

EXPLORING EARTH

BY SCIENTIFIC OCEAN DRILLING





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.

Scientific Ocean Drilling Through 2050

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 complex Earth system. It furnishes critical details about geologic processes as well as natural hazards that pose risks to society. Analyses of samples recovered by scientific ocean drilling establish the geologic context for interpreting human impact on climate and the environment, providing the data needed to improve the accuracy of computer models that predict the pace of rising sea levels and the melting of polar and glacial ice. Sampling and analyses also offer glimpses of the types of microbial life that might exist elsewhere in our solar system and beyond.

The *2050 Science Framework* guides scientists on important research frontiers that scientific ocean drilling should pursue. Seven *Strategic Objectives* focus on understanding the interconnections within the Earth system. Five *Flagship Initiatives* integrate these objectives into long-term research efforts that address issues facing society. Four *Enabling Elements* advance the goals of scientific ocean drilling through broader impacts and outreach initiatives, partnerships, collaborations, continued technology development, and innovative applications of advanced data analytics.

The 2050 Science Framework Structure

ENDURING PRINCIPLES

Open access to samples and data. Standard measurements. Bottom-up proposal submissions and peer review.
Transparent regional planning. Promoting safety and success through site characterization.
Regular framework assessments. Collaborative and inclusive international program. Enhancing diversity.



STRATEGIC OBJECTIVES

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



FLAGSHIP INITIATIVES

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



ENABLING ELEMENTS

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

HABITABILITY AND LIFE ON EARTH

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

Understanding what makes our planet habitable, and where and how life originated and evolved, requires knowledge of the complex exchanges that occur between the seafloor biosphere, Earth's crust, and atmosphere.

THE OCEANIC LIFE CYCLE OF TECTONIC PLATES

Investigating the genesis, aging, motion, and destruction of oceanic plates.

Sampling Earth's oceanic crust at different ages globally provides insight into the processes that govern the occurrence of earthquakes, tsunamis, and volcanoes and the global cycling of energy and matter that produces critical economic resources and makes Earth's surface habitable.

EARTH'S CLIMATE SYSTEM

Unraveling ice sheet history, sea level changes, and ocean-atmosphere interactions.

Comprehending how Earth's climate system operates requires documenting the onset, interconnectivity, and resilience of potentially vulnerable components of the system, including global ocean circulation, sea ice and large Arctic and Antarctic ice sheets, and patterns of precipitation and aridity.

FEEDBACKS IN THE EARTH SYSTEM

Constraining the processes that regulate or destabilize the Earth system.

Investigating Earth system feedbacks that have resulted in the repeated reconfiguring of continents, climate alternating between hot and cold extremes, and the evolution of vastly different plants and animals at different periods provides insight into our planet's processes and responses over time.

TIPPING POINTS IN EARTH'S HISTORY

Using Earth's geological past to illuminate future environmental change.

Studying critical environmental thresholds in Earth history that led to rapid transitions into much warmer or colder states provides the information needed to evaluate the rates and consequences of today's changing climate.

GLOBAL CYCLES OF ENERGY AND MATTER

Determining the role, mechanisms, and magnitude of Earth system cycles.

Examining energy, chemical, nutrient, and fluid exchanges between Earth's sediments and rocks, ocean, atmosphere, and life reveals how global cycles moderate Earth's climate, form natural resources, and control the long-term evolution of life.

NATURAL HAZARDS IMPACTING SOCIETY

Understanding natural hazards in the marine environment.

Analyzing the sedimentary record of past hazardous events and installing seafloor observatories to monitor conditions before, during, and after modern events, illuminate the seafloor conditions that influence hazardous events, the mechanisms that control their recurrence and timing, and the likelihood that they will occur in the future.



STRATEGIC OBJECTIVES



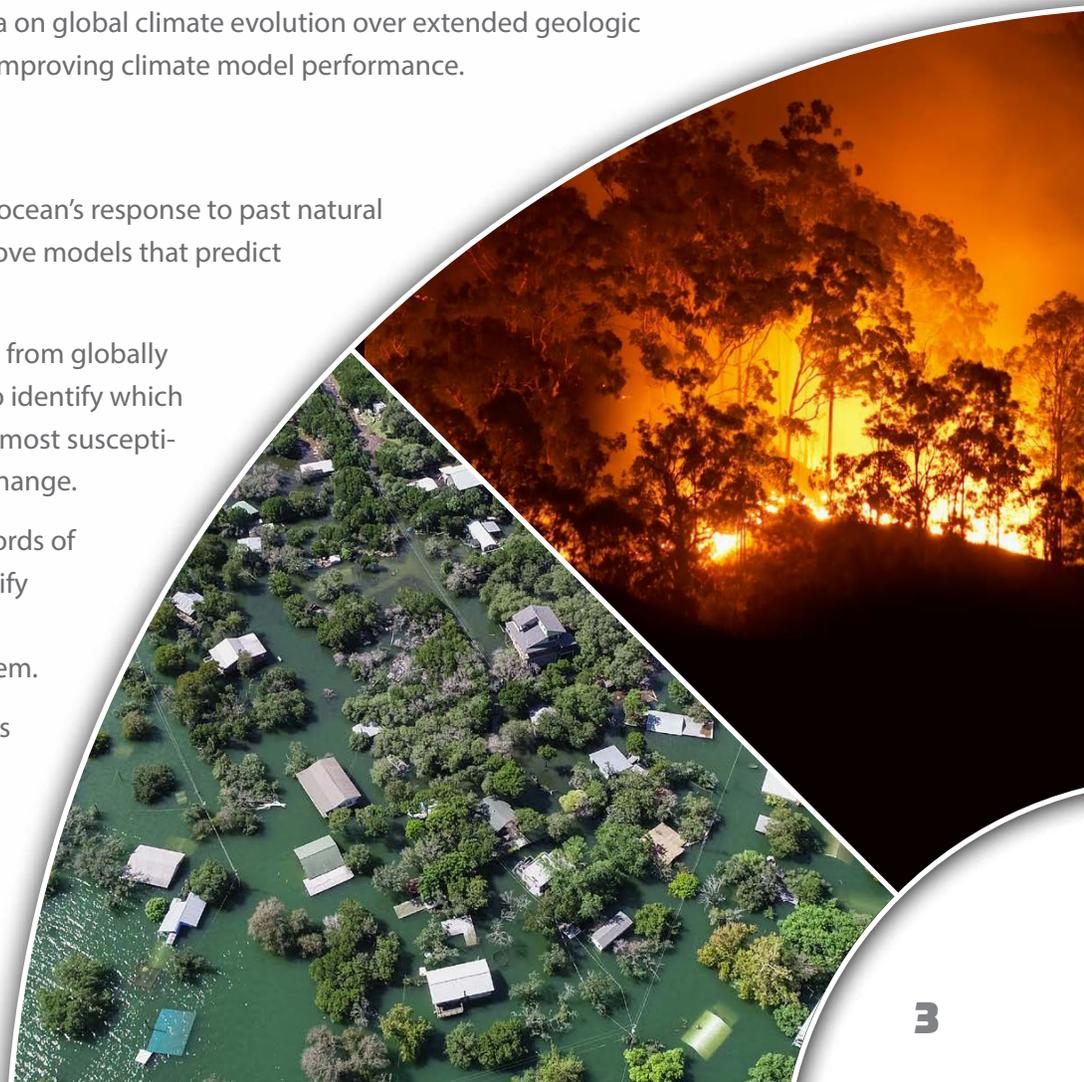
FLAGSHIP INITIATIVES

GROUND TRUTHING FUTURE CLIMATE CHANGE

Predicting how the Earth system will respond to increasing global temperatures is one of the greatest challenges facing geoscientists. Atmospheric CO₂ concentrations have already exceeded 410 ppm in 2020 and, without action to reduce anthropogenic CO₂ emissions, could surpass 900 ppm by 2100. Paleoclimate data collected through scientific ocean drilling established that atmospheric CO₂ last exceeded 410 ppm more than 3 million years ago. Values approaching 900 ppm were only realized during the hot “greenhouse” climate that existed ~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. 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.

Scientific ocean drilling will:

- Provide information about the ocean’s response to past natural climate variability to help improve models that predict future change.
- Assemble paleoclimate records from globally distributed sites in the ocean to identify which parts of the climate system are most susceptible to abrupt and irreversible change.
- Compare past and modern records of climate variability to help identify where human inputs are most influencing Earth’s climate system.
- Improve the accuracy of models of global and regional sea level changes by probing how the deep Earth cools down and how different mantle material gets redistributed.



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, geoscientists have been unable to confirm 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 Earth is the only solar system planet on which new oceanic crust is created in response to mantle upwelling and convection. New multidecadal scientific ocean drilling strategies seek to employ emerging drilling, coring, logging, and monitoring technologies to probe the deep Earth and finally reach the upper mantle. 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.

Scientific ocean drilling will:

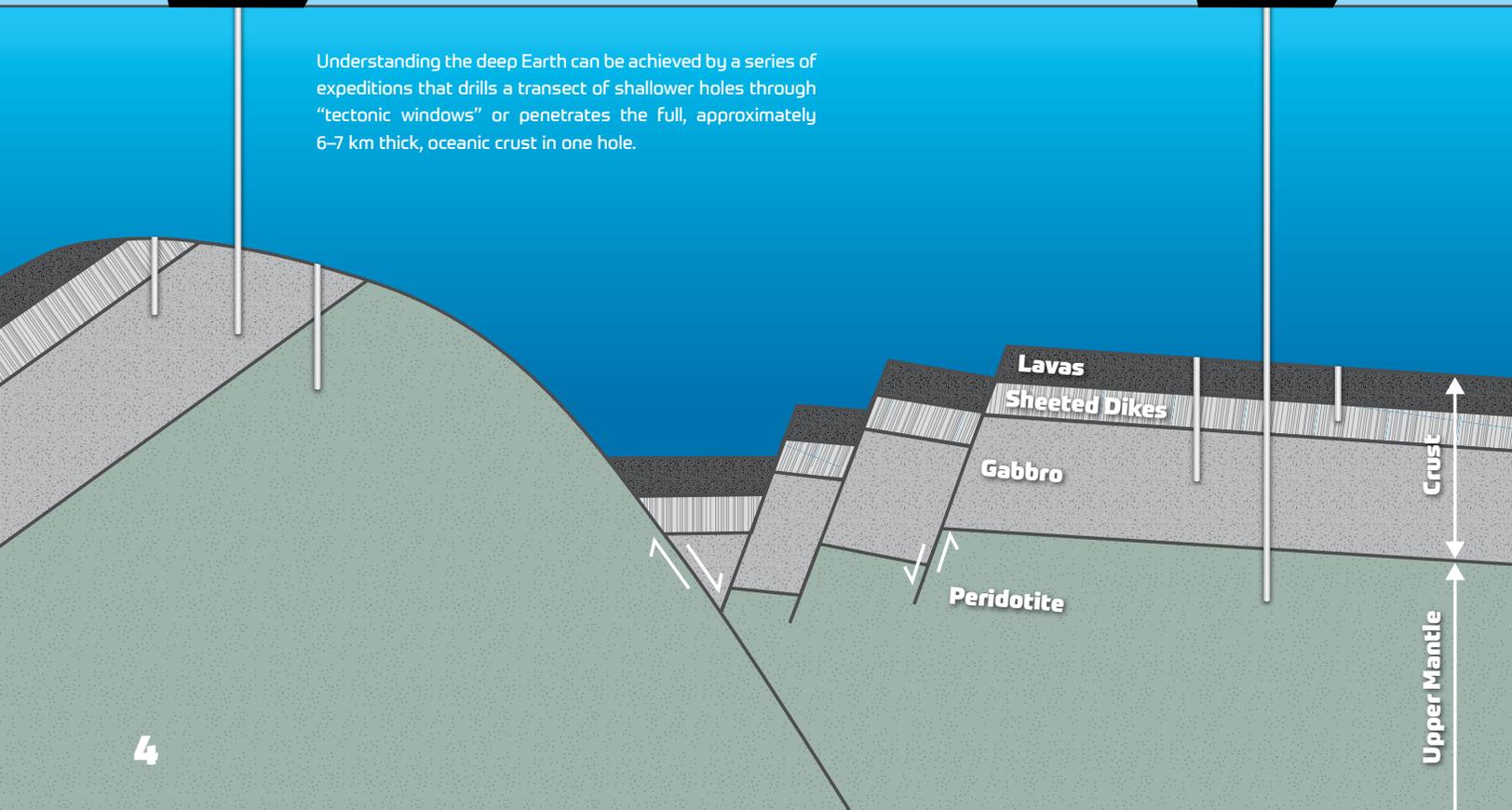
- Probe deep into the oceanic crust to better understand its composition and structure and the nature of the boundary between oceanic crust and mantle globally.
- Establish the rates, distribution, and significance of fluid exchange in the subseafloor between sediments, oceanic crust, and upper mantle.
- Examine how global geochemical cycling and recycling at Earth's subduction zones affect the composition of oceanic crust and upper mantle through time.

Tectonic Window



Understanding the deep Earth can be achieved by a series of expeditions that drills a transect of shallower holes through "tectonic windows" or penetrates the full, approximately 6–7 km thick, oceanic crust in one hole.

Intact Sections



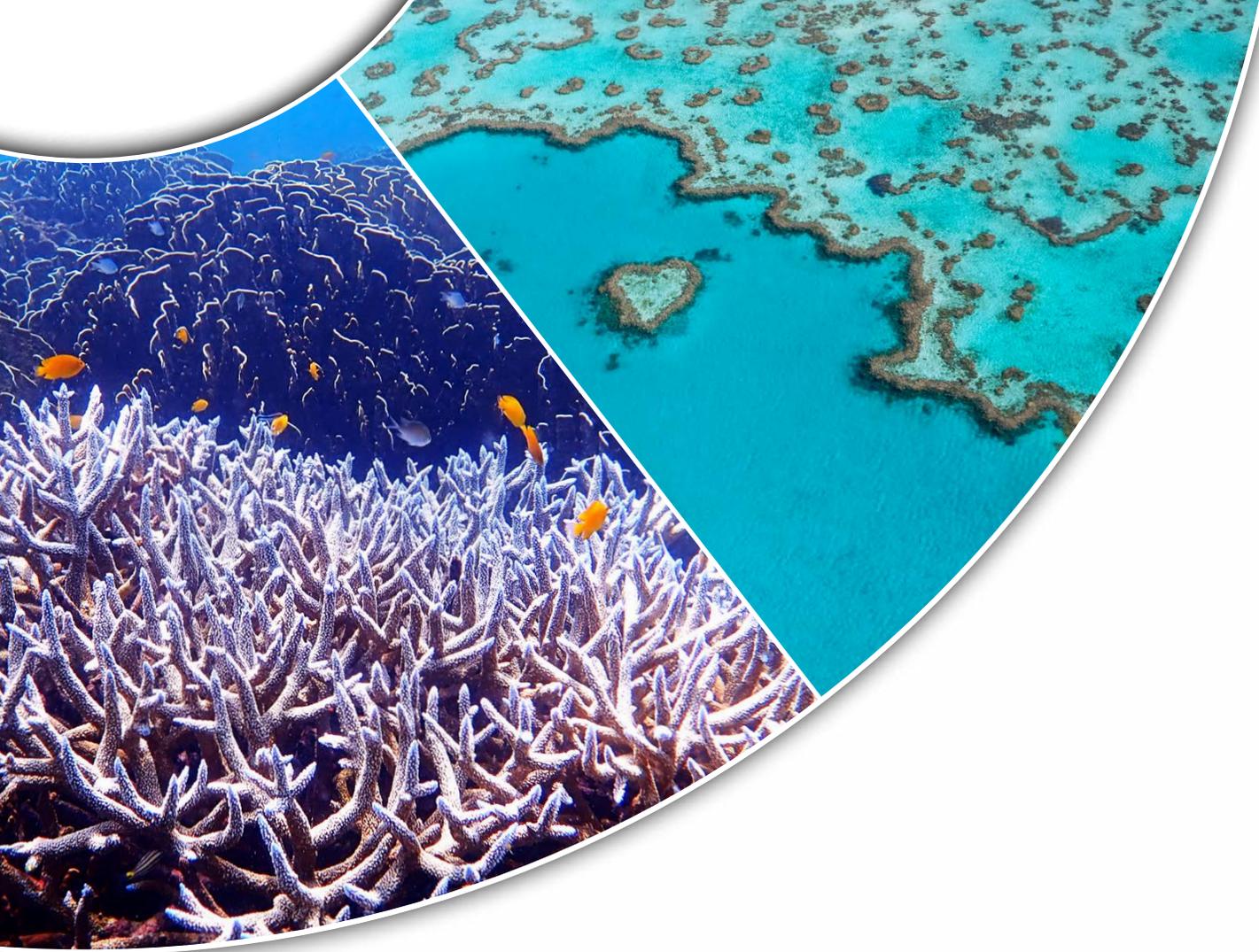


ASSESSING EARTHQUAKE AND TSUNAMI HAZARDS

Undersea earthquakes and associated tsunamis cause some of our planet's deadliest and costliest natural disasters. The 2011 magnitude 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 magnitude 9.2 Sumatra-Andaman earthquake and tsunami in the Indian Ocean killed more than 230,000 people in 15 countries and caused losses close to ~US\$15 billion. The potential earthquake and tsunami hazards of many of the world's coastal zones are poorly known, as many large events have no historical record due to their long recurrence intervals. Advancing our understanding of the earthquake and tsunami potential of tectonic plate boundaries worldwide through scientific ocean drilling and long-term sub-seafloor monitoring will enable more reliable forecasts of the risks posed to vulnerable populations and infrastructure and improve hazard preparedness and response.

Scientific ocean drilling will:

- Acquire a comprehensive set of continuous measurements of changes in Earth's crust over many decades to better understand the processes leading to the occurrence of large earthquakes.
- Use the ocean sedimentary record to document the spatial distribution and frequency of prehistoric large earthquakes and tsunamis.
- Collect a broad range of physical and chemical measurements from the sub-seafloor to establish the key factors that trigger large earthquakes and tsunamis.



DIAGNOSING OCEAN HEALTH

Ocean warming, acidification, deoxygenation, and rising and falling nutrient levels are causing global changes in marine ecosystems. Declining ocean health can devastate biodiversity, habitats, productivity, and fisheries, putting life at risk. Similarly, in the pre-Anthropocene epochs, periods of rapid global warming and cooling, ocean deoxygenation and acidification events, as well as meteorite impacts and episodes of excessive volcanism greatly perturbed ocean ecosystems. The ocean's sediment and rock records show how catastrophic environmental changes altered marine ecosystems and food webs. Scientific ocean drilling will offer a diagnosis of ocean health through geologic time and inform society about the expected rates, durations, and magnitudes of future ocean health deterioration.

Scientific ocean drilling will:

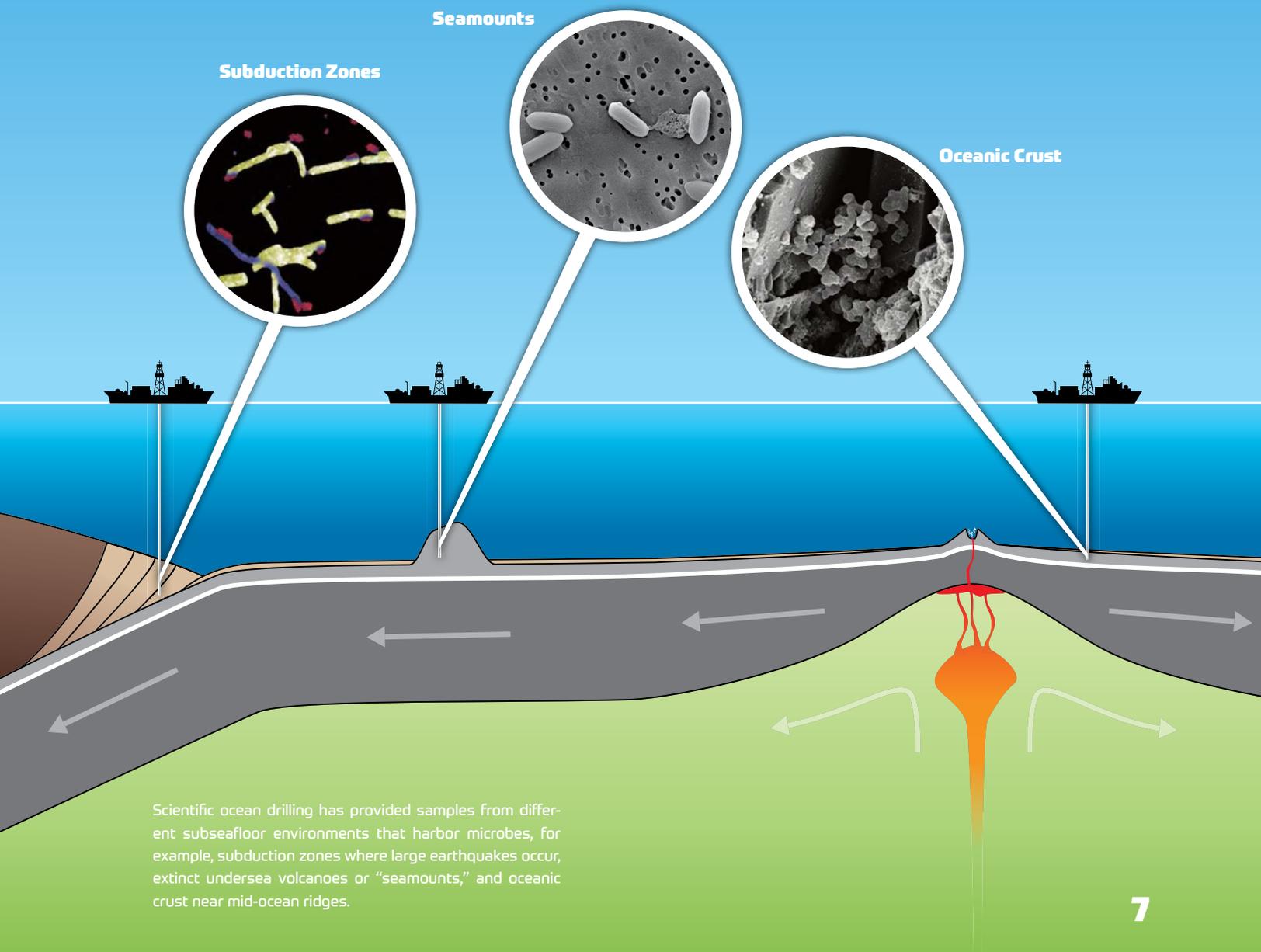
- Reveal how increased rates of change in ocean temperature and acidification affect marine ecosystems and establish the mechanisms and timeframes of adaptation and recovery.
- Establish how future climate change and excessive nutrient inputs may affect oxygen availability in the ocean and the magnitude and extent of the resulting ecological responses.
- Explore changes in ecosystem functioning in the geologic past to provide insight into how impaired, transformed, and potentially new ecosystems will respond to future warming.

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. Microbiologists know little about 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. Sustained scientific ocean drilling is required to sample and monitor a representative range of Earth's diverse seafloor environments and the multitude of microbial communities that they inhabit in Earth's interior.

Scientific ocean drilling will:

- Provide samples that will help elucidate the rules of life for microbes that persist in a range of sedimentary regimes and rock environments beneath the seafloor.
- Access the seafloor in diverse environments to reach the depths at which life is no longer able to survive.
- Provide insight into the potential adaptations of primordial life, the constraints under which it evolved, and hence the origins of life on Earth.
- Establish what life might look like in analogous environments on other worlds and what new organisms and functions reside in Earth's seafloor that might prove useful in biotechnology.





ENABLING ELEMENTS

BROADER IMPACTS AND OUTREACH

Scientific ocean drilling contributes vital data for improving climate models, advancing earthquake knowledge, and assessing the possibility of life on other worlds. Over the last 50 years, it has facilitated global collaboration in science that has resulted in enduring cross-disciplinary partnerships in science and engineering. By providing opportunities for a diverse population of early career scientists, graduate students, undergraduates, and educators to work alongside international teams of experienced scientists and engineers, scientific ocean drilling will remain a preeminent scientific and technical training ground. Communicating about the scientific process and sharing data and results from this international collaboration are essential for developing a scientifically literate global citizenry. Broader impact and outreach efforts will be designed to support educators and inform and inspire the public to be better stewards of our planet.

LAND TO SEA

Our multidisciplinary science does not stop at the shoreline. Strengthened collaborations between the ocean and land scientific drilling communities will advance their closely allied objective to establish the underlying causes of earthquakes, tsunamis, and explosive volcanism. Land-to-sea drilling collaborations will also enhance investigations of the connections between plate tectonics, Earth's climate system, ecosystems, life and habitability, sea level change, and subsurface freshwater flow beneath the coastline.



TERRESTRIAL TO EXTRATERRESTRIAL

Space agencies around the globe aim to expand knowledge of Earth and other worlds in our solar system. Through space exploration, humankind aspires to discover the fundamental physical laws of the universe, decipher the conditions required for 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, the requirements for planetary habitability, and the limits of life promote these goals. Collaboration between 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. 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.

TECHNOLOGY DEVELOPMENT AND BIG DATA ANALYTICS

Scientific progress requires continuous advances in the technology used to obtain samples and data and the tools used to analyze them. Developments in drilling, coring, logging, and observatory technologies are needed to establish more accurately how the Earth system responded to and recovered from past rapid environmental perturbations. They are also needed to continuously measure activity in zones where large earthquakes initiate and to collect pristine samples of microbes that survive under extreme conditions. Innovations in analytical tools and techniques will maximize the scientific potential of existing and future sediment and rock samples. Scientific advancements also depend on the cyber-infrastructure to store, process, analyze, and model the resultant large data sets and diverse data types and integrate them with information gathered by other programs and disciplines.



About the 2050 SCIENCE FRAMEWORK

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IMAGE CREDITS

FRONT 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/>). **Hurricane Damage:** [iStock.com/skrum](https://www.istock.com/skrum). **Coral Reef:** [iStock.com/skrum](https://www.istock.com/skrum). **Desert:** [iStock.com/gorsh13](https://www.istock.com/gorsh13). **Glacier:** [iStock.com/Bernhard_Staehli](https://www.istock.com/Bernhard_Staehli). **Volcano:** [iStock.com/KalypsoWorldPhotography](https://www.istock.com/KalypsoWorldPhotography). **Earth Image:** https://www.ngdc.noaa.gov/mgg/image/etopo1_large.jpg.

FRONT INSIDE COVER. (clockwise from the top)

- 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.*
- 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.*
- Enjoying some sunshine during Integrated Ocean Drilling Program Expedition 318, Wilkes Land Glacial History. *Credit: John Beck, IODP/TAMU.*
- IODP Expedition 381 Science Party and ECORD Science Operator team in the Bremen Core Repository. *Credit: V. Diekamp, ECORD/IODP.*
- 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.*

PAGE 3. (top right) Forest fire at night. *Credit: iStock.com/Byrnsdad.* **(bottom left)** Drone view of flooded neighborhood. *Credit: iStock.com/RoschetzkyStockPhoto.*

PAGE 4. Illustration by Antony Morris and Geo Prose.

PAGE 5. (top left) Tsunami devastation in Japan after the 2011 M_w 9.0 Tōhoku-oki earthquake. *Credit: iStock.com/enase.* **(bottom right)** Damage from the 2010 M_w 8.8 earthquake in Chile. *Credit: Simon Haberle, Australian National University.*

PAGE 6. (top right) Heart Reef aerial shot taken near Whitsunday islands, Queensland. *Credit: iStock.com/byrneck.* **(bottom left)** Tropical coral reef off of Nakinyo Island, Myanmar. *Credit: iStock.com/Waranya Sawasdee.*

PAGE 7. 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.

PAGES 8/9. (left) The IODP Bremen Core Repository at MARUM. *Image credit: MARUM – Zentrum für Marine Umweltwissenschaften; Universität Bremen; V. Diekamp.* **(middle)** 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.* **(right)** ECORD Summer School 2016 in Bremen, Germany. The goal of the summer schools is to train the next generation of scientists. *Credit: V. Diekamp, MARUM & IODP.*