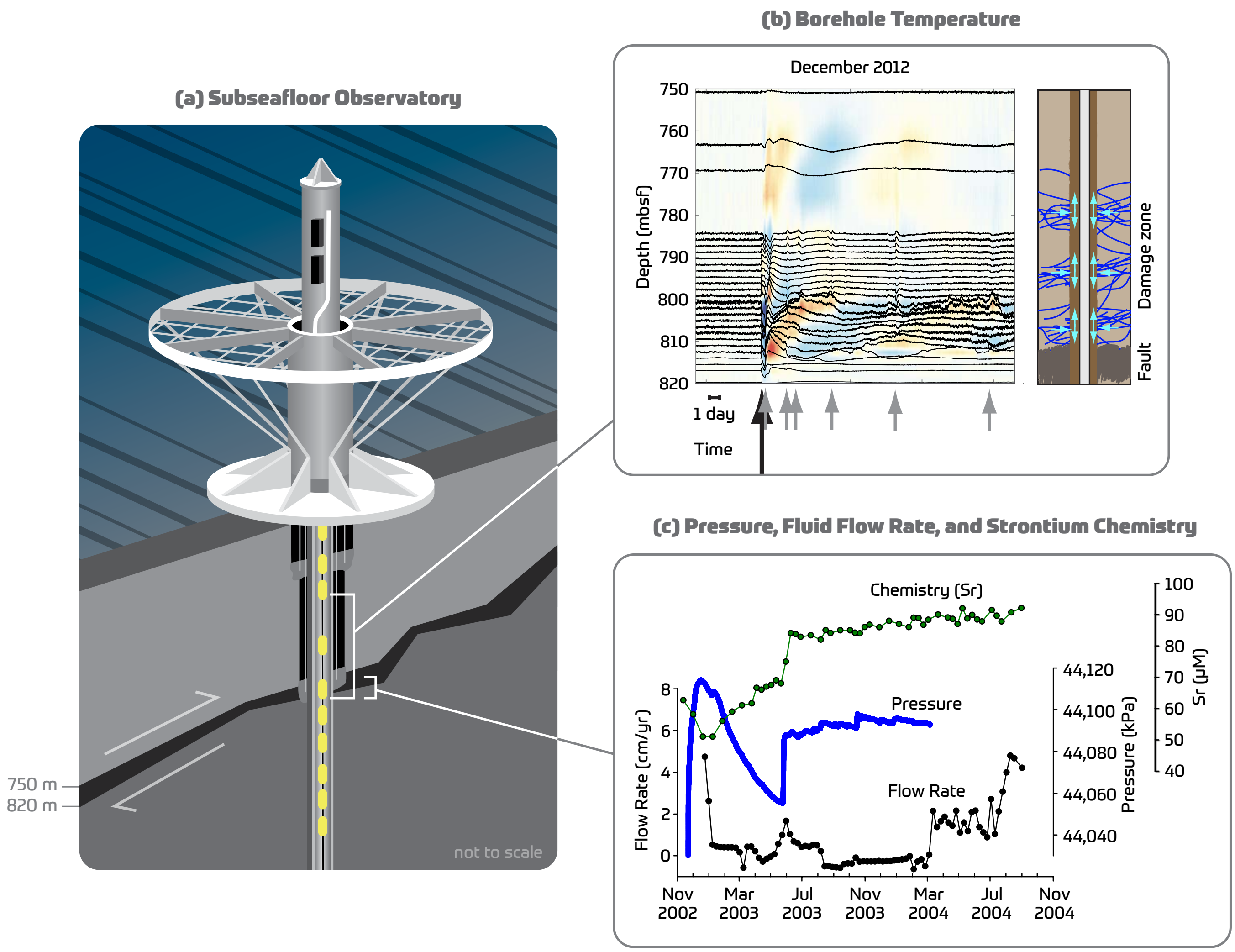
Scientific ocean drilling provides numerous opportunities to extend analyses of past events beyond a few targeted locales and to evaluate regional or global differences within the sediment and rock record. We will determine the history of past hazardous events by comparing global observations using a significantly expanded database in terms of geographic coverage, geologic setting, and timing within the hazard cycle. This analysis will provide a more robust understanding of the mechanisms controlling hazards and their potential spatial and temporal variability, which is crucial for assessing earthquake and tsunami hazard potential.

Scientific ocean drilling offers an opportunity to assess hazard variations over time through installation of offshore subseafloor observatories inside or very near faults, at and around landslide failure planes, and at volcanoes.

SUBSEAFLOOR MONITORING AND OBSERVATION

A long-standing goal within hazards science has been to provide robust, time-dependent hazard assessments. Although precise prediction of the timing of earthquakes, volcanic eruptions, landslides, and tsunamis is probably not feasible, improved forecasting of such events and their potential magnitude is within reach. Improved forecasting requires understanding the conditions under which earthquakes, tsunamis, volcanic eruptions, and landslides are generated and knowledge about how these conditions evolve, including in the lead-up to major events, during events, after events, and the long intervals in between.

Borehole monitoring for precursory hints. Precursory deformation and seismic activity have now been recognized prior to several **large M8 and M9+ tsunamigenic subduction zone earthquakes** and along strike-slip transform boundaries. Knowledge of precursory activity can help scientists identify in real time the short-term hazards expected from large events, much as is commonly done for volcanoes and some large landslides on land. Because of the paucity of instrumentation on and below the seafloor, our observational data sets are limited and much of what is happening beneath the ocean remains unknown. The potential to use possible event precursors for hazard assessment is simply unknown and remains an important target for the next phase of scientific ocean drilling, particularly in parallel with advances in ocean and subseafloor technology. Scientific ocean drilling offers an opportunity to assess hazard variations over time through installation of offshore subseafloor observatories inside or very near faults, at and around landslide failure planes, and at volcanoes. Instrumentation installed deep beneath the seafloor, where oceanographic noise is minimized and where pressure, temperature, stress and strain, and hydrologic and geochemical conditions can be directly monitored within active systems, will provide the data types and resolution needed for effectively assessing hazards over time and for comprehending the hazard-generating process itself.



Subseafloor observatories installed by scientific ocean drilling (e.g., panel a) permit characterization of in situ conditions and their temporal changes before, during, and after slip events. Observatories have noted changes in borehole (b) temperature and (c) formation pressure, fluid flow rate, and strontium chemistry during earthquakes and other slip events. *Sources: Fulton and Brodsky (2016), https://doi.org/10.1130/G38034.1; Solomon et al. (2009), https://doi.org/10.1016/j.epsl.2009.03.022*

Seafloor instrumentation and observatories. While less sophisticated, seafloor instrumentation is cheaper to install than high-fidelity borehole observatories, but any network should include both. Subseafloor observatories can directly sample and monitor at actual failure planes or hazard source regions and can be designed to characterize in situ properties and processes that cannot otherwise be determined. They reveal time-dependent variations required to resolve the physical processes involved in offshore natural hazards, allow strain buildup and release to be monitored, and reveal transient behavior that is largely undetectable by surface-based instruments. With current and future advances in sensor development and technologies for managing data and power to and from instrumentation deep underwater and beneath the seafloor, scientific ocean drilling has the opportunity to both use and drive advances in offshore technology and revolutionize science-based assessment of natural hazards in the marine environment. Many key questions associated with hazards revolve around how conditions within the subsurface change before, during, and after an event. These changes can be crucial to answering "why, how, and when" questions from society about hazard occurrence and recurrence. These questions cannot be fully answered without the involvement of scientific ocean drilling and the in-depth analyses that it affords through innovative seafloor instrumentation and observatory networks.

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FLAGSHIP INITIATIVES

The *Flagship Initiatives* comprise long-term research efforts that require multi-expedition scientific ocean drilling over 10- to 20-year time intervals. Each multidisciplinary research endeavor aims to test scientific paradigms and hypotheses that inform issues of particular relevance or interest to society. The *Flagship Initiatives* typically combine research goals from multiple *Strategic Objectives*. Their implementation will be shaped by science proposals that develop coordinated strategies, including long-term planning, technology development, and innovative applications of existing and new scientific ocean drilling data.

1 **Ground Truthing Future Climate Change**

2 **Probing the Deep Earth**

3 **Assessing Earthquake and Tsunami Hazards**

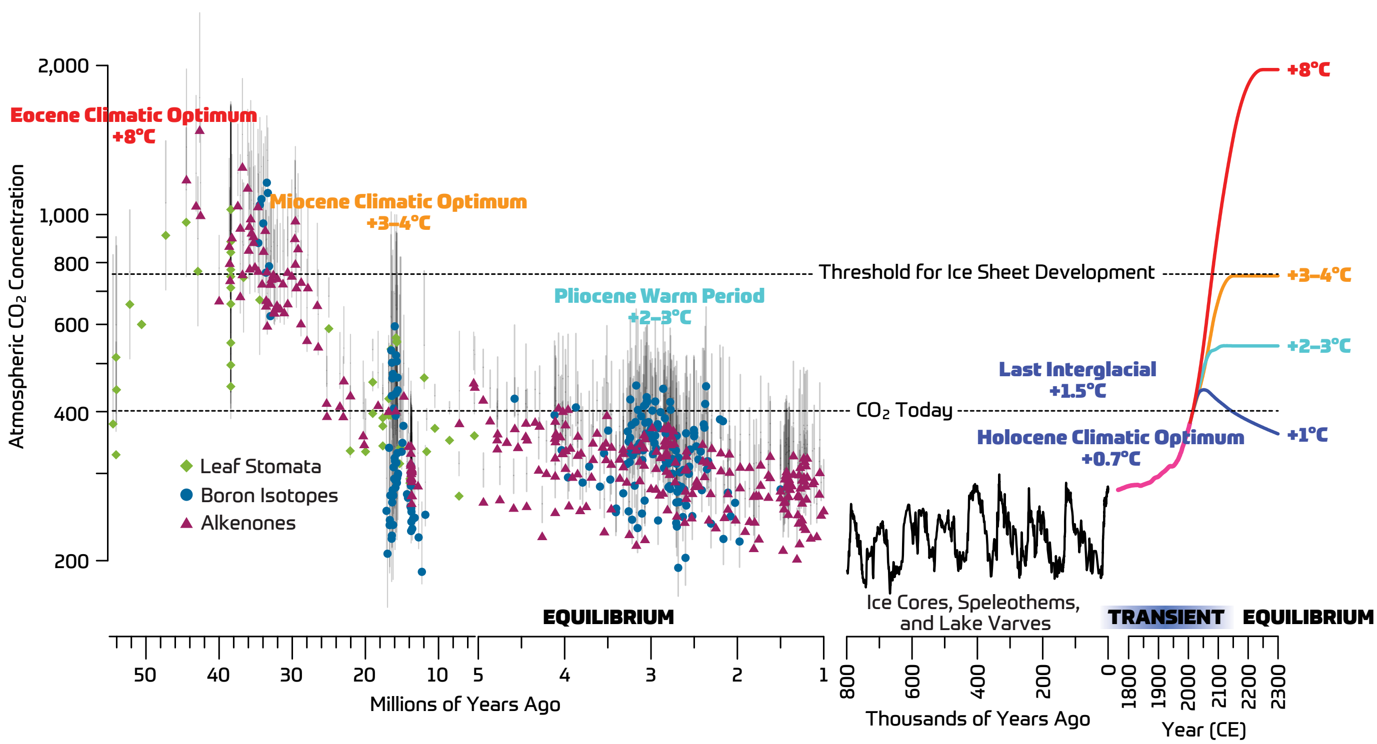
4 **Diagnosing Ocean Health**

5 **Exploring Life and Its Origin**

GROUND TRUTHING FUTURE CLIMATE CHANGE

SUMMARY

Predicting how the Earth system will respond to increasing global temperatures is one of the greatest challenges facing geoscientists. Atmospheric CO_2 concentrations have already exceeded 410 ppm in 2020 and could surpass 900 ppm by 2100 without action to reduce anthropogenic CO_2 emissions. Paleoclimate data collected through scientific ocean drilling established that it has been at least 3 million years since atmospheric CO_2 exceeded 410 ppm. Values approaching 900 ppm were only realized during the hot "greenhouse" climate of the Eocene ~50 million years ago. Numerical climate and Earth system models are used to simulate Earth's response to projected increases in atmospheric greenhouse gas concentrations. Model projections can provide information about shifts in rainfall and temperature patterns and rising sea levels that can be used in the design of mitigation and adaptation strategies. High-density, global scientific ocean drilling networks and transects will enable a more robust identification of feedbacks and tipping points in Earth's climate system and improve modeling and IPCC assessments of climate sensitivity to atmospheric greenhouse gases, ocean circulation changes, and other geologic boundary conditions.



Evolution of CO_2 over the past 55 million years, and projected to 2300. Scientific ocean drilling demonstrates the range, rates, and conditions of past climate changes, including the only opportunity to investigate the Earth system response to atmospheric CO_2 exceeding 400 ppm. Drilling provides the critical parameterization and validation of developing paleoclimate models, including paleo ice sheet and sea level reconstructions. *Data from Foster et al. (2017), https://doi.org/10.1038/ncomms14845, Masson-Delmotte et al. (2013), and DeConto et al. (2008), https://doi.org/10.1038/nature07337*

Ground Truthing Future Emissions Trajectories

Future emissions trajectories depend on society's choices. Assessments reported by the Intergovernmental Panel on Climate Change (IPCC) range from a "high emission scenario," with emissions peaking well after 2100, to one with "aggressive reductions," with emissions peaking between 2020 and 2050 and reducing to near zero before 2100. The latter trajectory is projected to stabilize atmospheric CO_2 concentrations between 350 ppm and 420 ppm, which is required to restrict global warming to less than 2°C above the pre-industrial temperatures of the nineteenth century.

Ocean sediments record Earth's climate system response to global "greenhouse" conditions 50–34 million years ago, which are analogous to high emission scenarios where CO_2 exceeds 650 ppm. They also record Earth's response to warmer climates in the "moderate" CO_2 worlds of the past 5 million years. Analysis of past climates, enabled by scientific ocean drilling, will provide vital information about how the Earth system may respond to climate warming of 2°C over the coming decades and centuries when tipping points in the climate system may be reached. The historical knowledge gained from examining sedimentary archives will inform society about the rates of change in and irreversibility of some Earth system processes such as ice sheet collapse and permafrost thawing, permitting informal assessment of mitigation and adaptation measures.

IMPROVING CLIMATE MODELS THROUGH SCIENTIFIC OCEANIC DRILLING

Increasingly sophisticated climate models are becoming better at capturing the complex interactions within **Earth's climate system** that are required to assess potential rates of future climate change. At best, however, these models are mathematical representations and simplify important Earth processes. They contain uncertainties, some of the largest of which are related to shifts in precipitation patterns and atmospheric water vapor, the drivers of recent sea ice trends, marine ice sheet stability, the mantle's response to melting ice volumes, and the sources and sinks of **carbon**. Many climate models are calibrated to modern instrumental records, so they may overlook or under-represent critical **feedbacks** and **tipping points** in Earth's climate system and may fail to capture the full scale of change.

Knowledge gained from studying past climates recorded in sediments recovered by scientific ocean drilling provides valuable benchmarks for testing climate models. State-of-the-art approaches permit us to reconstruct the many physical, chemical, and biological interactions between atmosphere-land-ocean systems that are relevant to climate models and to constrain leads and lags between components of Earth's climate system. Incorporating information about the **global ocean's response** to past natural climate variability is a robust way to improve and validate model skill and performance. Improving model skill and performance is especially relevant to the warmer-than-present climates projected for the end of the twenty-first century that Earth has not experienced since the Pliocene, more than 3 million years ago. We will assemble high-resolution paleoclimate records from globally distributed locations to permit more robust identification of feedbacks and tipping points in Earth's climate system and significantly improve assessments of climate sensitivity to atmospheric greenhouse gases, ocean circulation changes, and other geologic boundary conditions. Results from these studies can be used to improve models that predict future climate or simulations that focus on the pre-Anthropocene world.

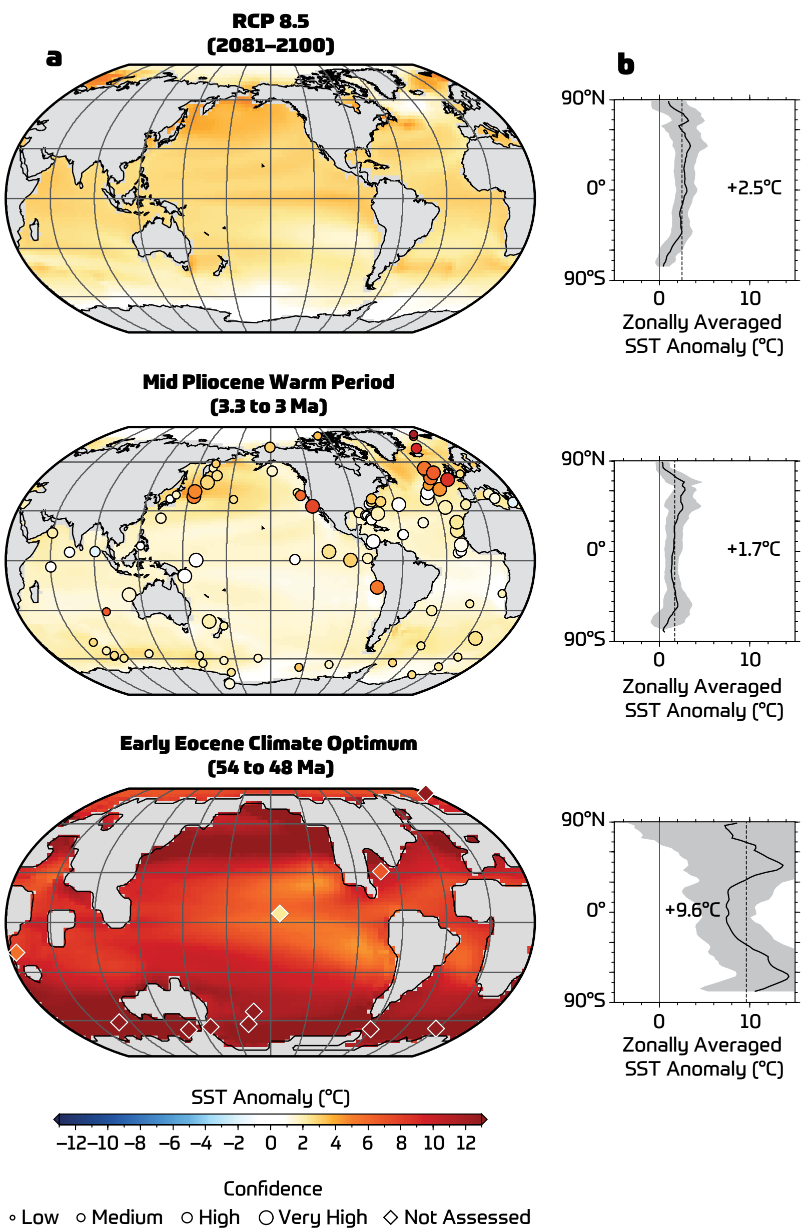
UNDERSTANDING CLIMATE SENSITIVITY

Defined as the average global surface warming that will occur in response to a doubling of atmospheric CO_2 concentration, climate sensitivity is one of the most important quantitative estimates of climate change. An understanding of Earth's climate sensitivity requires knowledge of different magnitudes and rates of **feedbacks** in **Earth's climate system**, as well as Earth's complex behavior when one or more **tipping points** are crossed. Ocean sediments contain information about Earth's past climate sensitivity, providing unique data-based insights into how Earth may respond to elevated greenhouse gas concentrations similar to those projected in climate models that estimate future anthropogenic emissions pathways.

We know from scientific ocean drilling results that Earth's climate is substantially more sensitive to increased atmospheric CO_2 than simulated in most numerical models. For example, models cannot yet reproduce the warmer conditions during the Cretaceous and Eocene in the Arctic known from studies of ocean sediments. In addition, scientific ocean drilling documented that the climate's response to rapid warming following past ice ages was very large in comparison to the small and gradual energy changes initiated by shifts in Earth's orbit, showing that climate sensitivity may have varied over time.

To assess Earth's climate sensitivity, scientific ocean drilling will assemble paleoclimate records from globally distributed drill cores to identify what parts of the climate system are most susceptible to abrupt and irreversible change. The marine geologic record contains many relevant examples of perturbations to Earth's climate that arose from large and **rapid carbon and aerosol input** into the atmosphere and resulted in changes to surface temperatures, rainfall and drought patterns, ice sheet dynamics, and sea level.

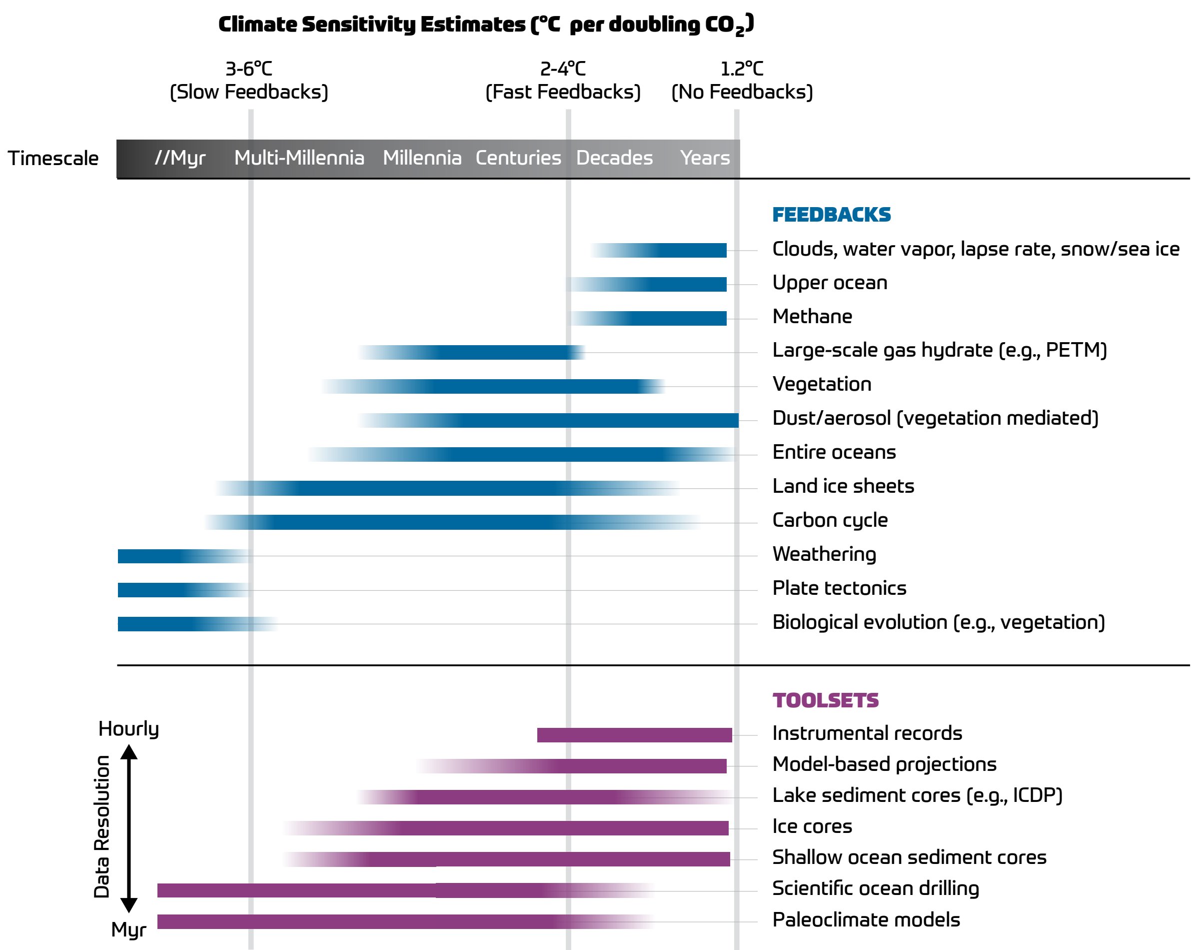
To better constrain the scales and rates at which key Earth system processes operate and to reduce climate sensitivity uncertainties in numerical models, the scientific ocean drilling community will collaborate with modelers and climate researchers to assimilate more **paleoclimate data** into models. Paleoclimate records also provide information about past variations in Earth's climate sensitivity that will help models better predict how sensitivity might vary in the future. Paleoclimate records can be used to identify what parts of the climate system have been most susceptible to abrupt and irreversible change. This information can be used to determine whether models fully resolve the wider consequences of crossing **tipping points**.



Scientific ocean drilling data remain instrumental in identifying the magnitude of polar amplification and model-data mismatches in IPCC assessment reports. Projected sea surface temperature (SST) anomalies, relative to pre-industrial values, from multi-model mean simulations (color maps; a) are compared to SST anomalies, relative to present site temperatures, determined from scientific ocean drilling paleoclimate proxy data (discrete data points, plotted using the same color scale as the model data, and a circle size scaled to estimates of confidence) for the mid-Pliocene warm period and Early Eocene Climatic Optimum. Model-data mismatches for these two past intervals help assess the reliability of the modeled 2081–2100 Representative Concentration Pathway (RCP) 8.5 (top row). The modeled zonally averaged SST anomalies (b) for each time interval reveal the degree of polar amplification (shaded band = 2 standard deviations). Model ensemble simulations are from the Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble using the RCP 8.5 for 2081–2100, and after Haywood et al. (2013), https://doi.org/10.5194/cp-9-191-2013, and Lunt et al. (2012), https://doi.org/10.5194/cp-8-1717-2012, for the Pliocene and Eocene, respectively. *Modified from Masson-Delmotte et al. (2013), Box 5.1, Figure 1*

DISTINGUISHING HUMAN INFLUENCE FROM NATURAL VARIABILITY

Comparing paleoclimate information collected through scientific ocean drilling with recent instrumental records of climate variability can help identify where anthropogenic inputs are most influencing **Earth's climate system**. Modern rates of increasing greenhouse gas concentrations are unprecedented in the last 800,000 years, but the amount of released carbon is not unprecedented in the deeper geologic past. For example, the Paleocene-Eocene Thermal Maximum 56 million years ago represents a similar magnitude of carbon release and can inform us about the rates and consequences of anthropogenic CO_2 increases on current carbon cycle feedbacks, ocean acidification, polar amplification, and global rising temperatures. For some other critical components of Earth's climate system, such as precipitation patterns associated with the El Niño-Southern Oscillation, it remains difficult to differentiate the role of natural multidecadal and longer climate cycles from changes in instrumental data sets that are attributed to anthropogenic activities. By capturing more repeat climate events, high-resolution marine sediment cores obtained through scientific ocean drilling can help define the magnitude and causes of natural variability in Earth's climate system over timescales of decades, centuries, and millennia. These marine archives will also provide information that is not available in land-based records and complement similar resolution paleoclimate data obtained from corals, ice cores, lake records, and speleothems, and they extend the current limit of ~800,000 years of climate history provided by ice cores.



Climate sensitivity is one of the most important quantitative estimates of climate change. Compared to most other toolsets, scientific ocean drilling allows us to investigate the influence of Earth system feedbacks on climate sensitivity over a wide range of timescales. PETM = Paleocene-Eocene Thermal Maximum. ICDP = International Continental Scientific Drilling Program. *Modified after Figure 1 in Rohling et al. (2012), https://doi.org/10.1038/nature11574*

SOLID EARTH INTERACTIONS AND IMPLICATIONS FOR MODELS

The **life cycle of oceanic crust** and the mantle processes that underpin it are key building blocks of climate models. For example, Earth's mantle viscosity and crustal heat flow impact local ice sheet retreat and regional rates of sea level rise. Major limitations in understanding the controls on such relationships also extend to the interpretation of instrumental data sets of modern change. Our poor understanding of how mantle viscosity influences post-glacial rebound rates limits our ability to use gravimetry or satellite altimetry data to accurately estimate the total modern-day ice sheet mass loss.

Scientific ocean drilling can advance understanding of mantle and crustal properties by probing deep Earth structures and materials and collecting measurements of geothermal heat flux. This information can improve spatial constraints on postglacial isostatic rebound rates. Sea level curves derived from scientific ocean drilling data can be used to evaluate and test assumptions about sea levels employed in whole Earth geophysical models. A priority will be identifying key solid Earth processes that influence Earth's surface geography and topography to improve model performance. Models can point the scientific ocean drilling community to regions with the greatest uncertainties, such as the Antarctica ice margins where sediments were deposited during past major climate shifts, and focus priorities toward capturing data that will elucidate mantle properties.

A priority will be identifying key solid Earth processes that influence Earth's surface geography and topography to improve model performance.

THE WAY FORWARD

Scientific ocean drilling will develop high-density networks in climatically sensitive areas to assess how multidecadal to centennial-scale natural climate states manifest themselves across the globe and whether polar to low-latitude teleconnections are appropriately represented in models. This endeavor will involve latitudinal (polar-to-equator) transects of drill sites, **land-to-sea** transects, and detailed grids in regions. Such data will permit better evaluation of the implications to society of increased climate variability and whether this variability is likely to become more energized or altered under a warmer-than-present, high CO_2 climate state.

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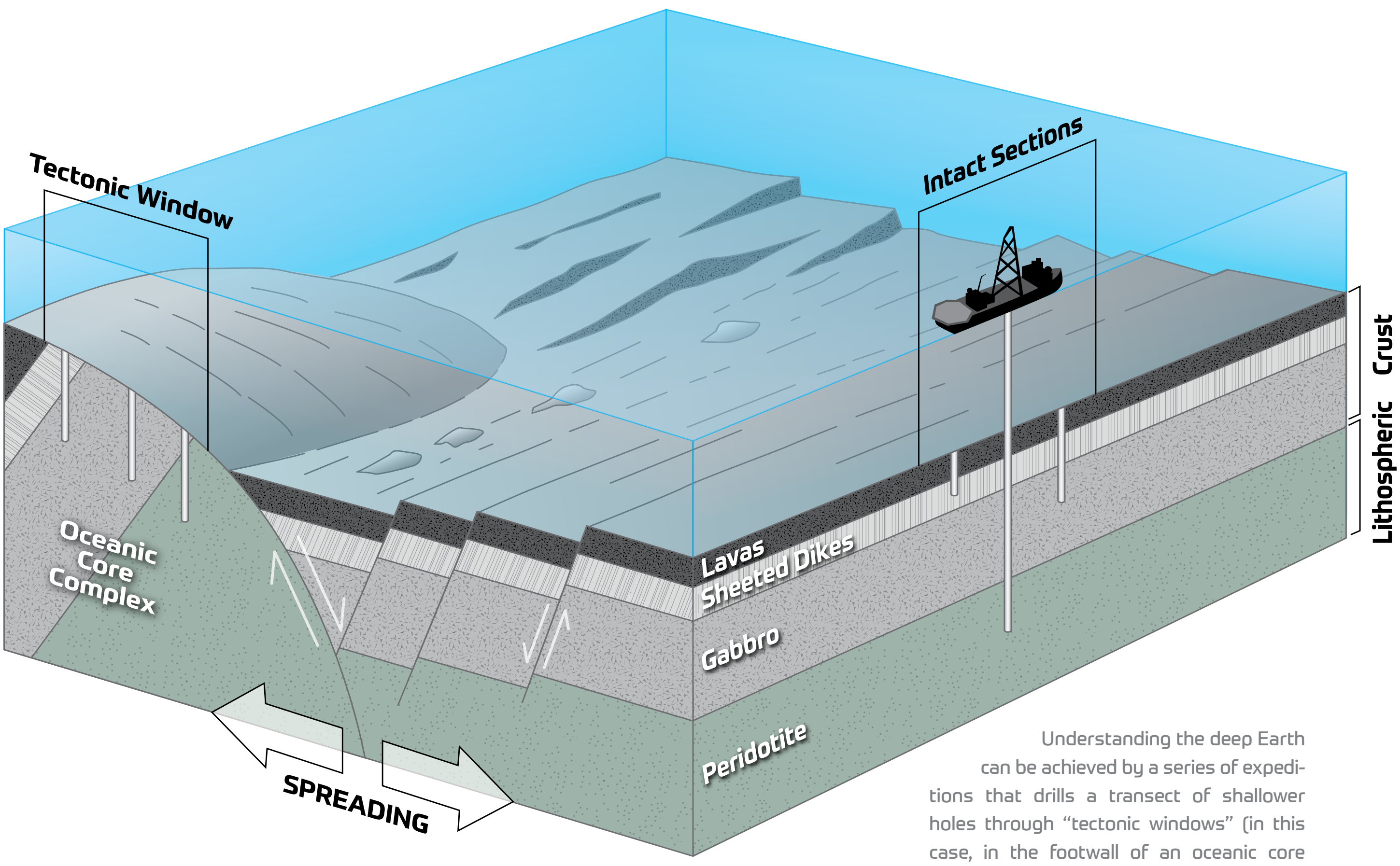
FLAGSHIP INITIATIVE 2

PROBING THE DEEP EARTH

SUMMARY

Scientific ocean drilling has long aspired to penetrate deep into Earth's oceanic crust and its underlying mantle. Achieving this objective is still pushing the limits of technology and thus remains elusive. New multidecadal scientific ocean drilling strategies seek to probe the deep Earth and to finally reach the upper mantle via a series of interconnected, ambitious expeditions that will take full advantage of emerging drilling, coring, logging, and monitoring technologies. This deep drilling will lead to a better understanding of Earth's formation and evolution; the nature of Earth's deep interior and its geodynamic behavior; the interrelationships between the deep Earth and geological, biogeochemical, and climate cycles; and the limits of life.



Understanding the deep Earth can be achieved by a series of expeditions that drills a transect of shallower holes through "tectonic windows" (in this case, in the footwall of an oceanic core complex) or penetrates the full, approximately 6–7 km thick, oceanic crust in one hole in normal magmatic crust. *Illustration by Antony Morris and Geo Prose*

PROBING EARTH'S INTERIOR WITH DEEP DRILLING

Probing the deep Earth remains a key exploration goal of scientific ocean drilling. Since the Mohorovičić seismic discontinuity ("Moho") was postulated in 1909, we still haven't confirmed that it forms the fundamental boundary between Earth's crust—oceanic or continental—and mantle, and if it varies globally. Through this *Flagship Initiative*, scientific ocean drilling will peel back the oceanic crustal layer to reveal the true nature of the Moho and the mantle beneath for the first time. Understanding the nature of this seismic boundary in Earth's overall structure is elemental, as the creation of new oceanic crust in response to mantle upwelling and convection makes Earth unique among our solar system's planets.

Deep drilling into oceanic crust and the underlying upper mantle will also contribute to the resolution of a range of other outstanding questions. How does the **oceanic life cycle of tectonic plates** control the sources, sinks, and pathways of heat and chemical transfer among the lithosphere, hydrosphere, and biosphere? How do seawater-derived fluids control the depth distribution of magma during crustal accretion? How does Earth's upper mantle permit microbial life to survive at extreme depths? Deep drilling allows us to investigate the interconnected magmatic, tectonic, hydrothermal, and microbial processes active in seafloor spreading and during the evolution of oceanic lithosphere that are responsible for the unique characteristics of more than 50% of Earth's solid surface.

Attempts to understand ocean crustal evolution through scientific ocean drilling have been hampered by the limited number of holes drilled, most of which have penetrated only the uppermost skin of the upper crust. Deeper crustal rocks have only been accessed where tectonism has brought them to shallow levels in dispersed, atypical locations scattered across the ocean basins or where they have been tectonically thrust onto continents. From these investigations, the nature of the Moho appears highly variable. It could be an igneous boundary between magmatic crustal rocks and mantle peridotites, an alteration front demarking the depth limit of fluid penetration and serpentinization, or something else. These distinct hypotheses imply different outcomes for the hydrological, chemical, and mechanical makeup and evolution of oceanic lithosphere and where and how earthquakes and volcanism may occur during its eventual subduction tens to hundreds of million years later.

To understand differences in the styles of ocean crust formation and maturation and the underlying large-scale mantle circulation patterns and evolution requires probing deep Earth sections globally through scientific ocean drilling. The Pacific represents a mature fast-spreading ocean basin surrounded by subduction zones along the Ring of Fire, whereas the Atlantic and Indian Oceans represent mature slower spreading ocean basins mainly bounded by passive margins. Understanding the role of these different plate tectonic environments in the formation of oceanic lithosphere requires planning for more than one total crustal penetration: one through fast spreading "normal" oceanic crust in the Pacific and a second one that completely penetrates slower spreading "normal'" oceanic crust in either the Atlantic or Indian Ocean. This deep drilling ideally will deliver two representative sections of oceanic crust that can be compared to shallower drilled sections in tectonic windows at slow and ultraslow spreading ridges that are formed with the lowest melt fluxes and may have atypical upper mantle rocks exposed at the seafloor.

Deep drilling allows us to investigate the interconnected magmatic, tectonic, hydrothermal, and microbial processes active in seafloor spreading and during the evolution of oceanic lithosphere that are responsible for the unique characteristics of more than 50% of Earth's solid surface.

EXPLAINING DIFFERENCES IN LOWER CRUSTAL ACCRETION

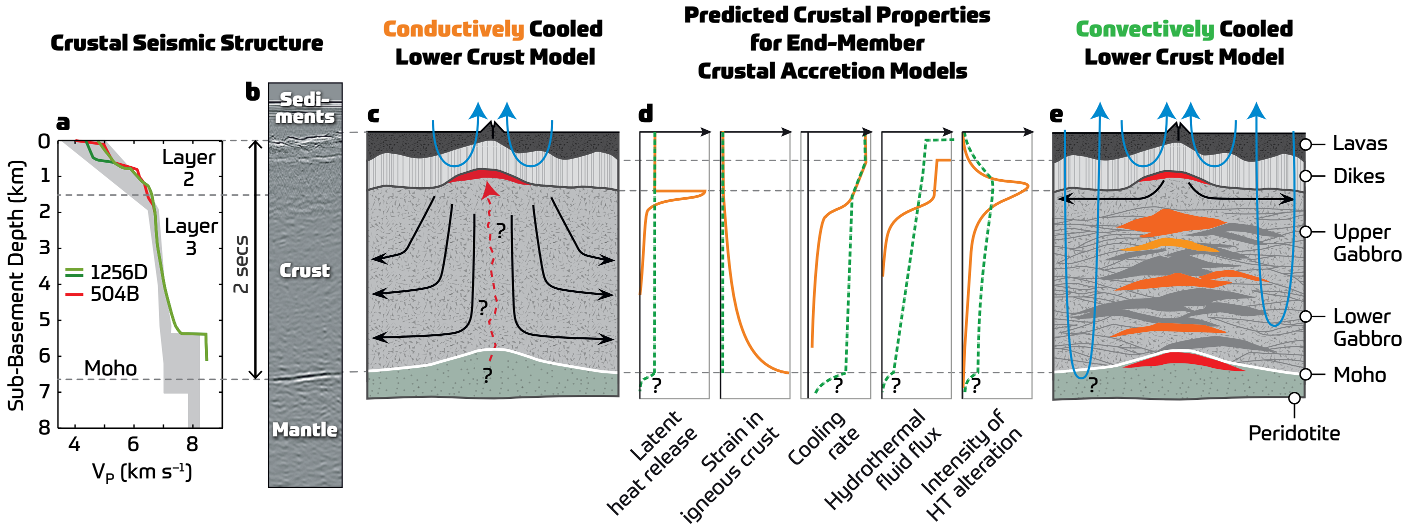
Our ability to understand oceanic crustal magmatism and composition is severely hampered by the limited availability of lower crustal rock samples. Seafloor accretion rates, which vary from 1 cm/yr to 20 cm/yr, are known to exert a first-order control on the structure and internal composition of crust formed during spreading. However, we do not know how differences in spreading rates result in variations in heat and chemical fluxes and in the extent of hydrothermal circulation and serpentinization. Lack of access to "normal" lower crustal rocks currently hinders our understanding of the nature of magmatism and how melt delivered from the mantle ultimately leads to construction of most of the crust. The roles magma chambers and magma transport play remain particularly controversial. The volume of all oceanic crustal rock samples retrieved by scientific ocean drilling to date amounts to about 20 cubic meters. Even when combined with fragments of ancient oceanic crust that escaped subduction and are preserved on land, and dredge and deep diving samples recovered from the seafloor, we have barely scratched the surface of the rich variety of oceanic crustal types.

To address the many fundamental questions related to lower crustal accretion, it is essential to first penetrate a complete crustal section through the crust-mantle boundary and into the shallow mantle at a fast-spreading center. Such centers account for creation of nearly 50% of the present-day oceanic crust while covering ~20% of Earth's surface. Those results will then be compared with the outcomes of targeted deep drilling in the slower spreading Atlantic or Indian and elsewhere in the ocean basins.

A high level of sampling is necessary to ground truth geophysical images to enable mapping of much greater volumes of crust formed at fast-spreading ridges. It will also enable us to test the depth **limits of life** in igneous oceanic crust. The long-term scope of the *2050 Science Framework* will allow us to exploit emerging deep drilling and logging technologies to achieve the first full penetration of oceanic crust through the Mohorovičić discontinuity and into the uppermost mantle.

DECIPHERING OCEANIC LITHOSPHERE BIOGEOCHEMICAL EXCHANGE

Our lack of knowledge about the **transfers of heat and mass** via hydrothermal exchange has left many questions unanswered. How deep does seawater penetrate into the oceanic crust and upper mantle? What crustal volume becomes hydrated? How do the heat and chemicals



Recovery of a complete crustal section via scientific ocean drilling will allow us to test two competing end-member crustal accretion models that were developed from seismic observations of the oceanic crust combined with geological and petrological evidence from the Oman ophiolite. In the gabbro glacier ductile flow model (c; for example, [1]) lower crustal cooling is predominantly conductive, whereas in the sheeted sill model (e) of on-axis intrusions[2], there is convective cooling of the lower crust. The two models predict profoundly different variations in a range of crustal properties (d) that can be determined from drill cores with depth, providing an opportunity to test these two models.

(a) Average seismic structure of fast/super-fast-spreading oceanic crust older than 7.5 million years. Gray shading: bounds of average "normal" crust older than 29 million years.[3] Green lines: Ocean Drilling Program (ODP) Site 1256.[4] Red line: Deep Sea Drilling Project (DSDP) Site 504.[5] (b) Example of a multichannel seismic reflection image showing a crustal column over a sharp, strong single Moho reflection.[6] Black arrows in (c) and (e) show the movement of the solid lower crust, and blue arrows show the dominant zones where hydrothermal circulation removes latent and sensible heat. The red arrow in (c) shows the tentative movement of magma. (d) Predicted differences in the relative variations of latent heat release, strain rate, cooling rate, hydrothermal fluid flux, and intensity of high temperature (HT) alteration with depth for the end-member gabbro glacier model (orange) and the sheeted sills model (green) provide an opportunity to test the accretion models using drill cores. *(a,b) Illustration by Benoit Ildefonse, (c,e) after Korenaga and Kelemen (1998), https://doi.org/10.1016/S0012-821X(98)00004-1. (d) Illustration by Rosalind Coggon. [1]Henstock et al. (1993), https://doi.org/10.1029/92JB02661; Quick and Denlinger (1993), https://doi.org/10.1029/93JB00698. [2]Kelemen et al. (1997), https://doi.org/10.1016/S0012-821X(96)00235-X. [3]After Christeson et al. (2019), https://doi.org/10.1029/2019RG000641. [4]Teagle et al. (2006), https://doi.org/10.2204/iodp.proc.309312.2006. [5]Swift et al. (2008), https://doi.org/10.1029/2008GC002188. [6]Modified from Nedimović et al. (2005), https://doi.org/10.1038/nature03944.*

delivered by fluid circulation support life? What mineral transformations are caused by the alteration of hot mantle rocks? Answering such broad questions requires multidisciplinary collaboration in the investigation of the coupling among hydrological, geochemical, thermal, mechanical, and biological processes and the relationship of these coupled processes to the architecture and physical nature of lithosphere below the ocean.

To establish the rates, distribution, and significance of fluid exchange within all seafloor components, from the overlying sediments to the igneous crust and upper mantle, requires knowledge of the temporal and spatial scales of seawater circulation and transport processes. Seawater circulation facilitates microbial growth beneath the seafloor and is critical to the transport and distribution of microorganisms. Yet, the size, activity, and connectivity of the crustal oceanic biosphere are unknown, as is its influence on global geochemical and biogeochemical cycles. To fully quantify the role that the **oceanic life cycle of tectonic plates** plays in global biogeochemical exchange and to determine the limits of **habitability and life on Earth**, scientific ocean drilling must penetrate the entire hydrothermally altered portion of the oceanic crust at a variety of locations to capture differing accretion styles and a range of crustal ages.

GLOBAL GEOCHEMICAL CYCLING

Although the fast-spreading Pacific constitutes about half of the extant oceanic crust, new crust formed by amagmatic spreading in the other ocean basins is far more reactive. The first reason amagmatic spreading is more reactive is that significant chemical reactions occur when mantle-derived melts and lower crustal rocks come into contact with seawater. The second reason is that slow-spreading environments contain large, tectonically exposed mantle outcrops, making hydrological exchange at slower spreading ridges more important than exchanges within new crust formed at fast-spreading mid-ocean ridges.

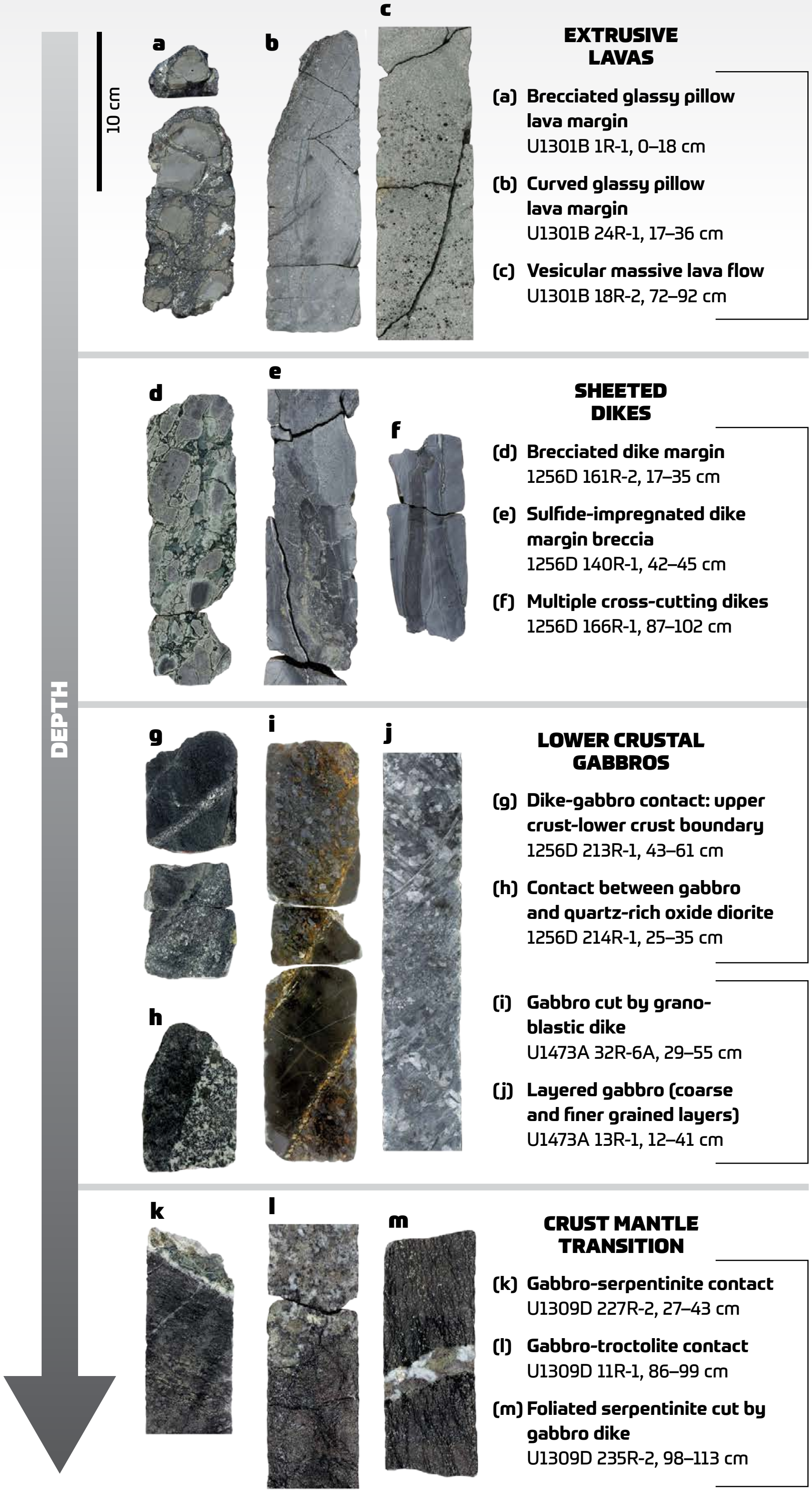
To understand the consequences for **global chemical cycles and budgets among large-scale reservoirs** in the mantle and oceanic and continental crust requires accurate determination of bulk crustal compositions. Currently, we cannot quantify the extent to which melt-rock interactions at mid-ocean spreading ridges are affecting estimates of the bulk composition of crust. In addition, our understanding of the bulk composition of oceanic crust is based on composite sampling profiles of rocks collected in dispersed shallow drill holes. These analyses include data from samples exposed to seafloor weathering and thus are of questionable quality. To make progress requires scientific ocean drilling to assemble inventories of the chemical compositions of representative ocean crustal sections. Such a database will allow us to quantify and remove the effects of alteration by late-stage magmatic fluids and those due to reaction with seawater. Importantly, a continuous ocean crustal section will include pristine samples of in situ residual mantle source rocks.

The long-term scope of the 2050 Science Framework *will allow us to exploit emerging deep drilling and logging technologies to achieve the first full penetration of oceanic crust through the Mohorovičić discontinuity and into the uppermost mantle.*

THE WAY FORWARD

To fulfill the ambition to drill through intact oceanic crust into the upper mantle requires innovative solutions to challenges that have thus far hampered progress. Recovery of pristine hard rock samples from different ocean crustal locations will provide fundamental insights into the nature of Earth's deep interior and its geodynamic behavior. It will also help constrain the exchange of heat, mass, and volatiles between Earth's interior and the crust, ocean, and atmosphere.

Achieving full penetration of the oceanic crust requires a coordinated and phased approach in parallel with significant advances in drilling technology to core igneous rocks at increased depths and temperatures. Solutions need to be found to overcome challenges of maintaining hole stability, increasing drill bit life, and drilling into rocks at elevated temperatures where cooler drilling fluids may cause thermal shattering of the borehole walls. New logging tools and geologic sensors need to be developed that can operate above 150°–200°C in crustal sections younger than 20 million years. These deep holes will also provide unique opportunities to install long-term observa-



a–c. Lavas (a–c) are from IODP Hole U1301B, which penetrates ~320 m into 3.5 million year old intact, in situ upper oceanic crust formed at an intermediate-rate spreading center (~6 cm/yr full rate) now overlain by ~265 m of sediment.[1]

d–h. The sheeted dike cores (d–f) are from ODP Hole 1256D, which penetrates ~1,270 m into 15 million year old intact, in situ oceanic crust formed at a super-fast spreading rate (>20 cm/yr full rate) at the East Pacific Rise, now overlain by ~250 m of sediment.[2]

Hole 1256D cored ~800 m of lavas and ~345 m of sheeted dikes, penetrating lower crustal gabbros at 1,157 m subbasement (g) and the uppermost 100 m of the dike-gabbro transition zone (h).

i–j. IODP Hole U1473A, located at the summit of Atlantis Bank, an 11–13 million year old elevated oceanic core complex on the slow-spreading (1.6 cm/yr full rate) Southwest Indian Ridge, penetrates ~809 m into uplifted, unsedimented massive gabbros cut by isolated dikes (i), with intervals of igneous layering within the gabbros defined by variations in grain size (j) or modal mineralogy.[3]

k–m. IODP Hole U1309D, located on the Atlantis Massif—a 0.5–2 million year old oceanic core complex on the slow-spreading (2.4 cm/yr full rate) Mid-Atlantic Ridge, penetrates into an uplifted and faulted lower crustal section, cut by diabase sills.[4] The U1309D crustal section comprises a stack of gabbroic bodies that surround pre-existing serpentinized peridotites and zones of olivine-rich troctolite formed by interaction with gabbroic melt (k–m).

Scientific ocean drilling has advanced our understanding of the structure and accretion of oceanic crust by recovering cores from different stratigraphic levels, allowing us to construct "composite stratigraphies" through the oceanic crust. However, this requires the compilation of results from crustal sections of differing age, produced at a range of spreading rates recovered from diverse tectonic settings. To further advance our understanding of crustal accretion we need longer continuous sections through the lower crust and into the underlying mantle. *[1]Fisher et al. (2005), https://doi.org/10.2204/iodp.proc.301.2005; [2]Teagle et al. (2006), https://doi.org/10.2204/iodp.proc.309312.2006; [3]MacLeod et al. (2017), https://doi.org/10.14379/iodp.proc.360.2017; [4]Blackman et al. (2006), https://doi.org/10.2204/iodp.proc.304305.2006* tories that will, for example, permit seismological monitoring of Earth's interior in a quiet environment isolated from on-land, anthropogenic noise.

Assessing global variability of the deep oceanic crust will require a suite of complementary drilling strategies. Sections of the lower crust must be recovered from a range of spreading regimes. Options include multi-kilometer-deep sites, networks of sites drilled to 0.2–1.0 km depth that sample different crustal depths exposed by faulting, and an extended array of ~100 m deep holes to document scales of lateral variability. Only through such an integrated approach and ceaseless scientific ocean drilling efforts continuing through 2050 can we reveal the fundamental nature of Earth's crust and uppermost mantle, whose dynamics have shaped this planet.

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FLAGSHIP INITIATIVE 3

ASSESSING EARTHQUAKE AND TSUNAMI HAZARDS

SUMMARY

Undersea earthquakes and associated tsunamis have been responsible for some of our planet's deadliest and costliest natural disasters over the past 20 years. The 2011 magnitude (M_w) 9.0 Tōhoku-oki earthquake and tsunami in northern Japan took over 15,000 lives, with economic losses estimated at US$235 billion, making it the most expensive natural disaster in history. The 2004 M_w 9.2 Sumatra-Andaman earthquake and tsunami in the Indian Ocean killed over 230,000 people in 15 countries and caused losses of ~US$15 billion. Undersea landslides and gravity flows can endanger coastal and offshore infrastructure and telecommunications, as happened in the pair of M_w ~7 Taiwan 2006 earthquakes that severed 22 seafloor cables. The potential earthquake, tsunami, and landslide hazards of many of the world's subduction zones are poorly known, as many of the large events have no historic record due to their long recurrence intervals. Scientific ocean drilling will significantly advance the study of the plate interface where mega-earthquakes nucleate, as it can directly access, sample, instrument, and monitor these dangerous offshore and nearshore fault zones. Advancing our understanding of the earthquake and tsunami potential of tectonic plate boundaries worldwide will enable more reliable forecasts of the risks posed to vulnerable populations and infrastructure and improve hazard preparedness and response.

By providing access to major subseafloor fault zones, scientific ocean drilling advances understanding of the earthquake and tsunami potential of tectonic plate boundaries. (left) Damage from the 2010 M_w 8.8 earthquake in Chile. *Photo credit: Simon Haberle, Australian National University.* (below) Tsunami devastation in Japan after the 2011 M_w 9.0 Tōhoku-oki earthquake. *Photo credit: istock.com/enase.*

TAKING THE PULSE OF THE EARTHQUAKE CYCLE

A complete understanding of the processes leading to the occurrence of large earthquakes requires high-resolution, continuous measurements of changes in Earth's crust for many decades, over different stages of the earthquake cycle. These measurements need to be collected at different locations globally. In the last five years, subseafloor observatories installed around Japan, New Zealand, and Costa Rica during scientific ocean drilling expeditions have been monitoring variations in crustal strain, geochemical and hydrological properties, and temperature at high temporal resolution, with detection limits comparable to the highest sensitivity instruments on land. These observatories are starting to fill major data gaps required to understand the physical controls on earthquake dynamics. They are also permitting investigation of the behavior of offshore earthquakes and other types of fault slip, potentially leading to identification of recognizable precursors to large, damaging **earthquakes and tsunamis**.

The discovery 20 years ago that slow-motion earthquakes—aseismic slip events lasting minutes to years—occur on many of Earth's major tectonic faults sparked a revolution in seismology and fault mechanics. Episodic slow-slip events play an integral role in subduction megathrust dynamics by slowly releasing stored energy. They have also been implicated in the triggering of subduction earthquakes in 2011 at the northern Japan Trench (M_w 9.0 Tōhoku-oki) and in 2014 near Iquique, Chile (M_w 8.2). An improved understanding of the relationship between slow slip events and large earthquakes will lead to better earthquake forecasting, but it requires near-field monitoring in the submarine source areas of large earthquakes and slow-slip events at subduction zones.

Scientific ocean drilling can provide a sustained subseafloor observational presence through installation of networks of **borehole observatories** in numerous fault zones around the globe. These observatories will collect a full array of spatiotemporal data throughout the earthquake cycle. Although such observatories have already been installed by scientific ocean drilling in a few subduction zones, more are needed to span a range of properties and behaviors, with sufficient spatial density in each locale to resolve the processes operating within the fault zones. Where logistically and economically feasible, co-location of subseafloor observatories with seafloor monitoring networks will maximize spatial coverage, enable integration of borehole monitoring data with other observables, and enable earthquake monitoring in real time.

Future scientific ocean drilling should also facilitate rapid response and monitoring efforts following major earthquakes, similar to the effort mounted following the 2011 M_w 9.0 Tōhoku-oki earthquake. Characterization and monitoring before and after major events are important for building a complete picture of the mechanics of fault slip behavior and variations throughout the earthquake cycle.

Scientific ocean drilling can provide a sustained subseafloor observational presence through installation of networks of borehole observatories in numerous fault zones around the globe.

ACCOUNTING FOR PAST EARTHQUAKES AND TSUNAMIS

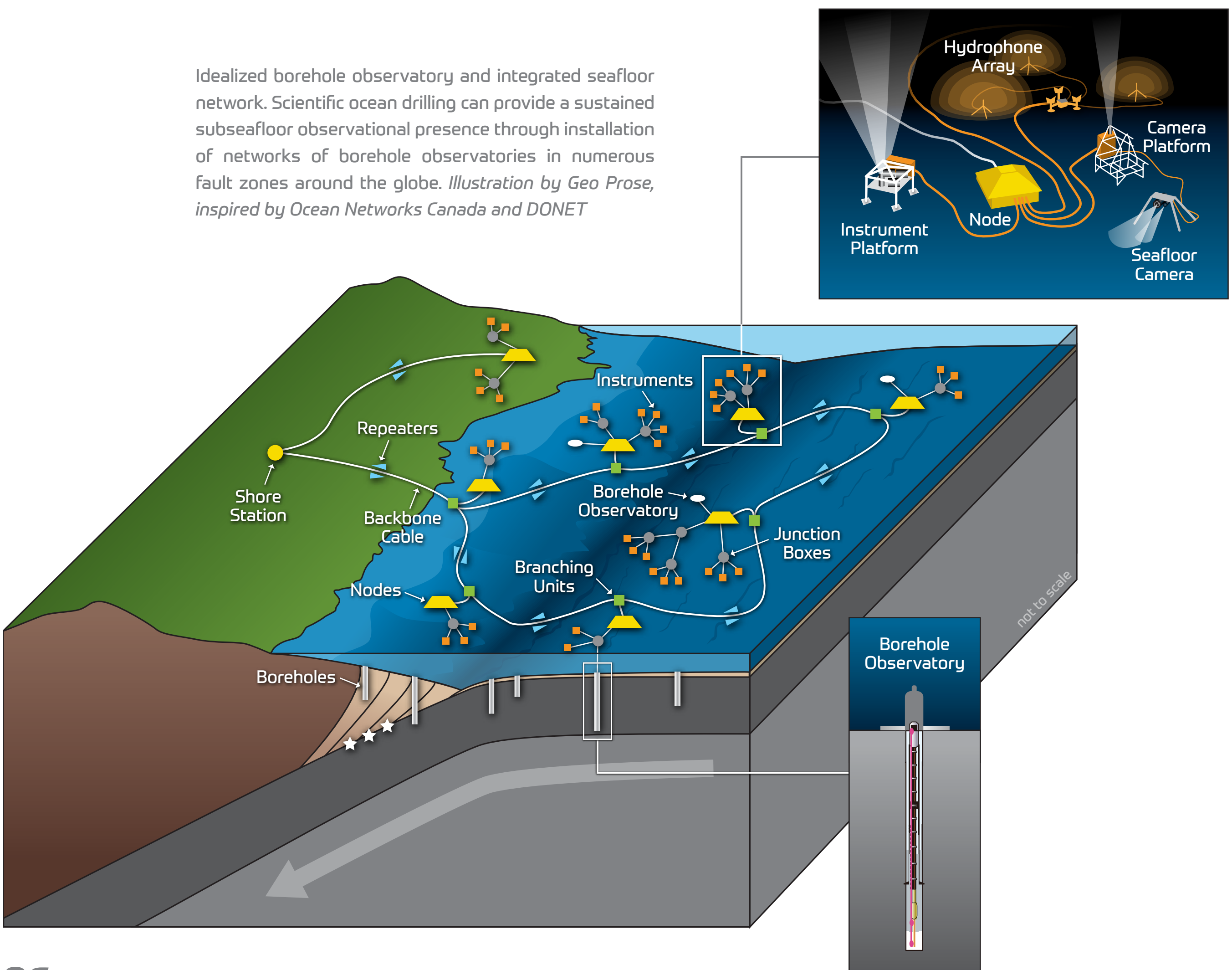
Sediments deposited in earthquake- and tsunami-prone regions contain information about the frequency of past large events. This information can be useful for assessing the likelihood of earthquakes and tsunamis occurring at those locations in the future. For example, ground shaking from major earthquakes can mobilize sediment-laden flows beneath the ocean that transport and redeposit the sediment into slope basins and trenches. Ground shaking can also trigger major, coherent submarine landslides. Such gravity flow deposits, in combination with onshore evidence for prehistoric earthquakes and tsunamis, have been used in places such as the Cascadia subduction zone and the Japan Trench to assess the spatial and temporal distribution of earthquakes associated with subduction plate boundary megathrust faults. Although many of these studies have used shallow piston cores that do not require drilling, scientific ocean drilling can provide complementary, longer prehistoric earthquake records, particularly in regions with high sedimentation rates such as the Alaskan margin and other continental shelf areas where shallow coring cannot adequately sample these critical records of past events.

Exciting new approaches have been developed for recognizing past earthquake slip on subseafloor faults. These techniques include quantifying the heating within a fault zone during seismic slip by probing the geochemical characteristics of rocks recovered through scientific ocean drilling and investigating the thermal maturity of organic material within them through laboratory experimentation. Various novel thermal proxies are being developed to estimate the amount of past frictional heating on faults. Estimates of temperature increases experienced by these fault rocks, particularly those in the near surface, can constrain the maximum displacement and seaward extent of past earthquakes in these fault systems. These parameters ultimately affect the earthquake magnitude and resulting tsunami extent and allow quantification of the frictional work accomplished during earthquake rupture. These and other approaches offer a tantalizing means to use scientific ocean drilling to improve records of past earthquake occurrence and assess the potential for near-surface rupture and tsunami generation.

WHAT FACTORS LEAD TO MASSIVE SUBDUCTION EARTHQUAKES?

The massive earthquakes in 2011 in Japan and in 2004 in the eastern Indian Ocean highlight our lack of understanding of the factors that promote and amplify seismic slip at subduction zones. In both cases, slip was larger and/or extended farther seaward toward the trench than expected. Scientific ocean drilling has already played an important role in revealing some of the physical properties of the subduction faults that led to the earthquakes and tsunamis in these two regions. To make significant headway in understanding the slip potential of major subduction zone faults globally requires collecting a broad range of observations from diverse environments at different stages in the earthquake cycle.

To understand how and why earthquakes occur requires knowledge about how fault zone lithology, chemical environment, and physical conditions such as temperature and



Idealized borehole observatory and integrated seafloor network. Scientific ocean drilling can provide a sustained subseafloor observational presence through installation of networks of borehole observatories in numerous fault zones around the globe. *Illustration by Geo Prose, inspired by Ocean Networks Canada and DONET* effective stress control the sliding stability and slip behavior of faults. Cores and in situ physical and chemical measurements collected within active fault zones, along with recovery of sedimentary sequences and **oceanic crust** from regions before they enter the subduction zone, can provide that needed information. To date, such investigations have been undertaken in only a few locations globally and most have targeted the earthquake-generating segments of subduction zones. Even there, only relatively shallow depths have been sampled and with limited spatial coverage. It is equally important to collect similar data on subduction zone faults that appear to creep without large earthquakes to resolve which properties cause some fault zones to lock up between large earthquakes while others creep without generating significant earthquakes, or why some may slip both slowly (aseismically) and rapidly (seismically) along the same part of a fault zone over time. Scientific ocean drilling will advance understanding of the key factors that generate large earthquakes and tsunamis, as it provides the only way to directly access, sample, and instrument major offshore fault zones.

The factors that produce sudden, large seafloor displacements that can generate tsunamis remain poorly understood. In particular, a class of earthquakes known as "tsunami earthquakes" generates much larger tsunamis than expected given the earthquake's magnitude. These events are a challenge for tsunami warning, as they do not generate strong shaking—typically the indicator that prompts evacuation from the coast and low-lying regions. The earthquake and landslide processes that cause large seafloor displacements and therefore tsunamis of all types remain poorly understood. Targeted scientific ocean drilling to reveal the physical conditions that promote tsunami generation in different tectonic or structural environments is needed to identify the sources of potential hazards.

THE WAY FORWARD

The underlying physical processes governing the spectrum of observed fault slip behaviors at subduction zones can only be addressed with an integrated, system-level approach that combines evidence of past and present fault behaviors, ground truth data on the physical conditions and materials within plate boundaries, and data collected by robust, high-precision, subseafloor instruments that continuously monitor the fault zones. This multifaceted approach requires a sustained scientific ocean drilling effort in a representative range of the world's subduction environments. Because many of the faults that produce devastating earthquakes and tsunamis, or faults' slip effects, reach across the coastlines, there are numerous opportunities to integrate observations from scientific ocean drilling with those from onshore geophysical networks, surface geology, and **continental drilling**. Such an effort will contribute important information about how some of the world's largest and most active undersea faults work and ultimately will improve hazard preparedness and response.

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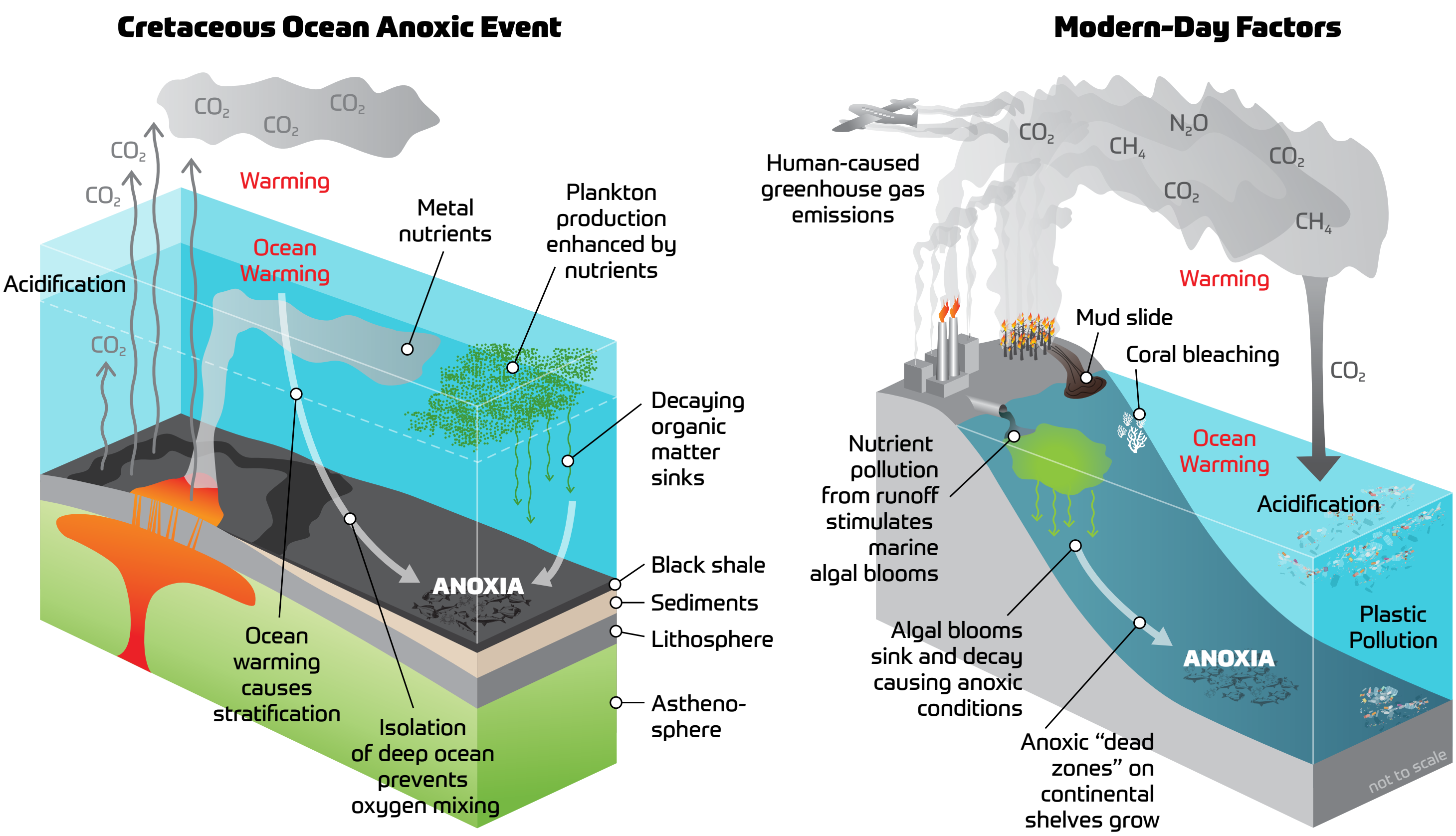
FLAGSHIP INITIATIVE 4

DIAGNOSING OCEAN HEALTH

SUMMARY

Ocean warming, acidification, deoxygenation, and rising and falling nutrient levels are causing global changes in marine ecosystems. Declining ocean health can lead to devastating losses in biodiversity, habitats, productivity, and fisheries, putting life at risk. Similarly, in the pre-Anthropocene epochs, periods of rapid global warming and cooling, ocean anoxic and acidification events, as well as meteorite impacts and episodes of flood basalt volcanism perturbed ocean ecosystems. Scientific ocean drilling will target these critical times in Earth history to assess the impacts of catastrophic environmental changes on marine ecosystems and food webs and the overall planetary carbon footprint. By drilling sites globally and using new analytical techniques and big data approaches, the high-resolution multidisciplinary data collected through scientific ocean drilling will offer a diagnosis of ocean health through geologic time that will in turn inform society about the expected rates, durations, and magnitudes of future ocean health deterioration.



Scientific ocean drilling retrieves marine sediment records that preserve key information on changes in ocean health through geologic time. Knowledge of how the ocean biosphere responded to major environmental perturbations in the past—for example as a result of volcanic perturbations to the carbon cycle during the Cretaceous (left)—will provide insights on the future of ocean health through the Anthropocene (right). *Illustration by Rosalind Coggon and Geo Prose*

OCEAN HEALTH THROUGH GEOLOGIC TIME

Scientific ocean drilling retrieves sediments that preserve key information on the interactions among **life on Earth**, ocean health, and **Earth's climate system**. These deep-time archives record the responses of biological activity in the ocean to natural cycles and occasional catastrophic perturbations over geologic time. Of particular interest is how shifts in **biogeochemical cycles** affected the recovery of life following mass extinctions and rapid climate change. Scientific ocean drilling will document the state of the pre-Anthropocene ocean. By comparing this baseline information to data from the modern ocean, we will gain important insights into how the ocean biosphere responds to greenhouse gas emissions, nutrient levels, and weathering, and what the possible consequences might be if humankind continues to over-exploit marine organisms.

OCEAN ACIDIFICATION AND WARMING

Current CO_2 emissions are altering the radiative heating of our planet, dialing up its thermostat. They are also lowering the ocean's pH toward levels that Earth has not encountered for tens of millions of years. Globally distributed deep-sea sedimentary records acquired through scientific ocean drilling will reveal how increased rates of change in ocean temperature and acidification affect marine ecosystems and will illuminate the mechanisms and timeframes of adaptation and recovery.

Increasing seawater acidity reduces biomineralization of pelagic and benthic calcifiers in the ocean, affecting their physiology. Many of these organisms play key roles in marine food webs as primary producers or as prey for larger animals, directly affecting the global carbon cycle. Rising seawater temperatures—even by a modest 0.5°C to 1.0°C over the last century—are making coral **microbial communities** (including bacteria, archaea, protists, fungi, and viruses) vulnerable to disease (bacterial or viral infection) and algal competition. These circumstances are increasingly causing coral bleaching events. By applying novel genomic methods, biomarkers, and pH and iso-

Ocean Acidification's Ability to Transform Ecosystems

Anthropogenic CO_2 emissions not only cause greenhouse warming, they also acidify the ocean. The ecological effects of acidification are many. In the coastal ocean, they include reduced biomineralization, carbonate dissolution of reef deposits and shelled organisms, and changes in the competitive balance of survival between microalgae and corals. In the open ocean, acidification affects fish physiology and the biomineralization of calcareous phytoplankton and pteropods, an important prey group for fisheries.

Scientific ocean drilling will collect pre-Anthropocene sediments to allow comparison of the rates of prehistoric ecosystem change with the rates of change today. Marine sediment archives can reveal how long episodes of acidification lasted and can be used to calibrate biogeochemical and ecosystem models to understand the feedbacks present in Earth's modern carbon cycle. By studying the numerous global warming events of the Cretaceous and Paleogene (from 145 to 23 million years ago), we will be able to gauge the impact of past acidification on ecosystem structure and productivity. Understanding how past ocean acidification transformed communities of carbonate-shelled organisms, including corals, and how fast they recovered, will inform scenarios of future ocean health and habitability.

Pteropods, tiny snails with aragonitic shells, thrive in shallow waters and play an important role in polar ecosystems. These photos show the time sequence of shell dissolution of the Antarctic pteropod *Limacina helicina* in waters simulating the saturation state of surface seawater with respect to aragonite that is projected for the Southern Ocean (Orr et al., 2005, https://doi.org/10.1038/nature04095) by 2100 under the IS92a business-as-usual CO_2 emissions scenario. These experimental results indicate that pteropods may cease to exist in polar latitudes by the middle of the twenty-first century, with potential major repercussions to organisms up the food chain. *Source: The photos were taken in the laboratory of Victoria Fabry from March 31, 2007, to May 15, 2007. Photo credit: David Liittschwager, National Geographic Stock* topic sea surface temperature proxies to ancient coral reef deposits obtained through scientific ocean drilling, we can establish a highly relevant geologic baseline for the state of health of today's coral ecosystems and the global ocean.

DECLINING OCEAN OXYGEN LEVELS

Modern observations reveal that oxygen availability has been declining in the global ocean over the past 50 years. Earth system models suggest that future deoxygenation may expand the world's oxygen minimum zones by 60% over the next 80 years in response to anthropogenic warming, with implied large impacts to all global marine ecosystems. The situation is particularly acute where nutrient-rich runoff fuels algal blooms and leads to the formation of "dead zones" where decomposition during die-off consumes most oxygen. Current models lack reliable data such as reproducible ocean oxygen records, or they underestimate the current decline in oxygen concentrations and fluxes between the ocean and atmosphere. Oxygen minimum zones such as those in the eastern tropical Pacific and northern Indian Ocean have changed over time due to numerous interconnected chemical, biological, and climatic processes acting on global scales. Scientific ocean drilling will fill critical gaps in our understanding of the mechanisms and history of oxygen fluctuations throughout Earth's ocean. To tease out various levels of ocean deoxygenation from the sedimentary record requires continued efforts to develop and calibrate reliable biotic and geochemical biomarker proxies.

At times in Earth's geologic past, oxygen became limited in the ocean at significant depths and over large paleogeographical areas. Many of these global ocean anoxic events are due to increased primary productivity in the surface ocean related to emplacement of large igneous provinces. Nutrient-rich runoff from rapidly weathering rocks and freshwater stratification in smaller basins such as the Mediterranean Sea, Sea of Japan, and Black Sea have led to the deposition of sapropels—layers of organic-rich sediment that formed under hypoxic conditions. These organic-matter-rich layers can span periods ranging from a few thousand years to more than 400,000 years. The abundance of oxygen-depletion events in the geologic record permits examination of the triggers and **tipping points** of anoxic events and their global scope and biological impacts. Knowledge of the ecological consequences of anoxic zone expansions, for example, during the Cretaceous, can be used to better predict the impact to ecosystems of declining oxygen levels in the modern ocean. By obtaining infor-

(below) Using proxies for pH and sea surface temperature, records of marine biodiversity, and cores from ancient coral reef deposits, scientific ocean drilling will provide insights into the global changes that can devastate coral ecosystems, as illustrated by these images of a coral reef in American Somoa—before (left) and after (right) a bleaching event. *Credit: XL Catlin Seaview Survey*

mation about the key controls on past ocean oxygen and nutrient levels, scientific ocean drilling can help to establish how future climate change and excessive nutrient inputs may affect oxygen availability in the ocean and the magnitude and extent of the resulting ecological responses.

NUTRIENT AVAILABILITY IN THE OCEAN

Humankind is altering nutrient availability in the ocean. Agricultural runoff and aerosol deposition of excess nitrogen and phosphorus modify the ocean's nutrient levels, enhancing ocean primary productivity. Anthropogenic CO_2 emissions are causing the planet to warm, leading to surface ocean warming and increased upper ocean stratification. In mid-latitudes, increased thermal stratification—which serves as a barrier between nutrient-depleted surface waters and nutrient-rich subsurface waters—is widely predicted to decrease the productivity of food webs in the open ocean, particularly in the ocean gyres. Reduction in polar sea ice is projected to increase nutrient availability in the upper ocean in these regions through increased upwelling and mixing and, combined with increased light levels, will increase phytoplankton biomass, resulting in ecosystem-wide changes.

Scientific ocean drilling is well suited to explore the response of Earth's ocean ecosystems to past changes in ocean nutrient levels. There are numerous examples from sediment record of dramatic changes in ocean nutrient supplies, whether from enhanced weathering on land due to increased intensity of the hydrological cycle, changes in intensity of coastal upwelling systems, increased thermal stratification, changes to organic matter cycling, or changes at the poles from ice-covered to ice-free environments. Scientific ocean drilling will obtain cores globally from an array of past environments that exhibit significant changes in nutrients levels to investigate how those changes affected ocean ecosystems. This information can be used to assess the potential rates, magnitudes, and global distribution of the anticipated future decline in ocean health due to human inputs.

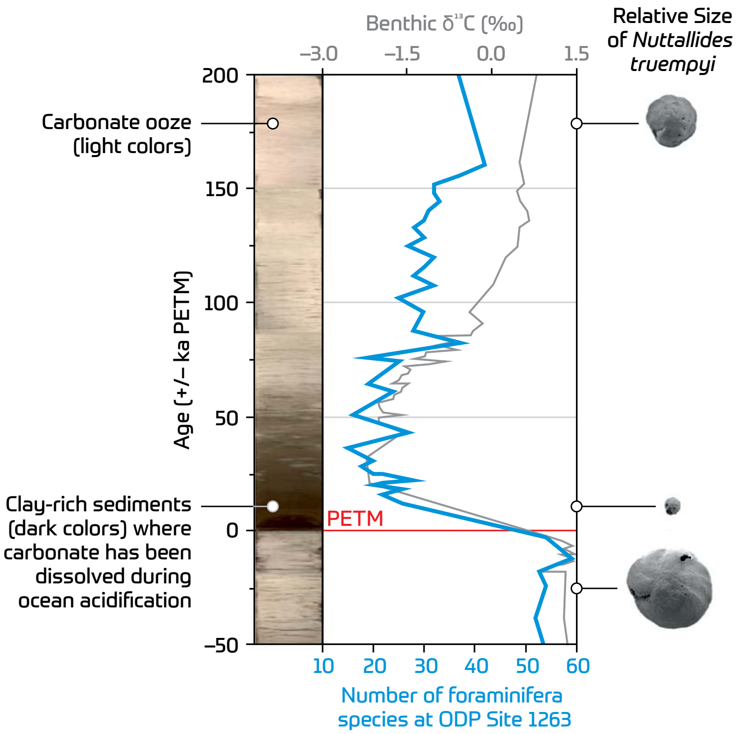
ECOSYSTEM DYNAMICS IN A GREENHOUSE WORLD

Global warming is severely disrupting marine and terrestrial habitats, threatening even the most remote ecosystems. In the tropics, increased stress on coral reefs caused by changes in temperature, light, or nutrients is causing many of them to bleach, while at the cold extreme, the loss of Arctic sea ice is transforming fisheries. Understanding changes in ecosystem functioning in the geologic past provides insight into how impaired, transformed, and potentially new ecosystems will respond to future warming. There are numerous opportunities for scientific ocean drilling to **explore the biodiversity and ecosystem dynamics** of viruses to microbial life and phytoplankton to micro- and macro-fauna, as well as land plants (through evidence of forests to grasslands delivered by wind and rivers to the nearby seafloor). Scientific ocean drilling will expand its high-resolution sediment archives to permit increased understanding of the future health, abundance, functioning, and resilience of marine ecosystems on a warmer and ice-free planet.

Globally distributed deep-sea sedimentary records acquired through scientific ocean drilling will reveal how increased rates of change in ocean temperature and acidification affect marine ecosystems and will illuminate the mechanisms and timeframes of adaptation and recovery.

THE WAY FORWARD

To better understand how human inputs to the ocean might impact ocean health, and the timescales of recovery from major perturbations, scientific ocean drilling will explore times in the geologic past that were punctuated by significant changes in ocean conditions. Drilling campaigns could examine cyclic anoxia/euxinia in the Mediterranean Sea and Southern Ocean, the oxygen minimum zone of the northern Indian Ocean, or widespread ocean acidification during the Paleocene–Eocene Thermal Maximum. Scientific ocean drilling will enable a more accurate global assessment of ocean health through time by collecting cores from globally distributed sites that span the ocean basins and the **transition from land to sea**. The fossil record in the cores chronicle the evolution of ocean properties, including temperature, oxygen concentration, pH, and nutrients, and provide information on biodiversity and biological productivity. Multidisciplinary approaches, state-of-the art analytical techniques, novel paleogenomic



Determining Future Biodiversity Shifts

The Paleocene-Eocene Thermal Maximum (PETM) and the Early Eocene Climatic Optimum (EECO) are excellent intervals to use in investigations of marine biodiversity and ocean health during past "greenhouse" climate states. Scientific ocean drilling cores are replete with fossilized skeletal and molecular remains of past life, whose chemistry, biology, and diversity reveal the health and resilience of ancient ecosystems and food webs. Future scientific ocean drilling could target bleaching episodes, for example, during a relatively brief interval of the PETM, when planktonic foraminifera discarded their algal symbionts in a process similar to what happens in corals exposed to higher temperatures. On longer timescales, larger benthic foraminifera and calcareous algae out-competed corals during the PETM and EECO, replacing coral-algal reefs with foraminifer-algal banks on a worldwide basis for more than 10 million years. These foraminifer-algal banks dominated coastal ecosystems throughout the tropics and can be found on atolls and guyots in the central Pacific. Deep-time reef records targeted by scientific ocean drilling can show us how long-lasting global warming can flip ecosystems such as coral reefs to an alternate state for millions of years.

The PETM (55.8 million years ago) provides an analogue for exceptionally high rates of ocean acidification and carbonate dissolution in the ocean of a high-CO_2 world. Scientific ocean drilling cores from Ocean Drilling Program (ODP) Site 1263 (Walvis Ridge) reveal a rapid and enormous loss of species of shell-forming foraminifera (blue line) occurs during ocean acidification, coeval with a carbon isotope ($\delta^{13}C$) excursion in shells of deep-sea benthic foraminifera. Surviving species, such as the depicted *Nuttallides truempyi* (all specimens to scale), show a severe reduction of test size. Species diversity eventually recovers, although at a much slower pace over tens of thousands of years. *From Thomas (2012), https://doi.org/10.22498/pages.20.1.37*

tools, and integrated data sets will allow us to diagnose past ocean health at centennial and millennial timescales. All the evolutionary and paleoenvironmental data collected from physically archived marine sediment cores will feed into publicly accessible databases for Earth system modeling and **big data exploration and interpretation**. Integrated data sets allow identification of teleconnections, feedbacks, and tipping points in ocean health, and allow us to put the rates and scales of current changes in context.

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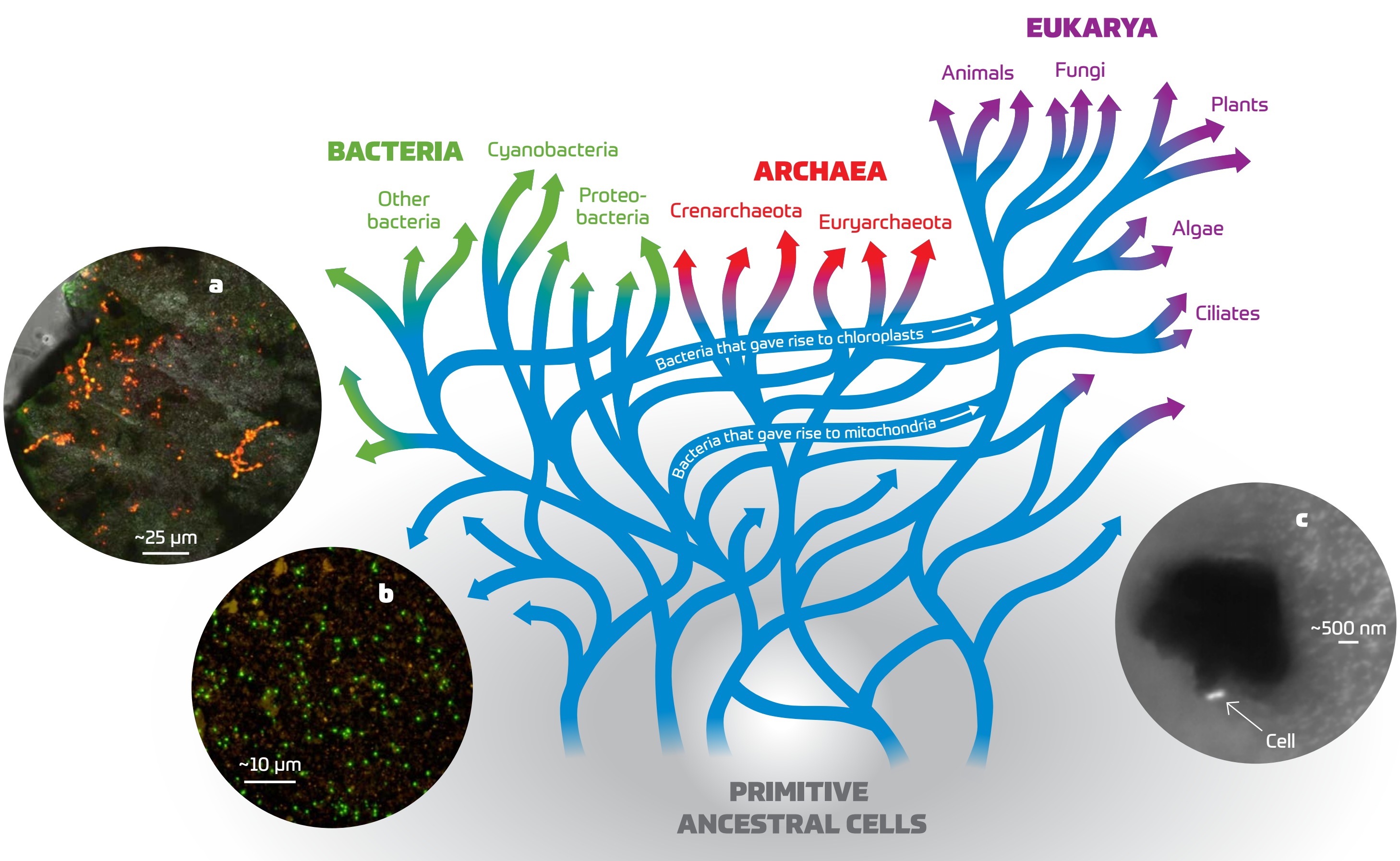
EXPLORING LIFE AND ITS ORIGIN

SUMMARY

Marine sediments and oceanic crust host a complex, active, globe-spanning ecosystem in which microorganisms live, interact, evolve, and die. The features and strategies that enable deep life to persist in these geologic habitats, what communities form under these extremely energy-limited conditions, and what geochemical and biochemical processes create their novel biosignatures remain largely unknown. To sample, monitor, and analyze a representative range of Earth's diverse subseafloor environments and the multitude of microbial communities that they inhabit in Earth's interior requires scientific ocean drilling. A sustained drilling effort will significantly advance understanding of the rules of life, the limits of life, and the origins and evolution of life on Earth. It also offers the opportunity to establish what life might look like in analogous environments on other worlds and what new organisms and novel biological functions useful in geobiotechnology reside in Earth's subseafloor.



The tree of life, based on analysis of DNA sequences from organisms across all three domains of life: Bacteria, Archaea, and Eukarya. Scientific ocean drilling allows researchers to access environments below the seafloor that resemble early Earth and/or are analogues to environments found elsewhere in the solar system (after illustration by Jayne Doucette in Teske and Edwards, 2005). By analyzing microbial communities in these environments, we can better predict what primitive ancestral cells may have looked like as well as clarify what types of lifestyles likely exist on extraterrestrial bodies. (a) Microbial colonization (orange dots) of mineral incubation experiments in subseafloor oceanic crust on the Juan de Fuca Ridge flank (Orcutt et al., 2011, https://doi.org/10.1038/ismej.2010.157). (b) A microscopic view of microbial life in a subseafloor sediment core sample obtained by drilling vessel *Chikyu* off Shimokita Peninsula, Japan. Green particles represent microbial cells (Morono et al., 2009, https://doi.org/10.1038/ismej.2009.1). *Photo credit: JAMSTEC.* (c) A microscopic image of a microbial cell (white) on a 2 km deep, 20-million-year-old coal particle (black) obtained by *Chikyu* during IODP Expedition 337 (Site C0020; Inagaki et al., 2015, https://doi.org/10.1126/science.aaa6882; Trembath-Reichert et al., 2017, https://doi.org/10.1073/pnas.1707525114). *Photo courtesy of Elizabeth Trembath-Reichert, Caltech*

DEFINING THE RULES OF MICROBIAL LIFE

The communities that live inside rocks, in the pore spaces between sediment grains, in fault zones, and in hydrothermal vents are different from those we are more familiar with in other, more accessible environments. These ecosystems remain essentially untouched by human activities. Results from previous scientific ocean drilling studies indicate that microbes living in subseafloor sediment have severely limited access to energy; on average, they respire and turn over their biomass hundreds to thousands of times more slowly than microbes in the surface world. The rules that predict an organism's behavior and structure at such slow rates of activities are essentially unknown. The rates of cell division and evolution in subseafloor populations as well as the extent and nature of communication within its communities are virtually a blank slate. We also know practically nothing about the adaptations that enable organisms to persist in subseafloor environments, far from the abundant energy at Earth's surface in the photosynthetic world.

By studying the life that inhabits extreme subseafloor environments, we will gain insight into the potential adaptations of primordial life, the constraints under which it evolved, and hence the origin of life on Earth.

Marine sediments and the underlying crustal rocks comprise fundamentally different environments. The microbes that inhabit the variable substrates in these different environments probably also differ. Marine sediments comprise a porous, but relatively impermeable, environment where diffusion usually dominates dissolved chemical transport, and opportunities for organismal mobility are limited. In this environment, we hypothesize that organismal lineages are introduced early in sediment deposition and then are subjected to burial for many millions of years. In contrast, the **upper basaltic oceanic crust** is a fracture-permeable but generally relatively low porosity environment, where fluid advection is probably the dominant process. There, organisms may be continually introduced by inflow of seawater from the deep ocean. How and why community interactions, organismal adaptations, population turnover, and evolution vary from marine sediments to the underlying rock is almost completely unexplored. The diversity of habitats is plausibly linked to biotic diversity in terms of the overall pace of metabolic activity, favored metabolisms, complexity of biological consortia, and abundance of living material. As yet, we have little notion of the inherent degree of complexity of these different biomes. In short, the rules of life within these two very different globe-spanning biomes are unknown.

Solving these fundamental unknowns will require scientific ocean drilling to target a diverse, yet representative range of sediment regimes and rock environments with biological, chemical, and geological sampling; biological experimentation; and continuous subsurface monitoring and manipulation via borehole observatories. This integrated, globe-spanning effort will ultimately elucidate the rules of life for the organisms that persist and thrive in these extraordinary systems.

EXPLORING THE LIMITS OF LIFE

Scientific ocean drilling provides an opportunity to explore the limits to **habitability on Earth**. The depths to which life extends beneath the seafloor and the properties that limit that extent of life, whether it is high heat, a low energy flux directly available to microbes, absence of liquid water, or some other property, are completely unknown and likely differ from one subseafloor environment to another. We will **drill deep into the seafloor** in diverse environments with the expectation of reaching the depths at which life is no longer able to survive. Such environments will span different combinations of potentially life-limiting factors, such as temperature, bioavailable energy flux, pressure, dissolved metal concentrations, water availability, and pH. We will sample and conduct in situ experiments at high-temperature hydrothermal systems, in deep hot sediment, in high-pH serpentinization zones, and at the greatest, but thus far unknown, depths where liquid water exists in oceanic crust. **Analytical approaches** in metagenomics, proteomics, lipidomics, and other potential omics techniques will guide scientific ocean drilling in exploring the limits of life.

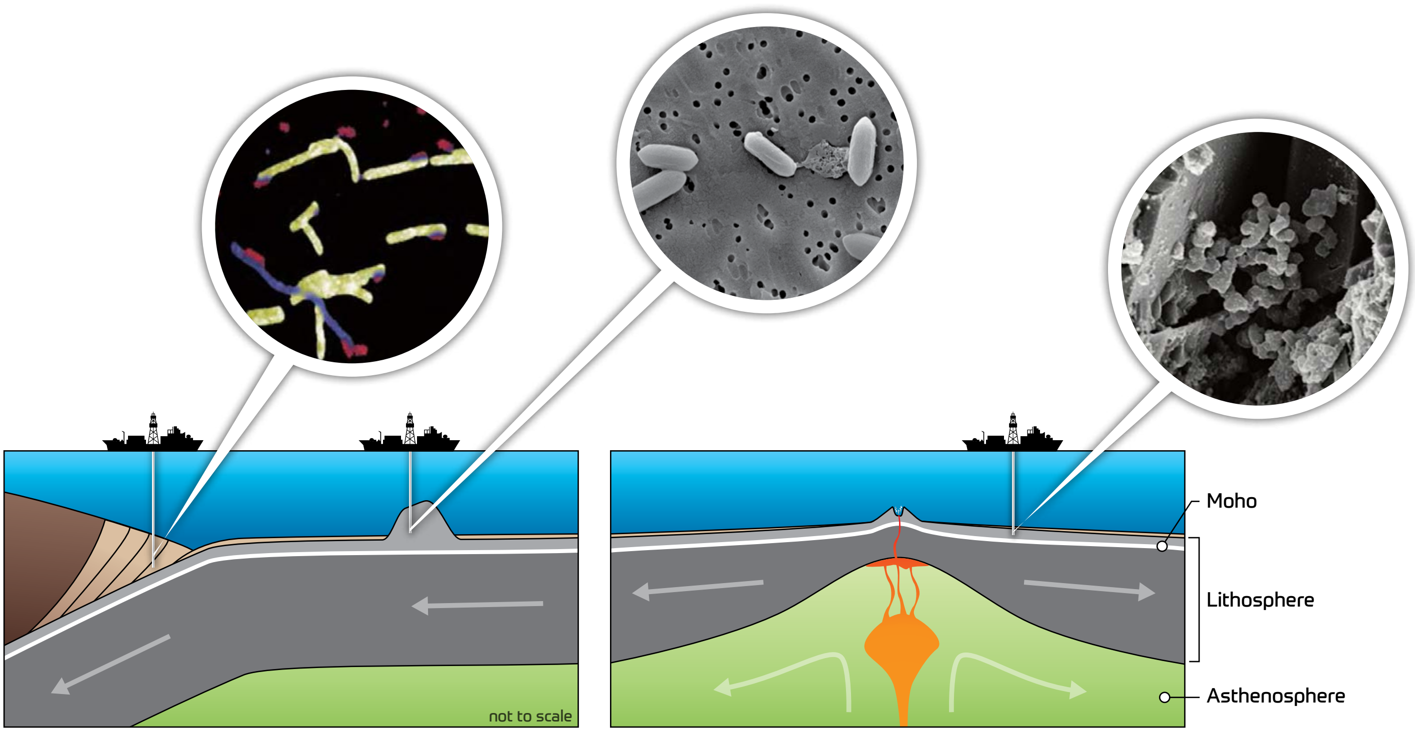
There are numerous examples of advances in biotechnology and medical fields based on studies of life in these extreme environments. There is a high potential for discovery of new organisms, enzymes, and more from deep-sea and subseafloor environments. Scientific ocean drilling can provide crucial information on the environmental factors that will allow better cultivation and isolation of a variety of organisms from these biomes that will help understand the potential for **life beyond Earth**.

CONSTRAINING THE ORIGIN OF LIFE

Constraining the fundamental conditions of life's origin and the core characteristics of the earliest life on Earth remains a significant scientific challenge. The origin of Earth-based life more than 3.5 billion years ago is only preserved in a very few ancient continental rocks. A direct assay of Earth's earliest life is not possible by scientific ocean drilling because the oldest ocean basins are only about 200 million years old. However, scientific ocean drilling can constrain aspects of life's origin by sampling **modern deep subseafloor environments** that are analogous to the early Earth, including the "warm pools" of hot vents, "clay mineral factories," impact-generated hydrothermal systems, and sulfide-rich seeps. Scientific ocean drilling provides access to the organisms that persist, and perhaps thrive, under these extreme subseafloor environmental conditions, such as constant anoxia, darkness, high pressure, locally high temperatures, highly restricted energy sources, and minerals that catalyze life-sustaining reactions. By studying the life that inhabits extreme subseafloor environments, we will gain insight into the potential adaptations of primordial life, the constraints under which it evolved, and hence the origin of life on Earth.

DISCOVERING THE SIGNATURES OF LIFE

The discovery that life exists beyond our planet would demolish the notion that Earth-based life is unique in the universe. Multiple discoveries would demonstrate the origin and persistence of life to be universally commonplace. How can we drive such discoveries? To gain further insights into the origin of life on Earth and the possible occurrence of **life on other worlds**, it is essential to effectively detect signatures of ancient life in sediments and rocks. A biosignature is "an object, substance, and/or pattern whose origin specifically requires a biological agent" that includes, but is not limited to, organic biomarkers, microfossils, stable isotopic compositions of minerals and organic compounds, and paleogenomic data sets.

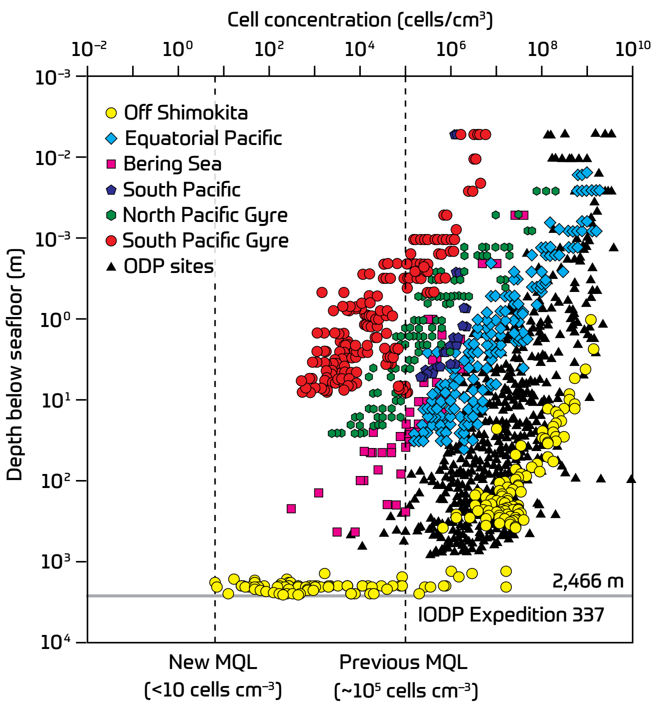


Scientific ocean drilling can access an array of potential habitats deep beneath the seafloor. It has provided vital samples that have yielded microbes, illuminating the features and strategies that enable deep life to persist in these diverse geologic habitats. *Illustration by Geo Prose, inspired by Figure 4 in D'Hondt et al. (2019), https://doi.org/10.5670/oceanog.2019.146. Photo credits: (left) Deep sediments. From Figure 2 in Inagaki et al. (2015), https://doi.org/10.1126/science.aaa6882. (middle) Young oceanic crust. From Figure 3 in Ramirez et al. (2019), https://doi.org/10.3389/fmicb.2019.01983. (right) Old oceanic crust. Courtesy of Jason Sylvan, Texas A&M University*

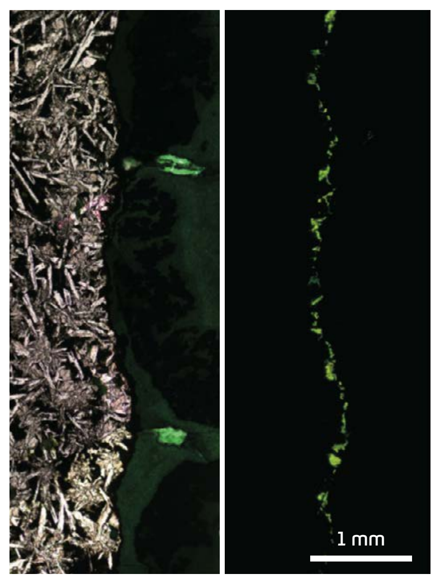
Scientific ocean drilling offers the opportunity to assess the preservation potential and meaning of biosignatures through deep time and under diverse environmental (e.g., oxygenated versus non-oxygenated) and chemical (e.g., high concentrations of sulfur or iron) conditions. Such knowledge will enable us to establish proxies for ancient life, document biosphere responses to past major environmental perturbations, and build new methods to predict biosphere response to future environmental changes. Scientific ocean drilling will enable us to explore genomic (biotic) and chemical (abiotic or prebiotic) evolutions. Further, if life did evolve on other worlds, it may be that in the now dry, former surface water bodies on Mars there still exists a rock record containing fossils of life that has been largely blasted away in the ~3.8 billion year old "heavy bombardment" of Earth, or the subsequent erosional and tectonic remolding of our planet's surface. Impact craters represent a potential microbial habitat for thermophilic life both on Earth and other planets. Continued exploration of the records of impact-generated hydrothermal ecosystems could yield insights into locations for exploration on other worlds. Terrestrial to extraterrestrial collaborations between the scientific ocean drilling and space science communities offer an avenue to predict what signatures of life may look like on the moons and planets of our solar system and beyond.

Sampling living subseafloor communities is a technical challenge. The ability to detect biosignatures requires minimizing contamination and the ability to preserve organisms for study at viable temperature and pressure conditions, cultivate communities within subseafloor boreholes, and image cells in their environmental context

(a) Microbial Cell Counts in the Sediment-Hosted Deep Biosphere



(b) Evidence of Ocean Crust-Hosted Microbial Life



(a) Scientific ocean drilling has made great advances in sampling the biosphere within the ocean sediment column globally, mapping regional variations in the exponential decrease in cell abundance with depth. Novel techniques have allowed scientists to lower the minimum quantification limit for sedimentary microbial cell enumeration (MQL) by several orders of magnitude and demonstrate that microbial life extends more than 2 km beneath the seafloor where cell counts were as low as 10 cells/cm^3 (yellow dots clustered around 2,466 meters below seafloor constitute the deepest subseafloor sediment samples examined for life to date; IODP Expedition 337 Site C0020; Inagaki et al., 2015, https://doi.org/10.1126/science.aaa6882). (b) Scientific ocean drilling is also significantly enhancing knowledge of the composition, origin, and heterogeneous distribution of communities in subseafloor igneous crust, as illustrated here by the microbial colonization of a basalt hosted hydrothermal celadonite vein (light [left] and fluorescence microscopy [right] of SYBR Green I-stained microbial cells). A future goal is to obtain microbial samples from within oceanic crust of all ages to determine cell counts and to investigate how the distribution of microbes relates to fluid pathways and the extent to which the biosphere facilitates hydrothermal exchange. *(a) From: D'Hondt et al. (2019), https://doi.org/10.5670/oceanog.2019.146. (b) From Suszuki et al. (2020), https://doi.org/10.1038/s42003-020-0860-1* (within sediment and rock). Detection of biosignatures will aid in identifying, characterizing, and understanding life below the seafloor and will directly benefit the search for extraterrestrial life, where similar barriers to discovery exist. Advancement of such shared interests between the scientific ocean drilling and space science communities requires identification of the best **subseafloor analogues to extraterrestrial habitats**. We will team with space agencies to design and test tools and to formulate criteria that will best assess biosignatures and aid in understanding habitability in Earth's subseafloor and on other worlds.

THE WAY FORWARD

The globe-spanning deep biome can only be understood through sustained scientific ocean drilling efforts to sample, monitor, and analyze sediments, rocks, and organisms from a representative range of Earth's subseafloor environments. Direct study of natural communities and hypothesis-driven experiments are critical for advancing understanding of these extraordinary biomes. Scientific ocean drilling will allow us to delineate the conditions in which subseafloor communities live and in which they fail to live, and characterize how these organisms evolve, interact, and die. Experiments, including in situ manipulations, will elucidate the features and strategies that enable microbes to persist and communities to form under specific subseafloor conditions and will allow us to identify the biochemical processes that create biosignatures.

Life detection and description will require interdisciplinary teamwork—a hallmark of scientific ocean drilling. Astrobiologists will analyze the DNA and RNA of the sparse organisms that must exist near the limits of life as well as the contrasting diverse communities in more energy-rich environments. Hydrologists will determine the connectivity of the deep-sea plumbing system to answer how life moves around and how it is interconnected in the confined worlds of sedimentary grains and rock fractures. Geologists will evaluate the trace fossil remains of microbial communities. Geochemists will examine the host of chemical and mineralogical waste products left by metabolic reactions and analyze authigenic minerals that record past pore water chemistry conditions influenced by microbial processes. Integration of these multiple lines of evidence to answer our fundamental questions regarding the origin of life will require big data analytics, which will aid us in robustly mapping the novelty of the various communities sampled throughout **Earth's globe-encircling deep biosphere**.

The quest to understand the origins, diversification, and evolutionary processes of life on Earth and the pursuit of life on other worlds are challenges of the first order. To accomplish these goals, the scientific ocean drilling community must collaborate with space science communities to identify the best Earth drilling targets that might be **analogues to extraterrestrial habitats** and develop the technologies most likely to yield insights about the organization of life below the seafloor and elsewhere in our solar system.

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ENABLING ELEMENTS

The *Enabling Elements* serve to significantly advance the goals of scientific ocean drilling through numerous and varied broader impacts and outreach initiatives, partnerships and collaborations with organizations that have complementary scientific goals, and continued technology development and innovative applications of advanced data analytics.

1. **Broader Impacts and Outreach**
2. **Land to Sea**
3. **Terrestrial to Extraterrestrial**
4. **Technology Development and Big Data Analytics**

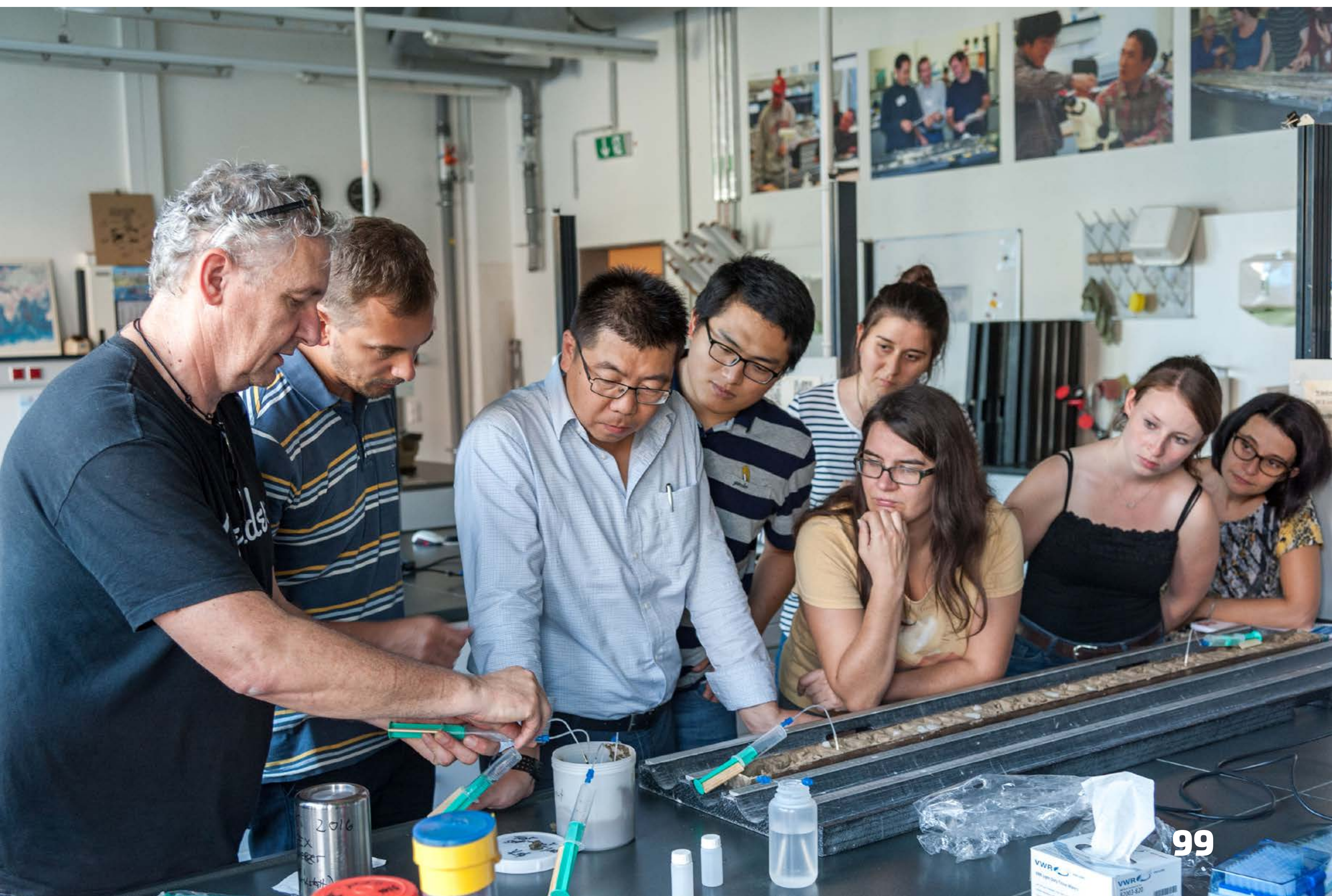
ENABLING ELEMENT 1

BROADER IMPACTS AND OUTREACH

SUMMARY

Scientific ocean drilling targets a broad array of topics that are of interest and importance to society, contributing vital data that will improve climate models, advance earthquake knowledge, and provide insight into the possibility of life on other worlds. It is a proven model for global collaborative research and an incubator for disciplinary partnerships in science and engineering. Widely recognized as a preeminent training ground for the next generation of Earth scientists, scientific ocean drilling will capitalize on its international, cross-disciplinary shipboard and shore-based science parties to advance participation of traditionally underrepresented groups. Using a variety of social media and web-based platforms, data and results will be broadly disseminated to educators, policymakers, and the public, securing scientific ocean drilling's position as the authoritative source of information about the Earth system.

ECORD Summer School 2016 in Bremen, Germany. The goal of the summer schools is to train the next generation of scientists. *Credit: MARUM – Zentrum für Marine Umweltwissenschaften, Universität Bremen, V. Diekamp*

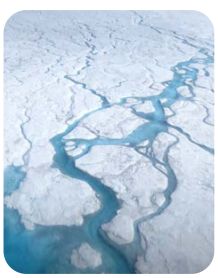


THE IMPACT OF SCIENTIFIC OCEAN DRILLING

Scientific ocean drilling advances understanding of how the Earth system has operated in the past by providing the means to access archives of sediment and rock that lie deep beneath the seafloor and by instrumenting borehole observatories to monitor the subseafloor and conduct experiments. Scientific ocean drilling has an impact on a wide range of issues of broad interest to society, exemplified here.

Advancing earthquake studies

Studies of **earthquake generation** at subduction zones are hampered by a lack of in situ samples and measurements from active plate boundary faults. In a rapid response to the magnitude 9.1 Tōhoku-oki earthquake in 2011, scientific ocean drilling penetrated the fault zone that ruptured during the earthquake and measured the frictional heating generated by it. Such data provide important constraints on the forces that influence earthquake hazards. Only by deploying a drilling platform that can penetrate into deep fault zones and by implementing sophisticated downhole technologies under challenging borehole conditions can scientists collect and record such important in situ data.



Improving climate models

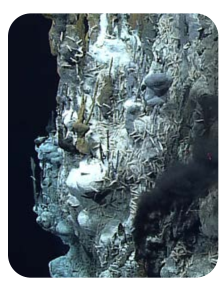
Studies of cores recovered globally through scientific ocean drilling have allowed reconstruction of the past 180 million years of Earth's climate history. Continued advances in drilling technology and analytical techniques and recovery of cores from carefully selected sites will increase the temporal and spatial resolution of assembled paleoclimate and paleoceanographic records. These records are needed to **ground truth**, and thus improve, global climate forecasts. They will also be used to test more refined hypotheses about the rates of change in temperature and sea levels as our climate warms and to pinpoint tipping points in the climate system.

Discovering the deep biosphere

Through new approaches to drilling and coring that allow collection of pristine samples, scientific ocean drilling has contributed to advancing understanding of the quantity, diversity, and global significance of life in subseafloor sediments and rocks. This deep biosphere may be the largest ecosystem on Earth, driving subseafloor geochemical processes, the global carbon cycle, and the alteration of sediments and rocks. Deep biosphere studies also seek to reveal how life can survive in hot, nutrient-deprived, high-pressure environments. These studies will lead to a better understanding of the **limits of life** on Earth and the potential for life elsewhere in the **universe**. Simultaneously, discoveries of new species within the subseafloor biosphere may offer opportunities to develop novel pharmaceuticals.

Assessing future ocean health

Seafloor sediments preserve information about the responses of ocean biological activity to natural cycles and catastrophic perturbations over geologic time. Shifts in biogeochemical cycles modulate the recovery of life following mass extinctions and episodes of rapid climate change. Cores recovered by scientific ocean drilling will provide baseline information about the abundance and diversity of microscopic organisms living in the pre-Anthropocene ocean. Comparing these data to contemporary responses of the ocean-biosphere system to changes in greenhouse gas emissions, nutrient levels, weathering, and the exploitation of marine organisms will contribute to projections of the **ocean's future health** and habitability.



Investigating the deep Earth

Geochemical exchanges between the solid Earth, ocean, atmosphere, and biosphere have influenced Earth's surface environment throughout its history. Emerging drilling, coring, logging, and monitoring technologies, will permit investigation of the interconnected magmatic, tectonic, hydrothermal, and microbial processes in seafloor spreading and **oceanic lithosphere** evolution that are responsible for the unique characteristics of Earth's surface.

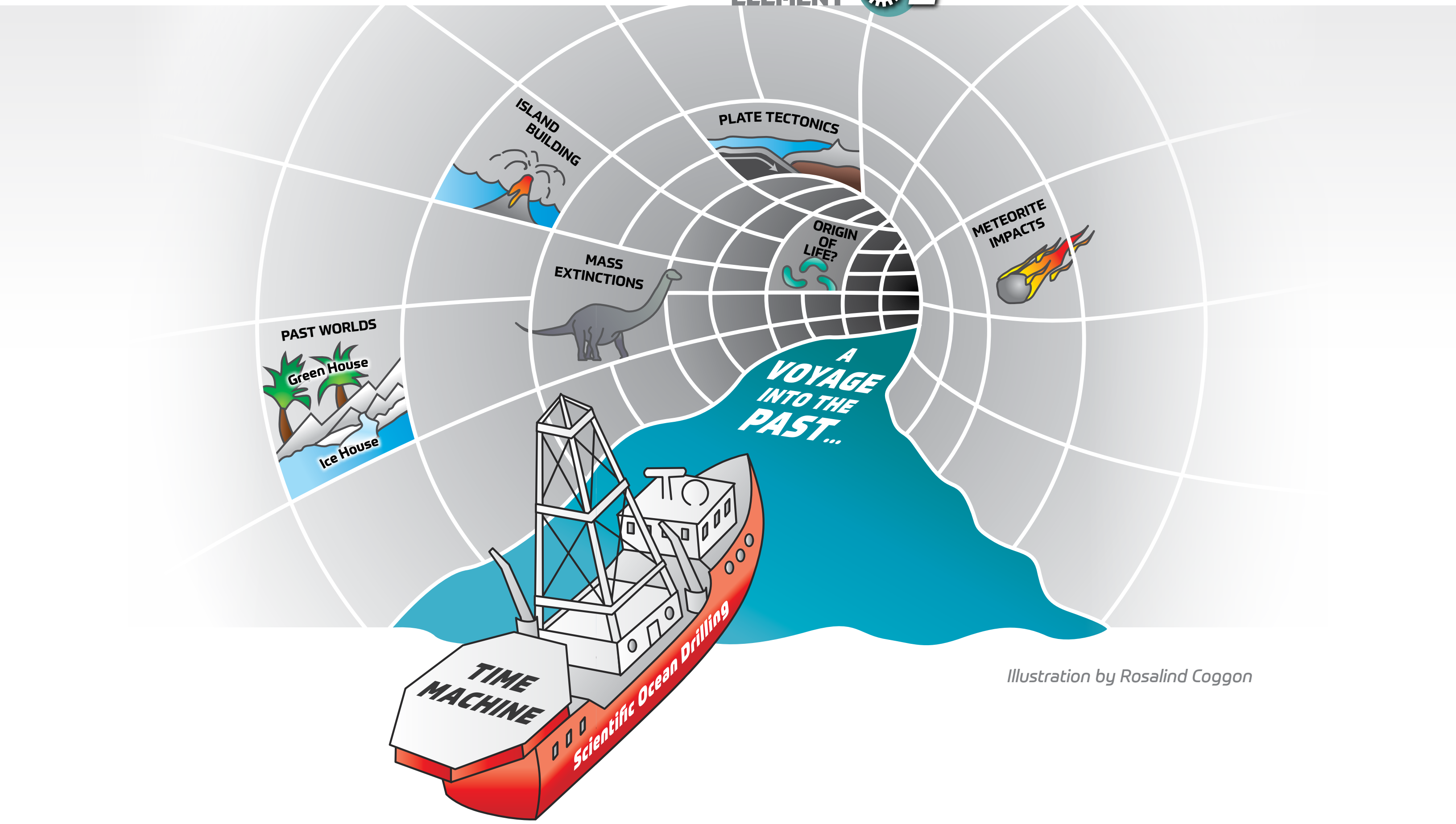


Illustration by Rosalind Coggon

INSPIRING EDUCATORS AND THE PUBLIC THROUGH DISCOVERY

A growing number of geoscience initiatives are working to incorporate real data into undergraduate classrooms and laboratory learning. Free and openly available, scientific ocean drilling data are a valuable resource for such projects. They cover a range of topics and disciplines that capture the imagination: asteroid impacts that led to the demise of dinosaurs, hot climates in the geologic past that may be akin to what a future Earth may look like, and extreme environments deep beneath the seafloor where microbes thrive. The scientific ocean drilling community will actively partner with education initiatives globally to ensure incorporation of drilling data into curriculum modules.

Web-based tools are available to broadly educate the public about scientific ocean drilling and disseminate information about exciting discoveries. For example, interactive websites and live ship-to-shore broadcasts can be incorporated into classroom lessons and museum exhibits. Online "story maps" can convey how scientific ocean drilling works, including technologies, life on the ship, tours through the laboratories, and the process from "core on deck" to answering a scientific question. As they are carried out over multiple expeditions, the *Flagship Initiatives* will provide unified messaging for research findings delivered as a story map, film, animation, or instantly sharable video that shows the moment of discovery. The lengthy timeframe of the *Flagship Initiatives* ensures ample time to develop focused messaging through workshops and external projects.

The public can discover scientific ocean drilling and its achievements through a growing number of venues. Traditional news media and social media outlets both can be leveraged to increase the profile of ocean drilling and its achievements. The scientific ocean drilling community will use the *2050 Science Framework* to develop common story themes, graphics, and educational materials as a basis for consistent messaging across the platforms. Photos, videos, animations, and artwork from individual expeditions can provide the public with an inspiring bird's-eye view of how science is conducted and what the results might mean for the planet. Partnerships with museums will provide opportunities to engage directly with the public through hands-on exhibits. Tours while the drillships are in port will allow for in-person ship-based educational initiatives.

TRAINING THE NEXT GENERATION OF SCIENTISTS

Scientific ocean drilling is a superb training ground for the next generation of geoscience researchers and university educators. Drilling expeditions will continue to provide large numbers of graduate students and early career scientists with the opportunity to contribute to the scientific endeavor, from the early planning stages to the publication of results. Through shipboard and shore-based participation, they hone analytical, research, and writing skills and learn from teams of international scientists representing a range of disciplines. The program's core repositories and databanks are entry points for many who are interested in scientific ocean drilling—including some who have not had the opportunity to go to sea on a specialized drilling platform. As the next generation takes the helm of the program, scientific ocean drilling will strive to advance participation of traditionally underrepresented groups and promote a more diverse group of students and researchers to become co-chief scientists of future drilling expeditions and leaders in the scientific community.

Development of the next generation of scientists must start at a younger age, at both the schoolchild and undergraduate levels, and from a broad spectrum of schools. Scientific ocean drilling will expand the suite of available educational resources for all age levels. Partnering with other programs and organizations that have experience and influence in the schoolchild and undergraduate arena will broaden distribution and use of these valuable materials. Because scientific ocean drilling covers and integrates so many science, technology, engineering, and mathematics (STEM) areas, the possibilities for developing successful programs and relationships are immense.

INTERNATIONAL COLLABORATION

Scientific ocean drilling is a model of international cooperation and interdisciplinary collaboration in science. Before, during, and after each expedition, the expedition scientists, technicians, and engineers bring their diverse expertise and perspectives to bear on the scientific investigation at hand. Collaborations last for years as drilling plans are developed, refined, and executed, and the results analyzed and published. Scientific and technical relationships endure over decades as the science matures, additional core is recovered on new expeditions, and analytical tools are improved and/or invented. Graduate students particularly benefit from these international collaborations. Many are provided with the opportunity to spend time conducting analyses at laboratories abroad, while others move into postdocs or jobs with scientists they met on a scientific ocean drilling expedition.

ADVANCING DIVERSITY AND INCLUSION

The geosciences are among the least diverse in the STEM disciplines. To date, scientific ocean drilling largely reflects this reality. Numerous pathways are available to help increase participation of underrepresented groups in scientific ocean drilling, where mentoring the next generation is embedded in their culture. Approaches to increasing diversity include actively recruiting diverse science parties, codifying the enhancement of diversity and inclusion in expedition objectives and as enduring principles in future scientific ocean drilling programs, conducting ship-to-shore video conferences with minority-serving institutions, promoting diversity in the selection processes for scientific

ENGAGEMENT

Examples of some of our broader impacts and outreach endeavors.

School of Rock

Live Ship-to-Shore Broadcasts

Documentaries

ocean drilling speaker and sponsored seminar programs and leadership roles, and linking early career scientists with educators from communities that are underrepresented in the STEM fields. As a large international research community in the geosciences, we will vigorously expand on these and other efforts to broaden the representation and participation in all aspects of the scientific ocean drilling endeavor.

Over the last half century, scientific ocean drilling has been successful in growing the number of women participating in and leading expeditions. Today, 34% of the science parties are women, compared to 12% in the earliest days of ocean drilling. Forty-one percent of graduate students and half of the co-chief scientists on drilling expeditions are women. While the trajectory is clearly positive, there is still work to be done. Future efforts will focus on bringing full gender parity to all aspects of scientific ocean drilling.

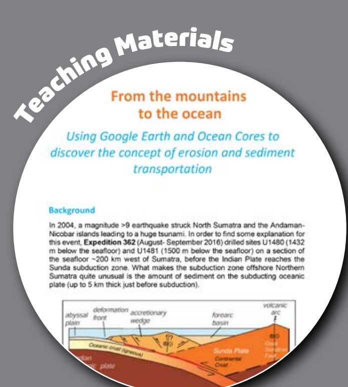
The scientific ocean drilling community will use the same successful approaches for achieving gender parity to enhance overall diversity and inclusion. Scientific ocean drilling community will be a leader in driving the push to widen participation in the Earth and ocean sciences among future generations of scientists and in removing internal barriers to becoming and staying involved.

KNOWLEDGE SHARING

The outcomes, data, and samples from scientific ocean drilling are made freely available via open-access publications, databanks, and core repositories. Scientists and graduate students from around the globe, even those who have never been involved with scientific ocean drilling, can use these materials. They often access international archives of carefully curated scientific ocean drilling cores and databanks for decades beyond the end of an expedition to answer questions that were never envisaged by the original seagoing participants. Expedition archives should include social media posts, photographs, interview recordings, and videos that convey how discoveries are made and how the drilling platforms work. Collectively, the archives from multiple expeditions capture and document the scientific process of discovery, personal stories, and post-cruise findings and inform the public, inspire future generations, and educate everyone about the Earth system.

ENGAGING WITH OTHER FIELDS

Scientific ocean drilling can build strong, mutually beneficial collaborations with other fields, such as engineering, **astrobiology, and space sciences**. Collaboration with scientists and engineers from other disciplines is vital for addressing fundamental **technical challenges** such as improving and deepening our recovery of undeformed sediments, minimizing contamination in order to collect the most pristine samples of the deep biosphere, and improving our ability to recover cores in hot crust and unstable, tectonically deformed terrain. The discovery of a biosphere deep beneath the seafloor has attracted to scientific ocean drilling microbiologists who are now taking leading roles in planning and implementing expeditions and in developing new tools to collect and analyze samples. Investigation of life in the high-temperature, nutrient- and light-limited environments deep below the seafloor can assist space scientists and engineers in designing tools and experiments that can be employed on space missions to investigate other potentially habitable worlds.



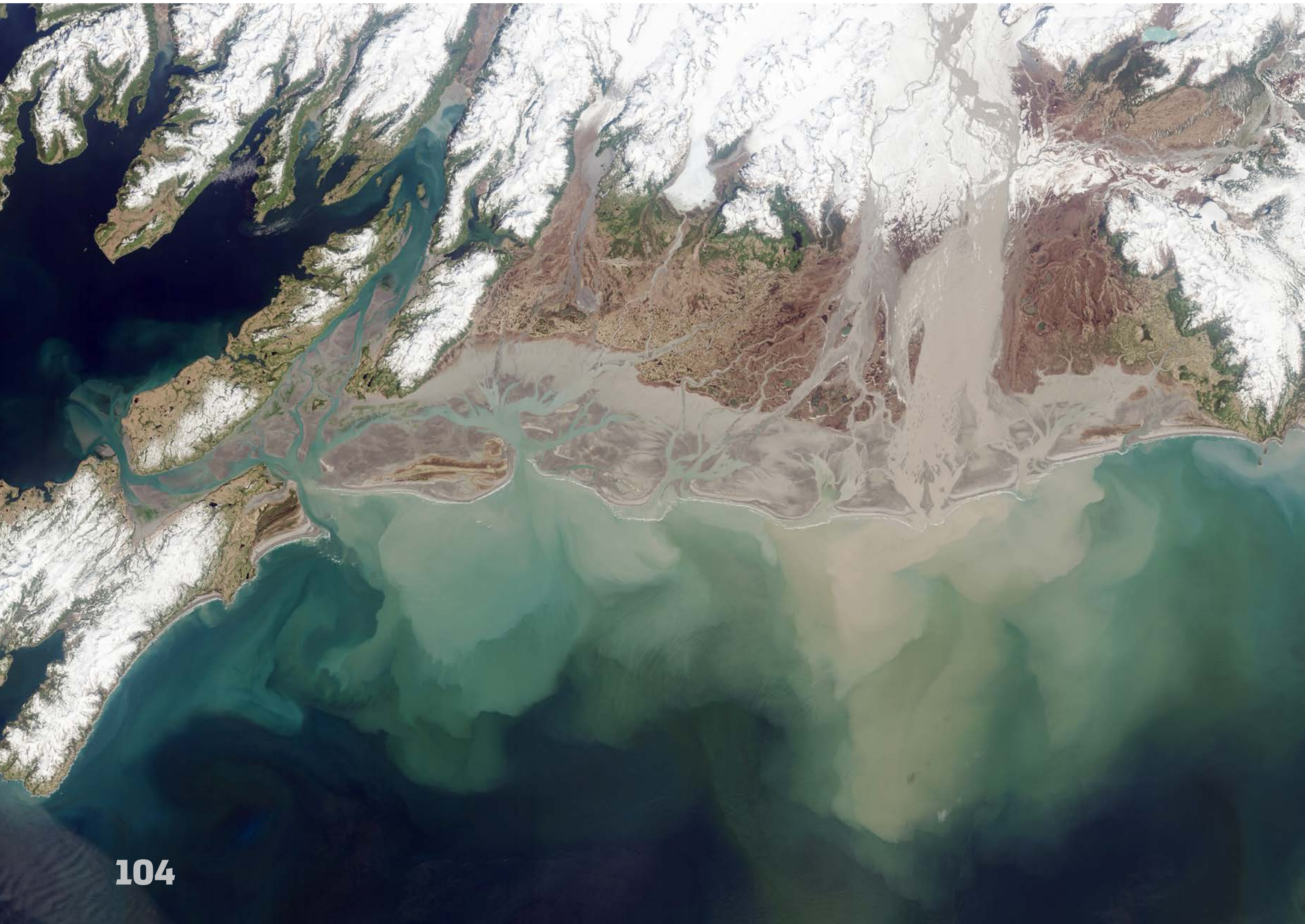
ENABLING ELEMENT 2

LAND TO SEA

SUMMARY

The scientific ocean and land drilling communities have built two of the most successful, long-lasting, international collaborative programs in the Earth sciences. The International Ocean Discovery Program (IODP 2013–2023) and the International Continental Scientific Drilling Program (ICDP) have brought together more than 30 countries, building on initiatives and programs first implemented in 1968 and 1996, respectively. Strengthened collaborations between these programs will advance their closely allied objectives to investigate the interconnected global Earth system. Future collaborative land-to-sea drilling campaigns will answer fundamental questions about Earth dynamics and natural hazards, as well as explore the connections between plate tectonics, Earth's climate system, ecosystems, life and habitability, sea level change, and subseafloor freshwater flow across the coastline.

Copper River Delta glacier runoff flows into the coastal waters of the Gulf of Alaska. *NASA Earth Observatory image by Robert Simmon and Jesse Allen, using Landsat 8 data from the USGS Earth Explorer.*



NEW SCIENCE FRONTIERS IN LAND-TO-SEA DRILLING

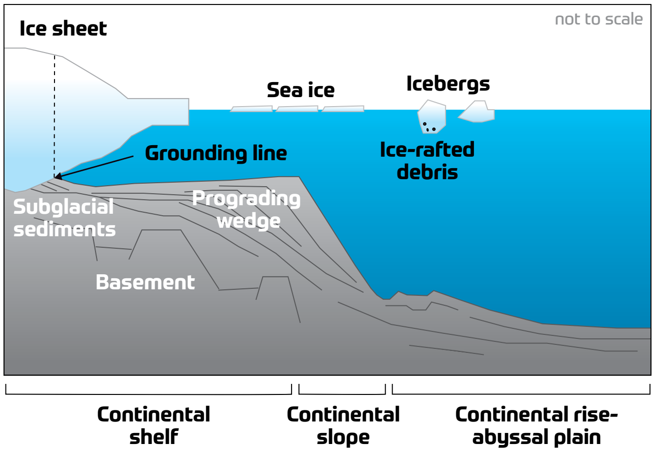
Sea level records collected across the shoreline by scientific drilling will allow us to unravel feedbacks between Earth's climate system, deep Earth and surface processes, and sea level.

The ***Strategic Objectives*** and ***Flagship Initiatives*** that underpin the *2050 Science Framework* for scientific ocean drilling aim to understand how the complex, interconnected Earth system works. This priority strongly aligns with research initiatives in allied programs such as the ICDP, which focuses on understanding geodynamic processes, geohazards, georesources, and environmental change through drilling and coring across continents, lakes, and oceanic islands.

Strengthening collaborations in land-to-sea drilling campaigns will advance several complementary scientific objectives. A unified database on Earth's paleoclimate, prepared jointly, will help to improve **model projections** of future climate and environmental changes by providing access to a wider array of ground truth data. Collaborative drilling will enhance our understanding of the interplay between freshwater and seawater along coastlines, the development of drought and desertification patterns and increased wildfire potential, the transition between continental and oceanic crust, and the formation of sustainable georesources from microbial life, volcanoes, and related element cycles. Together, scientific ocean and land drilling can furnish a more holistic assessment of natural hazards from earthquakes, tsunamis, and explosive volcanism, many of which occur close to Earth's coastlines. It can also deepen our understanding of how the Earth system recovers following large **meteorite impacts** or the emplacement of large igneous provinces on land, along continental margins, and in the ocean. The following provides details of some key opportunities for scientific ocean and land drilling collaborations.

Causes and consequences of sea level change. Ongoing sea level rise is having a significant impact on coastal communities and island nations. Projections of global sea level rise exceed 1 m by 2100. Determining the rates, amplitudes, and mechanisms that control sea level rise as well as its consequences requires sampling on both sides of the modern shoreline. Sea level is controlled primarily by global temperature, ice volume, and regional subsidence or uplift on human timescales and by tectonics on longer timescales. Global warming causes seawater to expand and ice sheets to melt, raising sea level. Removal of thick ice sheets since the last ice age is still causing uplift in some regions and subsidence in others. **Plate tectonic** changes related to rates of oceanic crust production, continental collisions, and mantle dynamic topography affect both global and regional sea levels.

Knowledge of how these processes contributed to past sea level rise will inform the future. Sea level records collected across the shoreline by scientific drilling will allow us to unravel **feedbacks** between **Earth's climate system**, deep Earth and surface processes, and sea level. Past studies have yielded critical constraints on the amplitude and timing of sea level change and the rates of rise due to ice sheet collapse. Critical environments for sea level studies include coral reefs, passive continental margins, polar margins, and deep-sea regions where geochemical proxies will yield information on ice volume changes. In addition, coordinated ocean and coastal drilling studies of more active settings will provide constraints on how deep and shallow Earth processes affect regional and local subsidence and uplift.



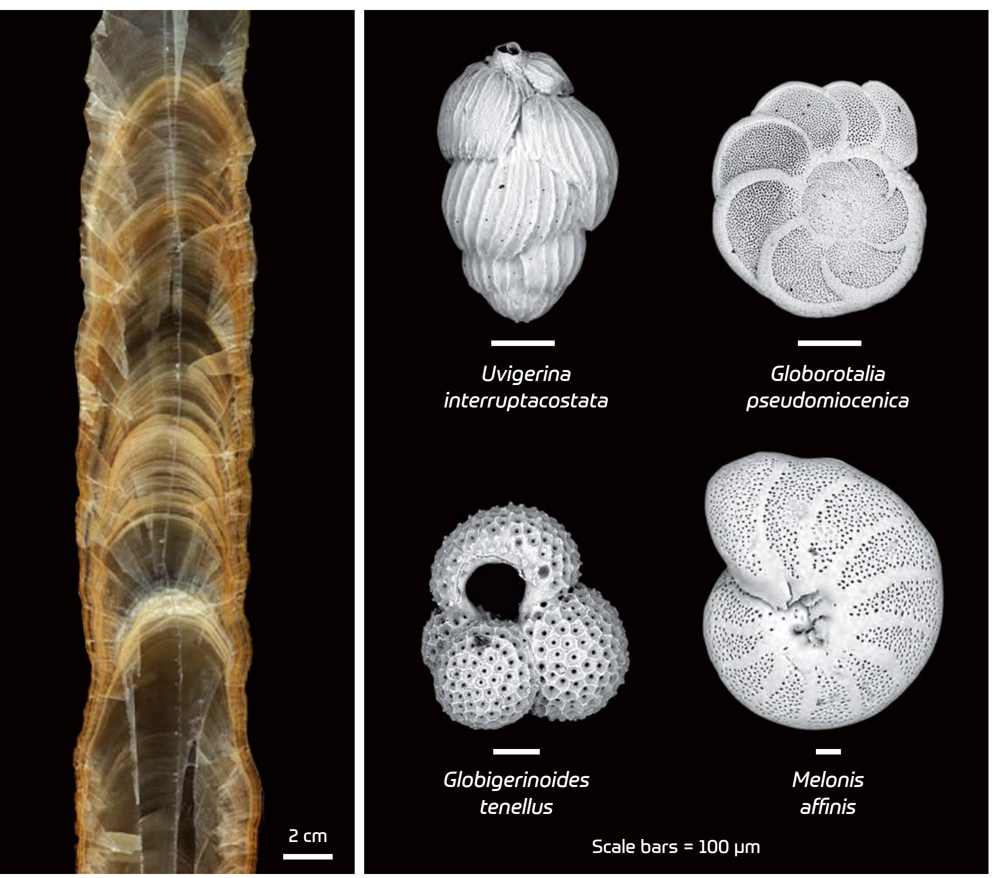
Conceptual cross section across the Antarctic margin. Subglacial to ice-proximal (coastal-shelf) to ice-distal depositional environments that contain the sedimentary record of past ice sheet dynamics result from changing atmosphere-ice sheet-ocean interactions. Land-to-sea drilling is required to target all parts of this system. *Modified from Escutia et al. (2019), https://doi.org/10.5670/oceanog.2019.117*

Future sea level investigations need to build on our understanding of the interconnections within the Earth system and how they affect sea level. Transects of continuous drill cores and logs across the shoreline in coral reefs, passive continental margins, polar margins, and active margins will provide the materials needed to advance understanding of the relationship between Earth system interactions and sea level. Such a coordinated research strategy will provide a better understanding of the roles CO_2 and astronomical forcing play in sea level changes and how sea level responded to past rapid climate warming and ice sheet collapse, and to evaluate the response of the Earth system in ice-free "hothouse," ice-transitional cool "greenhouse," and ice-dominated "icehouse" worlds.

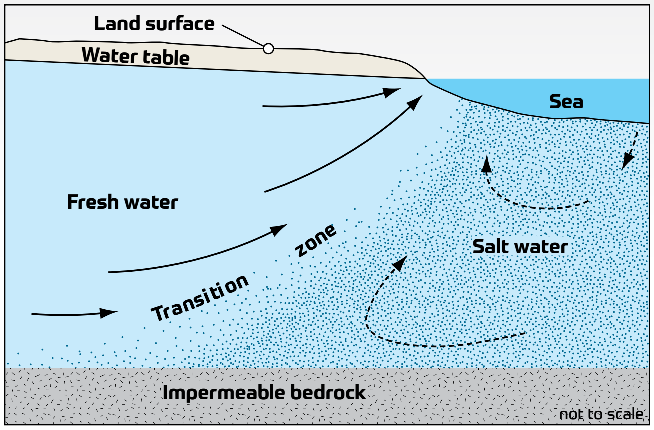
Toward an integrated global paleoclimate record. A common objective of scientific ocean and continental drilling is to improve understanding of **feedbacks** and **tipping points** within the Earth system and how they affect environmental conditions and the planet's **habitability**. Working together, the two communities can assemble a truly global, high-resolution, and fully integrated marine and terrestrial knowledge base of Earth's paleoclimate to address this goal. Such a comprehensive record will also provide the ultimate age model—an atomic clock and timescale from a couple of thousand to millions of years ago—that is essential for understanding the timing, rates, and complex interconnections among the processes that operate within the Earth system. The combined paleoclimate database will include information from marine sediments, lake sediments, ice cores, land stratigraphic sections, speleothems, and tree rings collected by scientists within and beyond the established drilling programs.

Fluid flow across the coastline. Land-to-sea drilling of active freshwater aquifers and hydrothermal systems in coastal and marginal regions will allow us to determine these systems' roles in **global water, carbon, and metal cycling** and their impact on georesources, **habitability** of the subsurface, and **life**. Groundwater is an essential natural resource, supplying many communities with water for drinking and for irrigation of crops. Groundwater circulation does not stop at the coastline; freshwater aquifers can extend offshore, beneath the seafloor, but salt water can also flow inland and underground. Freshwater sustainability in a greenhouse climate is critical, especially in regions of increasing desertification. Coastal aquifers may also support life beneath the surface by carrying nutrients to the subseafloor microbial biosphere.

To determine the current nature and extent of coastal aquifers and how they may respond to changing climate and sea level requires knowledge of the magnitude, rates, directions, and mechanisms of fluid flow through them. Onshore and offshore drilling will collect vital information about the physical and chemical properties of the rocks that comprise the aquifers, the fluid pressure and temperature



Paleoclimate information can be extracted from both land (left) and ocean (right) rocks and sediments. (left) Scientists analyze the thickness and chemical composition of speleothem layers to reconstruct climate changes over thousands to hundreds of thousands of years. (right) Microfossils in marine sediment cores collected by scientific ocean drilling have been instrumental in providing a continuous record of glacial history since the Cretaceous.



Groundwater flow patterns and the fresh water-salt water transition zone in an idealized coastal aquifer. Mixing of fresh water and salt water in the transition zone induces circulation of salt water from the sea to the transition zone and then back to the sea. *From Barlow (2003), https://doi.org/10.3133/cir1262*

conditions within the aquifers, and the horizontal and vertical extent of the aquifers. Installation of observatories in boreholes will allow us to sample fluids and quantify flow rates and solute fluxes through the aquifers. Land-to-sea drilling will also permit evaluation of the processes that affect the extent of offshore aquifers and salt water influx and the potential future impacts of groundwater extraction on these aquifers.

Active volcanic islands such as Iceland and Hawai'i often host onshore-to-offshore hydrothermal systems. Similar to deep-sea hydrothermal systems, **energy and matter cycle** through these "coastal" fluid flow systems as a result of fluid-rock reactions. In regions where the coastline comprises ancient uplifted oceanic crust (ophiolites), modern groundwater circulation results in lower-temperature fluid-rock reactions. The reactions within these coastal systems form ore deposits, sequester or trap atmospheric CO_2 in calcium carbonate minerals, and produce hydrogen through serpentinization of peridotites. Each of these processes can also impact subsurface habitability by supporting chemolithotrophic organisms in the deep microbial biosphere. The rocks that host these systems contain a mineralogical and biogeochemical record of past fluid-rock exchange. Land-to-sea drilling of the terrestrial and submarine portions of these systems and in situ monitoring and fluid sampling will enable determination of the hydrogeologic, chemical, and microbial transitions between them, and the nature and extent of biogeochemical exchange within the systems and the microbial communities they support.

Earth dynamics and natural hazards. **Plate tectonic** processes along active margins are responsible for generating most of the world's destructive earthquakes, tsunamis, and explosive volcanoes. Efforts to understand the mechanisms controlling the magnitude and recurrence time of these **natural hazards** and **assess hazard potential** to coastal populations will benefit from coordinated studies that cross the shoreline. Stratigraphic sections recovered both offshore and on land provide opportunities to determine the rates and magnitude of crustal uplift, subsidence, and tilting across fault zones and reconstruct more fully the activity and slip history of faults. Installation of borehole observatories in and above seismogenic zones will allow continuous monitoring of pressure, temperature, and stress and strain, and collection of hydrologic and geochemical data to help assess the evolution of hazard-generating processes. Land-to-sea drilling provides an opportunity to recover complementary paleoseismology records from submarine and lacustrine deposits. These sediments can contain information on the magnitude and frequency of past earthquakes and tsunamis, which can be used in assessments of hazard potential.

FUTURE COLLABORATION

Future plans for both scientific ocean and continental drilling emphasize the need to study Earth as an interconnected system, including the links between Earth processes, the environment, and society. The new focus requires development of integrated land-to-sea drilling campaigns where the science crosses the shoreline. Such studies will reinforce collaborations between the two scientific drilling communities, but more importantly, it will drive new opportunities for the mutually beneficial development of shared science strategies, novel analytical tools, syntheses of truly global data sets, and improved drilling technologies.

ENABLING ELEMENT 3 TERRESTRIAL TO EXTRATERRESTRIAL

SUMMARY

Future collaboration between international space agencies and scientific ocean drilling will benefit efforts to better understand planetary evolution, evaluate the potential for indigenous life elsewhere in the universe, and assess the risks posed by extraterrestrial impacts. Through space exploration, humankind aspires to discover the fundamental physical laws of the universe, decipher the conditions required to promote planetary formation and evolution, and ultimately, unravel the origin of the universe and life. Scientific ocean drilling's investigations into Earth's structure, magnetic field, and volcanism and the requirements for planetary habitability have similar goals. Earth's ocean basins provide a reference frame for exploring challenging environments and offer a natural laboratory for testing remote and space exploration robotic technologies. Integration of modern satellite data with historic records from scientific ocean drilling will be a powerful new approach to understanding Earth's interconnected processes today and climate evolution into the future.

A team of transatlantic scientists, using reanalyzed data from NASA's Kepler space telescope, discovered an Earth-size exoplanet orbiting in its star's habitable zone, the area around a star where a rocky planet could support liquid water. This artist's illustration shows what Kepler-1649c could look like from its surface. *Image credit: NASA/Ames Research Center/Daniel Rutter*

UNDERSTANDING PLANET EARTH

The overarching goal of all space agencies—to explore space and its planetary bodies—includes the study of Earth. Satellite-based sensors collect real-time data that are essential for understanding a wide variety of Earth processes and properties such as weather, **plate motions**, and active tectonics, including **earthquakes, tsunamis, and volcanism**. These data also provide calibration for the long-term records of Earth history that we access through scientific ocean drilling. The synthesis of remote-sensing data and drill core records of Earth processes and properties will enhance our ability to achieve our ***Strategic Objectives*** and implement our ***Flagship Initiatives***.

Sensors aboard satellites are also documenting a wide range of global environmental change indicators, from atmospheric greenhouse gas concentrations, to global and regional sea levels, to sea ice thickness. As we continue to observe the many far-reaching environmental changes, decision-makers will need to increasingly rely on model-based scenarios of future climate to inform planning. **Climate models** require robust baseline data of global climate evolution over extended geologic time periods to test model performance. For example, satellite observations paired with long climate histories obtained from scientific ocean drill cores will allow us to test different assumptions used in physical and dynamic models of **Earth's climate system**, as well as define boundary conditions and recognize potential **tipping points**.

During the last half century, space agencies have played a key role in providing data sets of global weather patterns and chlorophyll distributions throughout the ocean. Over the next decades, space agencies will continue launching new Earth satellite missions to further enrich our understanding and predictability of modern weather and ocean circulation patterns. To fully comprehend the extent to which the Earth system is fundamentally changing due to climate warming requires comparing modern data sets collected by satellites to the long-term records of global climate and ocean system evolution recovered by scientific ocean drilling. Space agencies and scientific ocean drilling can support future climate system modeling by collaborating on the location of future drill sites and integrating results.

Space agencies and scientific ocean drilling can support future climate system modeling by collaborating on the location of future drill sites and integrating results.

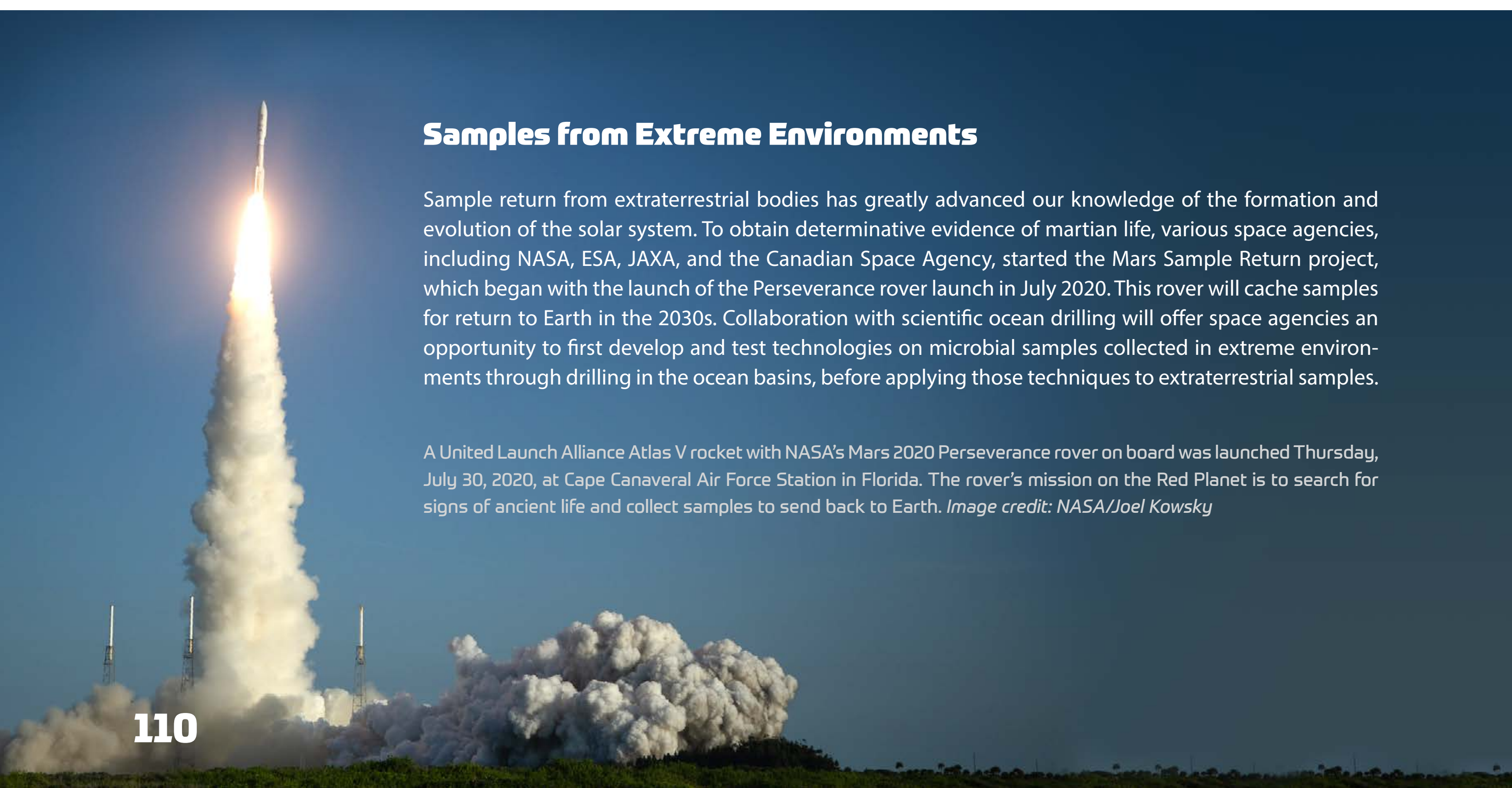
Exploring planetary evolution. Planetary scientists use remote sensing to investigate features at the surface of planetary bodies and rovers, landers, probes, and sample return to study the near-surface environment. These missions stand to gain from scientific ocean drilling investigations in Earth's ocean basins. By examining Earth's history recorded in sediments and rocks beneath the seafloor and by viewing this history in a planetary-analogue reference frame, it becomes possible to gain a holistic picture of **Earth's dynamics**, its **climate system**, and its **biological evolution** over geologic time, including the geologic and **biologic processes of impact events**. Investigations into the formation, cooling, and environmental evolution of other planetary bodies will benefit from a partnership between scientific ocean drilling and space agencies.

There has long been interest in exploring Mars. It is now hypothesized that the Red Planet's environment had once been much wetter and could have hosted carbon-based life. Stabilizing liquid water on the surface of Mars would have required a much thicker atmosphere, which could have been supplied by martian mantle plume volcanism. However, because of the small size of Mars, this low-gravity planet is not likely to have retained an atmosphere. The

NASA's Curiosity Mars rover captured this mosaic as it explored the "clay-bearing unit" on February 3, 2019. This unit has been an important scientific destination because it indicates that water may have played a critical role in its formation. *Image credit: NASA/JPL-Caltech/MSSS* halting of its geodynamo when the planet was relatively young, which resulted in a weak (residual) magnetic field, likely accelerated the loss of the atmosphere, killing any life that emerged or forcing it underground. Scientific ocean drilling studies of active plume **volcanism** on Earth and changes in the behavior of Earth's **geodynamo** over geologic timescales can be used to understand the development and retention of atmospheres on other planetary bodies and the possibility that life once developed there. Investigations of mantle plume and rift volcanism on Earth are also important for understanding how terrestrial planetary bodies in our solar system transfer heat, cool advectively, and influence surface landforms.

Searching for life in the universe. A primary pursuit of space agencies is to unravel the origin of the universe and life. The US National Aeronautics and Space Administration (NASA) Mars 2020 and European Space Agency (ESA) ExoMars missions will be the first to specifically examine the implications of a "thicker atmosphere" enveloping early Mars by seeking traces of ancient life at or near the surface. The 2019 *NASA Roadmap to Ocean Worlds* aims to identify new ocean worlds, characterize their oceans, evaluate their habitability and potential for preserving life, and ultimately understand any form of life that would be found. To ground truth and complement these important objectives, we need to determine the potential biosignatures in each habitable niche on planets. Such an endeavor requires learning first-order lessons from the evolution of life on Earth. By investigating the continuum from no life to life on Earth, scientific ocean drilling can provide a more holistic picture of the requirements for biochemical functioning of **life** and planetary **habitability**. Such knowledge will inform the search for life elsewhere in the universe and help identify the best candidates for extraterrestrial exploration.

This artist's impression shows the planet K2-18b, its host star, and an accompanying planet in this system. K2-18b is now the only super-Earth exoplanet known to host both water and temperatures that could support life. *Credits: ESA/Hubble, M. Kornmesser*.



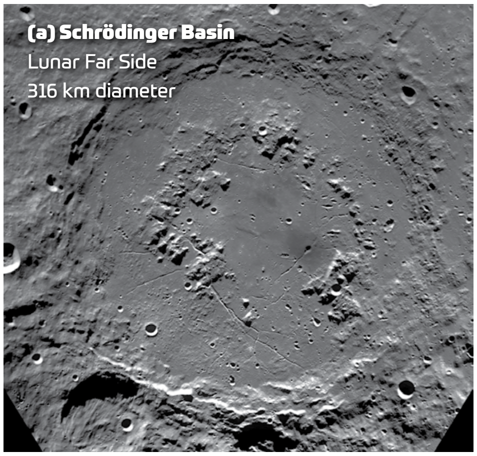
Samples from Extreme Environments

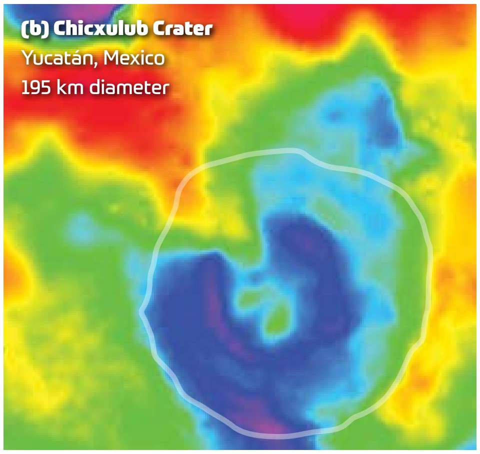
Sample return from extraterrestrial bodies has greatly advanced our knowledge of the formation and evolution of the solar system. To obtain determinative evidence of martian life, various space agencies, including NASA, ESA, JAXA, and the Canadian Space Agency, started the Mars Sample Return project, which began with the launch of the Perseverance rover launch in July 2020. This rover will cache samples for return to Earth in the 2030s. Collaboration with scientific ocean drilling will offer space agencies an opportunity to first develop and test technologies on microbial samples collected in extreme environments through drilling in the ocean basins, before applying those techniques to extraterrestrial samples.

A United Launch Alliance Atlas V rocket with NASA's Mars 2020 Perseverance rover on board was launched Thursday, July 30, 2020, at Cape Canaveral Air Force Station in Florida. The rover's mission on the Red Planet is to search for signs of ancient life and collect samples to send back to Earth. *Image credit: NASA/Joel Kowsky*

Investigating impact craters. Tracking of near-Earth asteroids for planetary protection is a priority of space agencies. Although asteroid impacts pose a clear natural hazard to our planet, the impact processes and **environmental aftermath** on a planetary scale are poorly understood. Scientific ocean drilling will provide greater insight into the processes involved in impact crater formation by investigating meteorite impact structures, such as Chicxulub in Mexico and in Chesapeake Bay in Virginia, USA, and their ejecta across Earth. These scientific ocean drilling investigations will permit comprehensive studies of the consequences of impacts on local, regional, and global scales and the process of the impacts themselves and the immediate planetary implications. They will also provide insights into recovery after the impact event, including a better understanding of the **resource potential** from any post-impact hydrothermal circulation. Samples of material in and around the impact craters recovered by scientific ocean drilling will capture pre-impact conditions, the impact itself, post-impact recovery processes, and impact-induced hydrothermal habitats.

Scientific ocean drilling will provide greater insight into the processes involved in impact crater formation by investigating meteorite impact structures and their ejecta on Earth.





(a) Mosaic of images from the Schrödinger Basin, an impact crater on Earth's moon. The impact structure looks very similar to the that of the (b) Chicxulub impact that occurred ~66 million years ago on Earth, here shown in gravity measurements. *(a) From http://lroc.sese.asu.edu/posts/161. (b) Modified from Lowery et al. (2019), https://doi.org/10.5670/oceanog.2019.133.*

FUTURE COLLABORATION

The perspectives of scientific ocean drilling and space agencies regarding the Earth system are complementary, presenting opportunities for mutually beneficial collaborations. For example, scientific ocean drilling requires teams to effectively and efficiently collect new scientific data in challenging and unexplored environments, which in turn can inform approaches for missions beyond Earth. We anticipate that close cooperation between scientific ocean drilling and space organizations will foster scientific and technological breakthroughs in drilling, coring, and analytical techniques and will facilitate new directions for scientific ocean drilling and remote robotic investigations of planetary bodies. Partner organizations will benefit by combining technical strengths to better recognize, extract, and preserve life signatures in extreme environments on Earth and other planets; by telling a unified story about how the Earth system functions; and by training the next generation of researchers to think in a fully interdisciplinary fashion.

ENABLING ELEMENT 4 TECHNOLOGY DEVELOPMENT AND BIG DATA ANALYTICS

SUMMARY

Progress in addressing the ambitious scientific objectives of the *2050 Science Framework* requires continued development of drilling, coring, logging, observatory, and laboratory tools and techniques. And, as capturing information from these sources becomes ever more digital and higher resolution, the requirements for maintaining the cyberinfrastructure to store, process, analyze, and model the resultant large data sets and diverse data types are growing significantly. Big data analytical techniques applied to scientific ocean drilling data will play an increasing role in advancing the science and informing policy. The five-year review cycle of the *2050 Science Framework* will allow scientific ocean drilling to update its approaches to investigating the interconnected Earth system as innovations in drilling and coring technologies, downhole and shipboard analytical tools, and big data analytics reshape how science gets done.

The International Ocean Discovery Program (IODP) Bremen Core Repository at MARUM. Cores from the Atlantic and Arctic Oceans and the Mediterranean, Black, and Baltic Seas are stored here. *Image credit: MARUM – Zentrum für Marine Umweltwissenschaften; Universität Bremen; V. Diekamp*

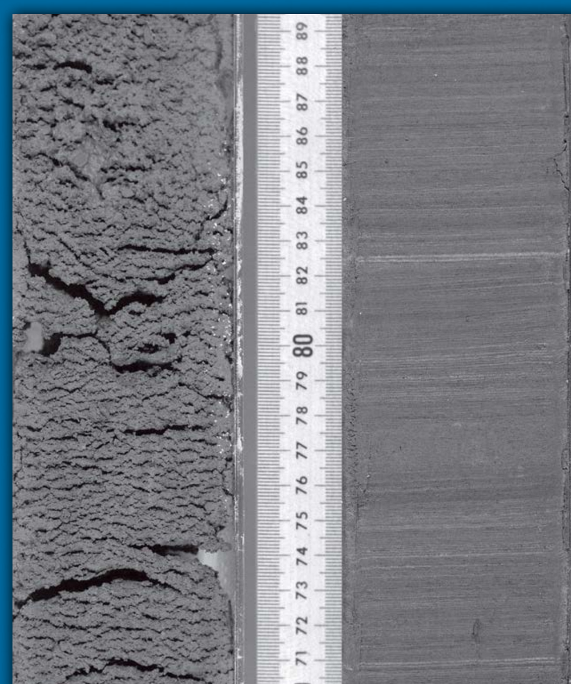
REVOLUTIONIZING SCIENTIFIC OCEAN DRILLING

Since its inception, scientific ocean drilling has established an excellent track record of developing innovative technologies in response to new scientific challenges and paradigms and exploring new scientific avenues that open up through external technological developments. Over the last two decades, the pace of such developments has been impressive and will keep driving progress in future scientific ocean drilling. Key innovations include installation of cabled borehole observatories that transmit real-time data of subsurface conditions and changes, development of improved coring techniques for sampling fault zones, application of the highest contamination control measures for microbial sampling, implementation of onboard X-CT scanning of core sections to ensure capture of critical intervals, and assimilation of proxy climate data from scientific ocean drilling cores into numerical climate models to evaluate and improve model performance.

Future developments in technology, monitoring, and observatory science will be needed to achieve the ***Strategic Objectives*** and implement the ***Flagship Initiatives*** of the *2050 Science Framework*. Some examples include the need to continue to improve and deepen the recovery of undeformed sediments. Core orientation advancements will help minimize magnetic overprinting so we can obtain the best quality paleomagnetic records. Another goal is to minimize sample contamination to enable collection of pristine samples of the deep biosphere. We need to continue to improve our ability to recover cores in hot crust and unstable, tectonically deformed terrain. These technical innovations should be matched with better capturing shipboard and land-based measurements to improve our ability to visualize complex data and instantly be able to compare new data streams with those collected on previous expeditions. Innovations in analytical tools and laboratory techniques will allow us to maximize the scientific

Pioneering Research and Engineering in the Ocean

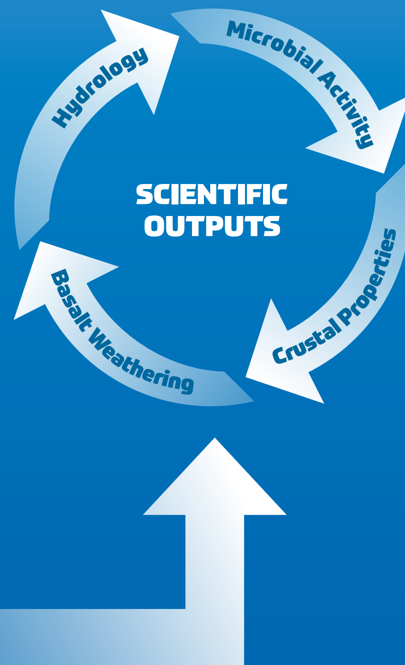
Scientific ocean drilling pioneered drilling in deep ocean basins at a time when the petroleum industry was only operating on the shallow continental shelves. Drilling in the deep ocean required engineering innovations such as development of a dynamic positioning system to maintain location over a drill site for several weeks at a time, despite wind and ocean currents. This versatile system is now regularly deployed on research vessels, commercial drillships, cable-laying ships, and even cruise ships. Over subsequent decades, scientific ocean drilling invented and refined hydraulic piston coring tools that today allow us to retrieve continuous, high-fidelity sediment cores that provide a detailed history of Earth's climate. Borehole observatories developed by scientific ocean drilling isolate the drill holes from the ocean, allowing physical, chemical, and biological conditions within the boreholes to be monitored during and after the fluids have re-equilibrated.

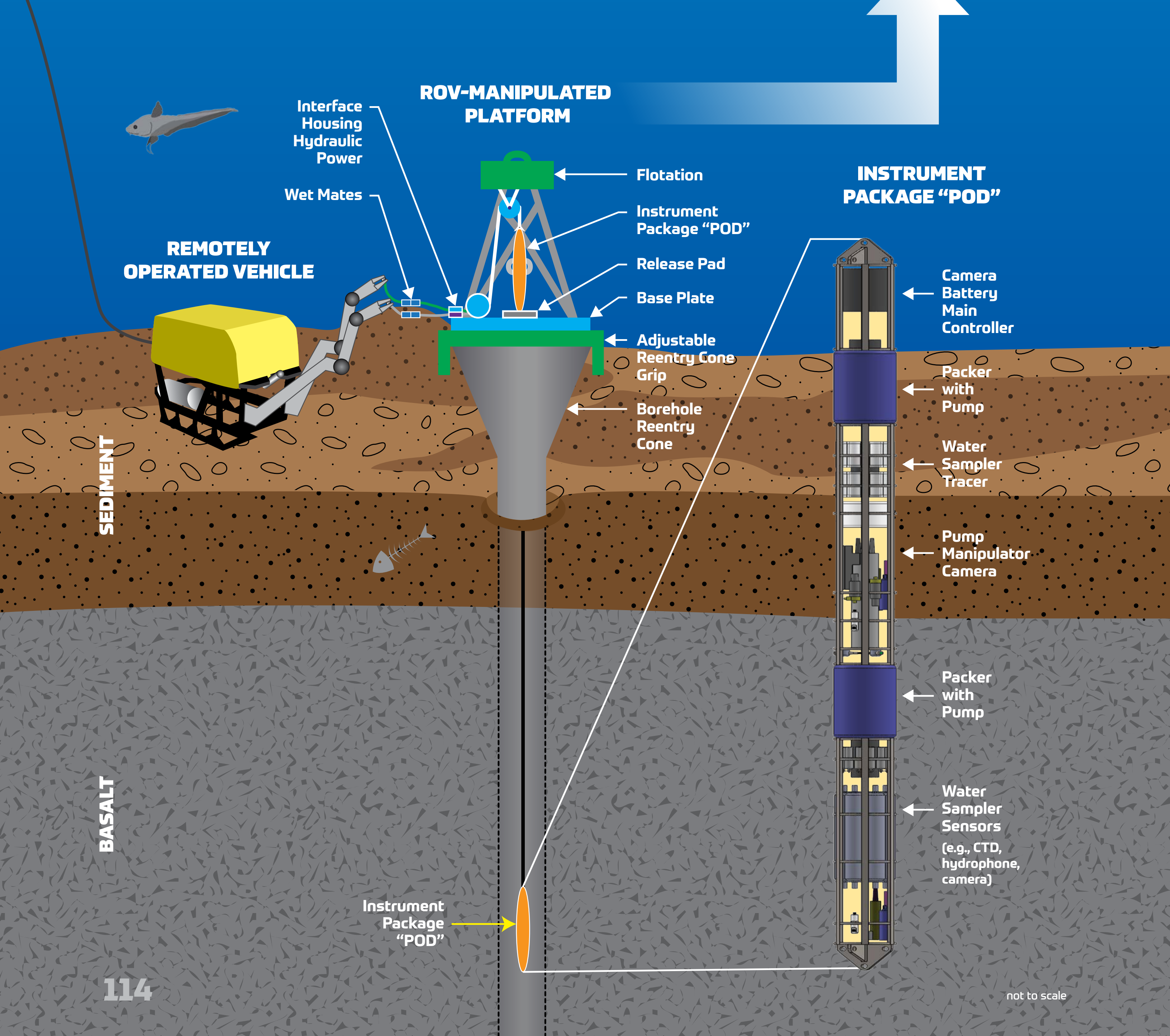


Comparison of sediment core quality between rotary drilling and piston coring.

Example Technological Innovation for Future Drilling

We are at a technical inflection point where prior operational successes, multi-disciplinary needs, and broad scientific support will accelerate the pace of technological advancement to further our understanding of processes that shape the evolution of the oceanic crust. For example, several *Flagship Initiatives* will benefit from the design, fabrication, and commissioning of a remotely operated vehicle-manipulated platform that, when lowered to the seafloor, will allow a flexible array of sensors and samplers to be deployed in existing scientific ocean drilling boreholes in the upper volcanic oceanic crust. Such a platform will benefit from the availability of many off-the-shelf sensors, samplers, and systems within a flexible and modular framework. Such a tool will benefit experiments and exploration today, while allowing future generations of sensors and samplers to be incorporated. *Illustration by Geoff Wheat, Claudia Paul, and Geo Prose.*





potential of five decades of scientific ocean drilling cores housed in our core repositories, make new discoveries from these legacy samples, and inform new avenues of inquiry for scientific ocean drilling.

Science leading innovation. Given the long timeframe of this *2050 Science Framework*, the science proposed in the *Scientific Objectives* and *Flagship Initiatives* can drive technological developments. **Probing the deep Earth** will require us to drill deeper than ever before into oceanic lithosphere, leading to the development of new coring capabilities to operate at more extreme in situ temperatures and pressures. **Assessing tsunami and earthquake hazards** will be most effective if it includes real-time monitoring of the critical in situ pore fluid pressures, temperatures, and strain in the fault zone. Such monitoring will require improvements in or development of rig-deployable borehole instruments and development of affordable infrastructure to transmit data between observatories and the shore. **Exploring life and its origin** on Earth and assessing the pharmaceutical potential of the deep biosphere will require new techniques to conduct in situ manipulative experiments and methods to isolate and culture subsurface life. Among the technologies requiring development are coring tools that can be used in difficult-to-sample environments and that can preserve critical fabrics in uncemented sandy sediments.

State-of-the-art contamination control was used for microbiological sampling from sediment cores during International Ocean Discovery Program Expedition 370. In order to avoid the intrusion of drilling fluid into the inner part of the "mbio" sample, the outer part was carefully removed with sterile tools inside an anaerobic chamber. *From Heuer et al. (2019), https://doi.org/10.5670/oceanog.2019.147*

Industry innovation enabling science. Scientific ocean drilling recognizes that external technology developments will enable new scientific opportunities. Industry is continually introducing novel coring approaches and platforms, downhole tools, artificial intelligence applications, and core-log interpretation protocols. Scientific ocean drilling into exposed rock outcrops and recovery of hard rock material have been particularly challenging, in part because historically industry did not work in such environments. The frontier exploration in basalt-hosted oil and gas reservoirs on some continental margins and ultrahard formations on the Brazil margin has led to industry development of new hard rock drilling technologies that could be adopted for scientific ocean drilling purposes.

Scientific ocean drilling will also benefit from future industry-led developments in seismic reflection data acquisition. These new techniques will yield higher resolution site survey data that will significantly improve targeting of coring sites and penetration depths and provide invaluable regional context. Scientific ocean drilling will continue to benefit from collaboration between its scientists and engineers and industry experts, allowing us to realize our scientific ambitions and ensuring successful and safe scientific ocean drilling operations.

Since its inception, scientific ocean drilling has established an excellent track record of developing innovative technologies in response to new scientific challenges and paradigms and exploring new scientific avenues that open up through external technological developments.

Need for big data analytics. Although the foundation of scientific ocean drilling is the recovery of core samples from marine environments, each drilling expedition also collects an array of geophysical, geochemical, and biological data that are equally important. Core analyses, in situ downhole measurements, and monitoring data from borehole observatories are all linked to regional geological and geophysical observations. Automation of data collection in laboratories will expand and become routine, vastly

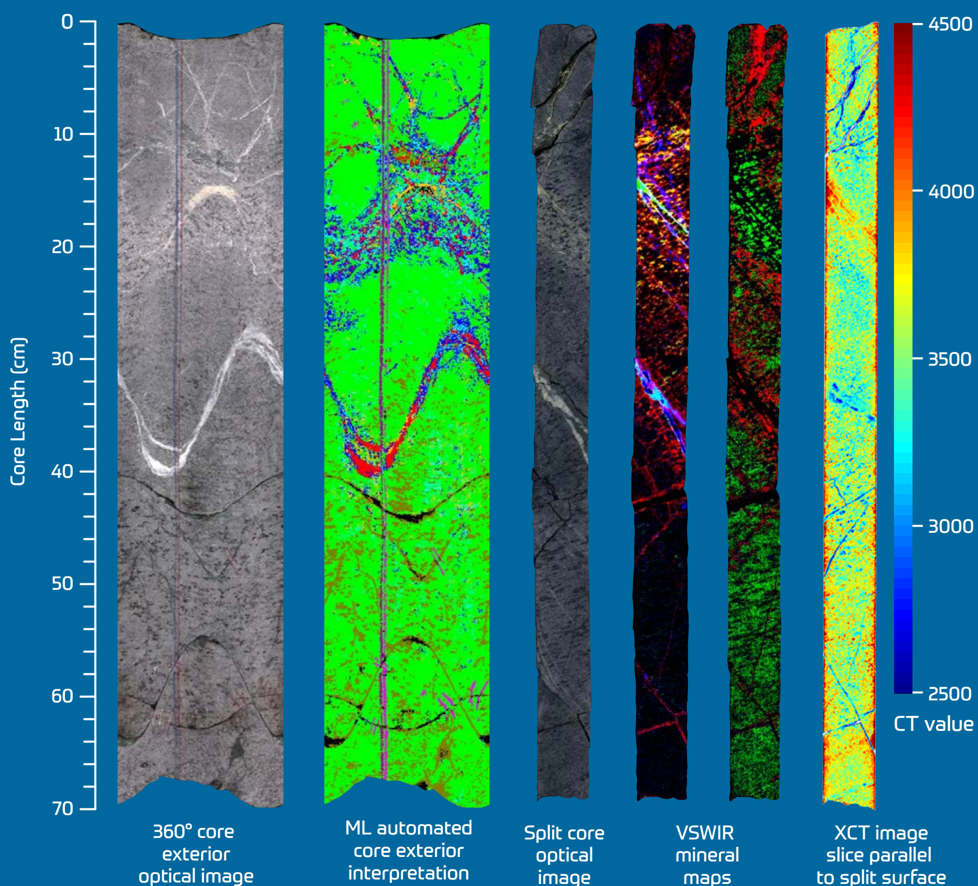
Data Innovation for Future Drilling

For many of the science goals laid out in the *2050 Science Framework*, the objective quantification of the subsurface is mandatory to reach useful conclusions and avoid misleading results. This applies to all rock types recovered by scientific ocean drilling but is especially true of hard rock coring, where recovery is usually incomplete and biased to more robust rocks. The rocks that record the greatest hydrothermal exchanges and biological activity are the most fragile, fractured, and/or altered. Core-log integration to characterize the missing materials remains challenging and human intensive and requires improved high-resolution imaging tools to more precisely locate these intervals.

New approaches already used by industry and some terrestrial scientific drilling experiments, such as the Oman Drilling Project in collaboration with the International Continental Scientific Drilling Program, allow cores to be more thoroughly recorded before splitting and further processing. Optical imaging of the external surface of cores freshly released from the core barrels provides high-resolution digital records of the cores when they are most intact, preserving context and enabling feature recognition and objective quantification by artificial intelligence/machine learning (AI/ML) approaches. Digital observations need not be restricted to the visual spectrum, and current photographic imaging of exterior and split surfaces can be supplemented by visible to short wavelength infrared (VSWIR) spectroscopy, so-called "hyperspectral scanning" by industry, that allows mineral identification and mapping at submillimeter spatial resolution. X-ray computation tomography (XCT) complements these surface imaging techniques by providing three-dimensional density maps of the core interiors, assisting with the recognition of veins, fabrics, and layering, and revealing hitherto unavailable internal imaging of faults and breccias.

With the right instrumentation, these approaches can be fit into onboard workflows. It is critical to recognize up front that they produce very large amounts of data and demand big data analytical approaches that until recently remained in the domains of particle physics or astronomy, but are increasingly required for Earth and environmental sciences. Supervised and unsupervised convoluted neural networks (CNN) can objectively recognize, measure, and quantify the presence of minerals and features, arguably better than the most experienced scientist over a two-month drilling expedition. These approaches should never take the scientists "out of the loop" but will improve the consistency, efficiency, and accuracy of observations once calibrated and tested.

Digital Observations of Oman Drilling Project Core GT2A-120Z2 and Machine Learning Image Interpretations



Example of existing non-destructive core scanning approaches and automated interpretations of digital data for hydrothermally altered gabbros from the lower oceanic crust of the Semail ophiolite, Oman. Note the damage caused to the upper 12 cm of this section (split core optical image) as a result of cutting with a diamond saw blade. *Credits: Optical images from the Oman Drilling Project. Machine learning automated interpretation from Peter Hopkins, Blair Thornton, and Damon Teagle. VSWIR from Rebecca Greenberger and Bethany Ehlmann. XCT analysis from Katsu Michibayashi.*

ML Key

- Background rock
- Altered Gabbro
- Altered olivine
- Epidote
- Clinozoisite
- Zeolite

VSWIR Key

Left panel

- Chlorite
- Chlorite + epidote/clinozoisite
- Epidote/clinozoisite
- Prehnite + epidote/clinozoisite
- Prehnite
- Prehnite + chlorite
- Chlorite + epidote/clinozoisite + prehnite

Right panel

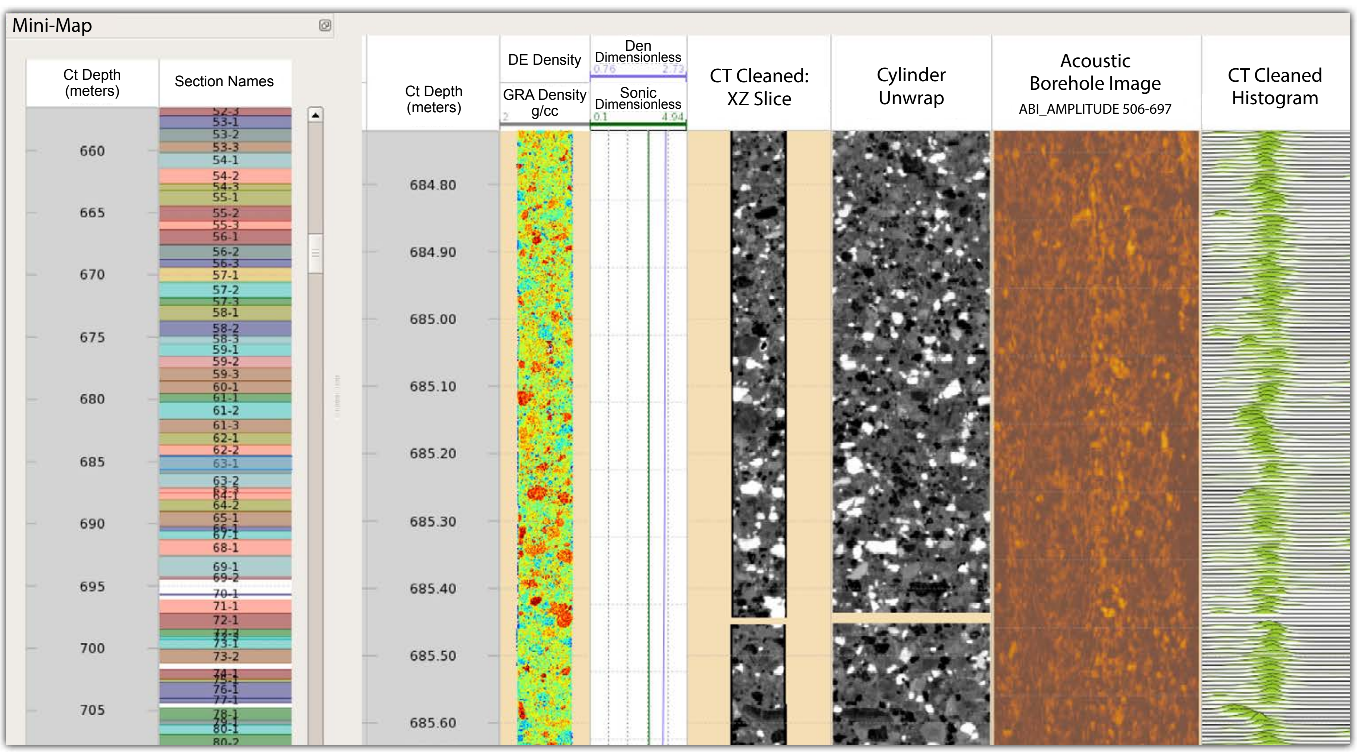
- Zeolite
- Clinopyroxene
- Amphibole

increasing the number and size of data files. Progress in scientific ocean drilling increasingly depends on the compilation and integration of these very large and varied data sets ("big data") and the sophisticated computational tools used to analyze them.

Intergovernmental Panel on Climate Change **climate projections** can be improved by incorporating real data on past climates acquired through scientific ocean drilling. These ground truth data must be aggregated from hundreds of globally distributed sites spanning millions of years of **Earth's climate history** and acquired over many scientific ocean drilling expeditions. Similarly, to make significant progress in **exploring life and its origin** on Earth may require building a databank of subseafloor microbes. The vast amounts of data that will be collected by scientific ocean drilling through 2050 will be complemented by an equally vast legacy database from the previous 50 years of scientific ocean drilling, including the supplementary data collected prior to drilling during site surveys and post-expedition, as well as data collected by downhole instruments. By compiling these huge data sets, mining the holdings, and examining them with big data tools, previously unrecognized patterns, correlations, and trends may be revealed, advancing the science and informing policy.

Progress in scientific ocean drilling increasingly depends on the compilation and integration of these very large and varied data sets ("big data") and the sophisticated computational tools used to analyze them.

To achieve *Strategic Objectives* and *Flagship Initiatives* outlined in this *2050 Science Framework*, we need to maximize the scientific potential of all existing and future scientific ocean drilling data. These data must be findable, accessible, interoperable, and reusable (FAIR) in order to take advantage of new and existing data analytics tools that will reveal patterns and trends within the interconnected Earth system. A key strength of scientific ocean drilling has always been ensuring open access to its databases. By focusing on FAIR data practices, and by developing common standards among the future platform providers, scientific ocean drilling will continue to produce data that will benefit the global science community and the wider public.



Screenshot of Virtual Core visualization software with various types of data added. Left to right: Mini-Map (navigation tool), X-ray computerized tomography (CT) density, sonic well log and multisensor core logger (MSCL) density, CT XZ slice, CT unwrapped, acoustic borehole image, and CT cleaned histogram. *From Figure F13 in Gulick et al. (2017), https://doi.org/10.14379/iodp.proc.364.102.2017*

Countries Involved in Developing the

2050 SCIENCE FRAMEWORK

Australia, Austria, Brazil, Canada, China, Denmark, Finland, France, Germany, India, Ireland, Italy, Japan, Netherlands, New Zealand, Norway, Portugal, South Korea, Spain, Sweden, Switzerland, United Kingdom, United States of America

2050 SCIENCE FRAMEWORK
Document Development

Six international planning workshops were organized in 2018 and 2019 in India, Japan, Europe, Australia and New Zealand, the United States of America, and China. More than 650 scientific ocean drilling scientists participated; about 30% were female and 40% early to mid-career scientists. The results from those workshops were presented, discussed, and distilled in July 2019 during the first meeting of the *Science Framework Working Group*. The 19 international scientist delegates in this working group—representing all current International Ocean Discovery Program (IODP) member countries and consortia—established a consensus roadmap to develop a new science framework in support of *Future Scientific Ocean Drilling Through 2050*. In August 2019, a draft of this proposal was posted on IODP.org for commenting by the overall IODP community, and based on the constructive and positive community input, a final revised proposal was presented to and endorsed by the IODP Forum during its September 2019 meeting in Osaka, Japan.

A diverse international writing and reviewing team was established, including more than 45 scientists from all career stages, with an emphasis on early to mid-career scientists. This team has worked on four different drafts, involving two internal reviews. Two full drafts of the *2050 Science Framework* were circulated for community review in February and July 2020. Following those reviews, the final framework documents were endorsed by consensus during the virtual IODP Forum meeting in September 2020.

The outcome of this extensive peer review process and the high level of community input and involvement has resulted in an exciting outlook on more than 25 years of future scientific ocean drilling, with a focus on new scientific frontiers and a strong emphasis on research that will have societal impact as seen through the lens of a diverse next generation of Earth scientists. The *2050 Scientific Framework* demands strong interdisciplinarity in scientific ocean drilling, enhanced by collaborations with external partner organizations. It also shows how our science informs society, while addressing foundational Earth system research questions.

FIGURE CREDITS, SOURCES, AND REFERENCES

Cover .... **Microbes**: Jason Sylvan, Texas A&M University.
Hydrothermal Vent: MARUM – Zentrum für Marine Umweltwissenschaften, Universität Bremen (CC-BY 4.0, https://creativecommons.org/licenses/by/4.0/).
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Earth Image: https://www.ngdc.noaa.gov/mgg/image/etopo1_large.jpg.

TOC .... **(left)** Publications Specialist Ekant Desai (IODP/JRSO) and others on the catwalk with a core during International Ocean Discovery (IODP) Expedition 383, Pacific Antarctic Circumpolar Current. *Credit: Sian Proctor & IODP.*
(middle) Structural Geologist Joann Stock (California Institute of Technology, USA), Igneous Petrologist S. Khogenkumar Singh (National Centre for Antarctic and Ocean Research, India), and Co-Chief Scientist Daniel Lizarralde (Woods Hole Oceanographic Institution, USA) examine a core on the description table during IODP Expedition 385, Guaymas Basin. *Credit: Andreas Teske & IODP.*
(right) Sipan Issa rinses off the core halves after splitting during the Expedition 381 onshore science party at the Bremen Core Repository. *Credit: V. Diekamp ECORD/IODP/MARUM.*

Mission .... **Marble Earth:** iStock.com/pixalot.

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Page 4............ **Background Photo | *Glomar Challenger.***
Inset Photos (from left to right)
D/V *Chikyu*: JAMSTEC.
***JOIDES Resolution*:** William Crawford, IODP/TAMU.
Icebreakers *Vidar Viking*, *Oden*, and *Sovetskiy Soyuz*: IODP-ECORD.

Page 10.......... **Ground Truthing Future Climate Change:** iStock.com/Byronsdad.
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Page 13.......... **Photo credit:** John Beck, IODP/TAMU.

Page 15.......... **Modified from Figure 1 in:** Lineweaver, C.H., and A. Chopra. 2012. The habitability of our Earth and other Earths: Astrophysical, geochemical, geophysical, and biological limits on planet habitability. *Annual Review of Earth and Planetary Sciences* 40:597–623, https://doi.org/10.1146/annurev-earth-042711-105531.

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Archaea: Methanogens in buried coal beds off Japan, ©JAMSTEC., http://www.jamstec.go.jp/gallery/e/organism/micro/004.html.
Bacteria: Figure 7b in Imachi, H.E., Tasumi, Y. Takaki, T. Hoshino, F. Schubotz, S. Gan, T.-H. Tu, Y. Saito, Y. Yamanaka, A. Ijiri, and others. 2019. Cultivable microbial community in 2-km-deep, 20-million-year-old subseafloor coalbeds through ~1,000 days anaerobic bioreactor cultivation. *Scientific Reports* 9:2305, https://doi.org/10.1038/s41598-019-38754-w.
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(left) Reentry cone from legacy DSDP Hole 395A.

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(1) Core Description Scientist Jianghong Deng (University of Science and Technology of China) and Organic Geochemist Olivier Sissmann (IFP Energies Nouvelles, France) sample a core, International Ocean Discovery Program (IODP) Expedition 366, Mariana Convergent Margin. *Credit: Tim Fulton, IODP/JRSO.*

(2) Sedimentologist Francesca Meneghini (Università degli Studi di Pisa, Italy), Structural Geologist Heather Savage (Lamont-Doherty Earth Observatory [LDEO], Columbia University, USA), Sedimentologist Hannah Rabinowitz (LDEO, Columbia University, USA), and Structural Geologist Ake Fagereng (Cardiff University, UK) describe a core during IODP Expedition 375, Hikurangi Subduction Margin. *Credit: Tim Fulton, IODP/JRSO.*

(3) Engineer Yuichi Shimmoto (JAMSTEC, Japan) and Physical Properties Specialist Aida Farough (Kansas State University, USA) examine a core during IODP Expedition 376, Brothers Arc Flux. *Credit: William Crawford, IODP/JRSO*.

(4) IODP Expedition 381 Science Party and ECORD Science Operator team in the Bremen Core Repository. *Credit: V. Diekamp, ECORD/IODP*.

(5) Paleontologist Thiago Pereira dos Santos (Universidade Federal Fluminense, Brazil) works at the sample table, IODP Expedition 361, South African Climates. *Credit: Tim Fulton, IODP/JRSO.*

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