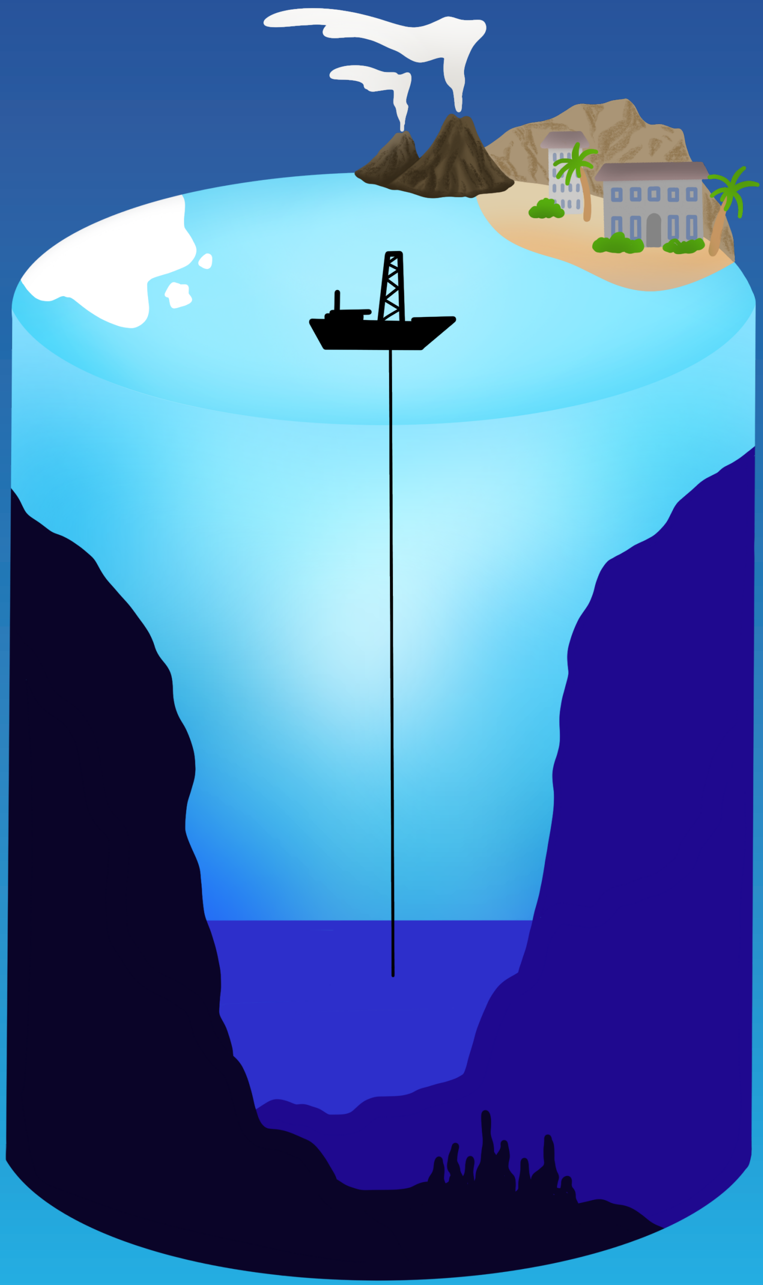
SCIENCE MISSION REQUIREMENTS

FOR A GLOBALLY RANGING, RISERLESS DRILLING VESSEL FOR U.S. SCIENTIFIC OCEAN DRILLING



U.S. Science Support Program Response to the National Science Foundation Request for Assistance

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Executive Summary

Through the collection and analysis of shallow and deep subseafloor sediments, rocks, fluids, and life, scientific ocean drilling has enriched our understanding of the complex Earth system. Scientific ocean drilling has documented the history of Earth's climate, the waxing and waning of polar ice sheets, the past changes in ocean and atmospheric circulation, the existence and function of microbial life in the subseafloor, the compositional variations in Earth's crust and underlying mantle, and the physical and chemical processes acting at subduction zones, including those associated with tsunamigenic earthquakes. Over the decades, more that 12,000 articles that depend on analyses of scientific ocean drilling samples and geophysical data have been published, many detailing breakthrough contributions to global knowledge about the Earth system. Approximately 45% of these publications were led by U.S.-affiliated authors (International Ocean Discovery Program Publication Services, 2021).

Since the mid-1980s, the workhorse of this multidisciplinary, international research effort has been the riserless D/V *JOIDES Resolution*, operated by Texas A&M University with funding from U.S. National Science Foundation (NSF). D/V *JOIDES Resolution* has conducted the vast majority of scientific ocean drilling expeditions and collected most of the scientific cores over that period, including 82% of the expeditions and 93% of the cores in the last decade alone despite being one of three platforms within the International Ocean Discovery Program. D/V *JOIDES Resolution* is approaching the end of its useful life.

With the strong commitment to continue scientific ocean drilling beyond the end of the current phase, the community developed a document outlining the research frontiers that should be pursued. *Exploring Earth by Scientific Ocean Drilling: 2050 Science Framework* (Koppers and Coggon, 2020) describes seven scientific strategic objectives that focus on understanding interconnections within the Earth system and five flagship initiatives that integrate these objectives into long-term research efforts that address issues facing society. Additional elements in the *Framework*, including STEM education, workforce development, technology development, and innovative applications of data analytics, will advance the goals of scientific ocean drilling. Addressing the *2050 Science Framework* also requires building partnerships with allied U.S. and international science programs and strengthening existing ones.

To implement a significant portion of the *2050 Science Framework*, the U.S. scientific community seeks to lease or acquire a newly built, globally ranging, riserless drilling vessel. The many and varied technical and human resources requirements for successful accomplishment of scientific and educational goals summarized in this document and described in detail in the *2050 Science Framework* require broad community input and careful consideration.

Following receipt of NSF's formal Request for Assistance to the United States Science Support Program (USSSP), the U.S. scientific ocean drilling community conducted a one-year exercise to identify its national scientific needs and priorities in order to determine the Science Mission Requirements (SMRs) presented here. This effort included: (1) a U.S. community-wide survey to identify the specific operational and technical capabilities critical to addressing science in the *2050 Science Framework*; (2) a series of online workshops focusing on critical capabilities identified by the survey; and (3) a large in-person workshop to synthesize the results of the survey and the virtual workshops (Appendix 1). This approach was designed to reach as many participants as possible. Overall, 278 survey responses were received from U.S. community members, representing 104 unique institutions from 39 states and the District of Columbia, and 135 unique individuals participated in the workshops (Appendix 2).

The results of this effort comprise two classes of SMRs: Foundational Science Mission Requirements and Primary Science Mission Requirements. Foundational SMRs define minimum criteria for a new riserless drilling vessel that can address significant portions of the *2050 Science Framework*. Primary SMRs build upon the Foundational SMRs to create more robust science opportunities and data collection capabilities, to increase the impact on the *2050 Science Framework*, and to provide more real-time ship-to-shore interaction to improve science engagement and outreach.

Foundational Science Mission Requirements include:

1. **Modern safety and environmental standards,** including meeting standards to access protected waters such as exclusive economic zones, extended continental shelves, or high latitudes, while being cognizant of the vessel's environmental footprint.
2. **Capability to operate safely and efficiently in water depths ranging from 70 m to 6000 m, with total drill string length of at least 7000 m.**
3. **Capability to collect high-quality core from key environments.**
4. **Advanced heave compensation, dynamic positioning, and drill pipe stability.**
5. **Modern mud and cement/casing systems.**
6. **Critical onboard measurements** for safety, operational decision-making, mission-specific science, and long-term science goals that extend beyond a single expedition.
7. **Appropriate space for sample and data preservation**.
8. **Appropriate onboard personnel**, including technical staff for curation and core handling; support for safety, time-sensitive, and critical shipboard measurements; computer support; equipment and instrument repair; application support; and data assurance.

Primary Science Mission Requirements include:

1. **Flexibility in shipboard space** to ensure safe, successful implementation of science objectives and operations.
2. **Minimizing contamination of recovered samples**.
3. **Over-the-side capabilities** for science-supporting technology (e.g., remotely operated vehicles).
4. **Downhole logging and measurements**.
5. **Expanded borehole observatory capabilities**.
6. **Reliable and consistent ship-to-shore communications**.

NSF's investment in a new globally ranging, riserless drilling vessel will have a powerful economic multiplier effect. This includes the infusion of additional science support funds in the United States for training and research, the development of new techniques and tools, and the associated scientific and technical workforce development. The skills and knowledge gained through scientific ocean drilling are translatable to careers in fields such as sustainable energy development (e.g., geothermal and offshore wind), carbon sequestration, data management and infrastructure, biotechnology, communications, science education, policy, hazard mitigation, and environmental management.

The United States is currently a leader in a well-established and internationally collaborative scientific ocean drilling community. A new globally ranging, riserless drilling vessel will allow the United States to retain and grow its leadership position and cultivate equitable international, multidisciplinary collaborations that will ensure scientific ocean drilling's future success.

Importance of Scientific Ocean Drilling

Since its inception more than five decades ago, scientific ocean drilling has transformed, and continues to transform, our understanding of the Earth system. The scientific return on investment in ocean drilling began almost immediately, when one of the earliest expeditions revealed that the age of basal sediments in the South Atlantic increased with distance from the Mid-Atlantic Ridge, thus confirming the theory of plate tectonics (Maxwell et al., 1970). Decades of exploration and hypothesis testing followed this first revolutionary finding, with results impacting our understanding of the fundamental operation of Earth from its interior to its atmosphere, as well as the complex interactions among the components of Earth's system (e.g., Hussong and Uyeda 1981; Saffer and Tobin, 2011; D'Hondt et al., 2019).

The need to drill deeper and in difficult environments, obtain continuous sediment cores, collect minimally contaminated samples, and establish subseafloor observatories has motivated huge advances in drilling and coring technology. These developments have enabled significant progress in understanding of the history of Earth's climate and the potential impacts of future climate change, the global conditions leading to the waxing and waning of polar ice sheets, the timing and consequences of changes in ocean and atmospheric circulation, the existence and function of microbial life in the subseafloor, compositional variations in Earth's crust, and the physical and chemical processes acting at subduction zones, including those associated with tsunamigenic megathrust earthquakes. Over the decades, more that 12,000 articles that depend on analyses of scientific ocean drilling samples and geophysical data have been published, many detailing breakthrough contributions to global knowledge about the Earth system. Approximately 45% of these publications were led by U.S.-affiliated authors (International Ocean Discovery Program Publication Services, 2021). Continued technological and coring advances are likely to enhance our understanding even more.

This multidisciplinary research effort was made possible with funding from the U.S. National Science Foundation (NSF) to the various scientific ocean drilling programs (Table 1). Additional funds from NSF, NASA, Department of Energy (DOE), U.S. Geological Survey, and institutional funds to individual U.S. scientists for training and research had additional positive effects on the programs and outcomes. Conducting cutting-edge research at sea and in the lab fostered the development of new ideas, techniques, and tools that drove considerable scientific and technical workforce development. During 2014–2021, more than 280 U.S. scientists from 44 states and more than 100 U.S. institutions have participated offshore as contributors to scientific ocean drilling expeditions. These scientists have also contributed their scientific ocean drilling discoveries to numerous textbooks and classroom activities that are used to teach many thousands of K–16 students each year.

TABLE 1. Chronology of U.S.-led, NSF-supported scientific ocean drilling riserless drillship programs with coordinated multi-institutional scientific guidance and participation (excludes a few independent, single-PI seafloor drilling programs also supported by NSF).

	PROGRAM DATES	PROGRAM NAME (ACRONYM)	US RISERLESS DRILLSHIP	SCIENTIFIC GUIDANCE GROUP
SINGLE-EXPEDITION PROJECTS	1964	Project Mohole	*CUSS 1*	American Miscellaneous Society (AMSOC)
	1965	Blake Plateau transect	*Caldrill*	
SUSTAINED PROGRAMS	1968–1983	Deep Sea Drilling Project (DSDP)	*Glomar Challenger*	Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES)
	1983–2003	Ocean Drilling Program (ODP)	*JOIDES Resolution* (JR)	
	2003–2013	Integrated Ocean Drilling Program (IODP-1)		IODP Science Advisory Structure (SAS)
	2013–2023	International Ocean Discovery Program (IODP-2)		JOIDES Resolution Facility Board (JRFB) and its panels

As it remains the only way for scientists to gain access to the subseafloor, over the coming decades scientific ocean drilling is poised to contribute considerably more to studies of the interconnections among Earth system components. Sediment cores will continue to provide critical data over geological time periods extending tens of millions of years into the past. These data are needed to improve the accuracy of computer models that predict future climate, including the pace of rising sea levels and the melting of glacial and polar ice. Data gleaned through drilling deep into subduction zones, including the installation of borehole observatories, will yield key information about fault slip that leads to great earthquakes and tsunamis. Scientific ocean drilling is the only way further our understanding of the globe-spanning subseafloor ecosystem and obtain samples that will provide a window into Earth's deep interior.

The planning document, *Exploring Earth by Scientific Ocean Drilling: 2050 Science Framework* (Koppers and Coggon, 2020) outlines the community-defined research frontiers that should be pursued by scientific ocean drilling, as well as their linkages to societal issues, STEM education, workforce development, and allied programs. To implement a significant portion of the *2050 Science Framework*, the U.S. scientific ocean drilling community seeks to lease or acquire a new globally ranging, riserless drilling vessel and to develop an accompanying scientific program. Successful riserless drilling conducted by D/V *JOIDES Resolution*, including 82% of operations in the last decade, demonstrates the efficacy of this approach.

Broad international and multidisciplinary collaboration is critical to scientific ocean drilling's success. The extraordinary range of intellectual, creative, and energetic researchers who have contributed to the efforts over the decades cannot be overstated (Figure 1). These collaborations are fundamental to the success of any drilling program, and past programs have cultivated a community based on respect and inclusion. The U.S. and international scientific ocean drilling communities seek future collaboration, as demonstrated by the international effort to define the science goals in the *2050 Science Framework*. A new U.S.-led riserless drilling program with broad international participation will benefit the United States by strengthening its position as a leader in the international science and technology arenas, by exposing U.S.-based participants to global state-of-the-art technology and science, and by

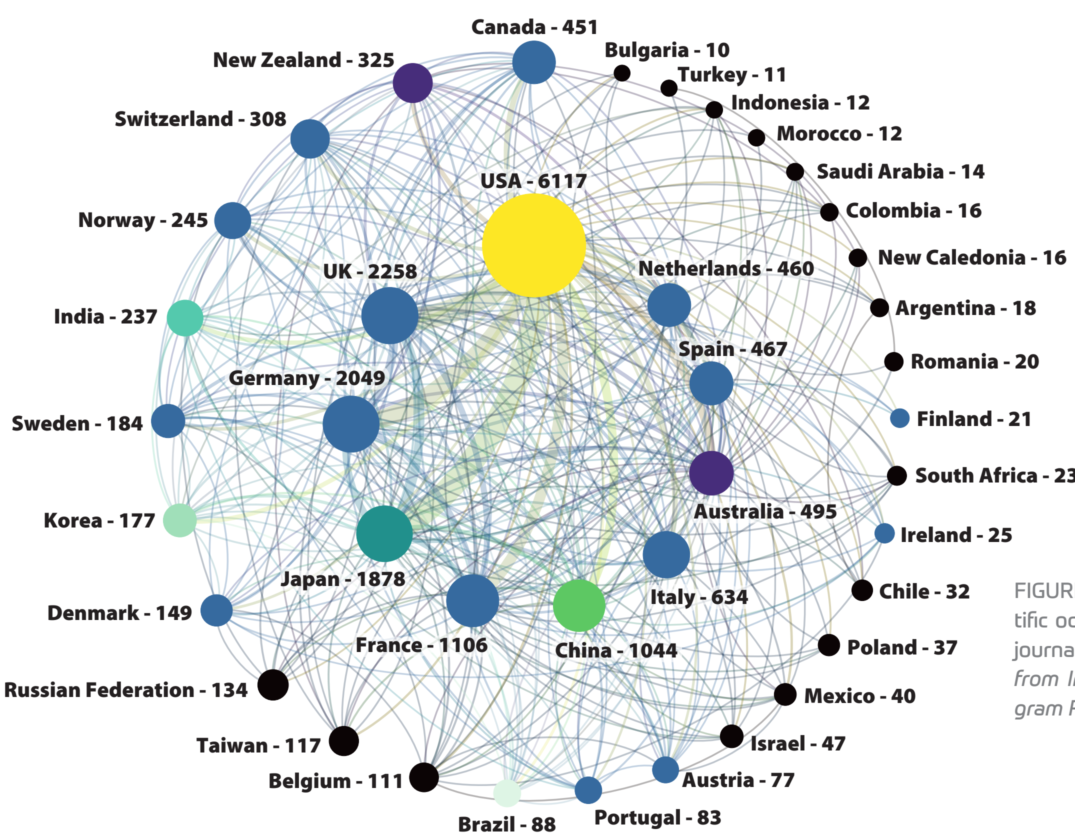


FIGURE 1. Coauthor networks of scientific ocean drilling-related, peer-reviewed journal articles from 2003 to 2021. *Figure from International Ocean Discovery Program Publication Services (2021).*

enhancing collaborations. A new U.S.-led riserless drilling program will also provide a unique resource for the international scientific ocean drilling community; while other riserless drilling vessels exist, they are more expensive (mobilization/demobilization, operations) and are not well prepared for the specifics of scientific ocean drilling. Thus, a dedicated riserless drilling vessel would be valued both within the United States and globally.

In addition to the enormous scientific and societal benefits of scientific ocean drilling, there are very significant risks to the nation if we lose scientific ocean drilling capabilities. With U.S. leadership in scientific ocean drilling over the last six decades, we have leveraged global science and technological excellence to tackle global challenges. Leasing or acquiring a new U.S.-led riserless drilling vessel and development of an associated science program will continue to enhance:

- **U.S. leadership** globally in ocean, Earth, and life sciences.
- **Scientific understanding** of natural hazards, leading to mitigation of impacts to U.S. coastlines from earthquakes and tsunamis; of climate change, including implications related to sea level rise, hurricane frequency and patterns, heating of ocean- and land-based ecosystems, biodiversity loss, and freshwater availability; and of the origin and extent of life on Earth and on extraterrestrial worlds.
- **Innovation in analytical tools and techniques** used to obtain and analyze samples and data, with implications to other fields of study.
- **Workforce development**, providing a training ground for future generations of scientists, engineers, technical support personnel, computer and data scientists, teachers, technology developers.
- **Scientific literacy** of the Earth and planetary scientific community and the general public.

Community-Derived Criteria for Success for a New Facility

The results of the community consultation effort include a complete set of Science Mission Requirements (SMRs) that encompass the community's vision for a modern, riserless drilling facility capable of addressing a significant portion of the science priorities outlined in the *2050 Science Framework* (Figure 2; see Appendix 1 for details on the SMR development process). To achieve success, a new riserless vessel must be capable of:

1. Working in unexplored worldwide locations, including high latitudes (>60°), water depths of 70 m to 6000 m, and coring to 1500+ meters below the seafloor (mbsf).
2. Recovering high-quality cores, with emphases on collection in characteristically difficult settings (e.g., sand or unconsolidated sediments, glacial and glaciomarine sediment, fractured fault zones) and on collection that minimizes sample contamination.
3. Collecting continuous petrophysical logs throughout cored holes, including the upper 50–100 mbsf that is inaccessible with current capabilities, as well as implementing a range of tools for in situ measurements (e.g., pressure, temperature) to 1500+ mbsf.

FIGURE 2. Schematic of the diverse environments where riserless scientific ocean drilling can provide essential scientific data required to address the goals of the *2050 Science Framework*.

4. Efficiently installing modern-design observatories to collect time-series data (e.g., pressure, temperature, resistivity, strain), with the ability to test observatory sensors immediately after installation.

To satisfy these criteria requires a new globally ranging, riserless drilling vessel that meets modern safety and environmental standards, is ice strengthened, can deploy up to 7000 m of total drillpipe, and can drill and core to 1500+ mbsf in favorable formations. Community science goals require the collection of the highest quality cores, the measurement of in situ properties, and the establishment of borehole observatories. These requirements are met by a vessel with adequate heave compensation, dynamic positioning, and drillpipe stability. Deep drilling and coring will require modern, industry-standard mud and cementing systems. Once cores and data are recovered, a new vessel must support state-of-the-art laboratories, with appropriate power, water, ventilation, and data networking. A new vessel should provide scientists with the facilities to make critical onboard measurements and to curate and temporarily store core materials onboard under the appropriate environmental conditions. The curation system should allow for additional onshore curation beyond 2050, and all data acquired on the vessel should be made accessible to the entire science community in FAIR online databases. All of the shipboard activities require trained technical and scientific personnel. Adequate space for safe working environments, personal well-being, and scientific success is critical.

As the complexity of scientific ocean drilling goals increases, so do the technical needs. A new vessel should be able to deploy instrumentation and/or underwater vehicles (both autonomous and remotely operated) over the side. These tools could provide high-resolution site characterization and visual and/or mechanical support for coring or observatory installations, and environmental monitoring and sampling as needed or required. Complex expeditions will require the use of specialized or non-standard tools or workspaces. The new vessel design should incorporate flexible and adaptable spaces within the laboratory as well as on a dedicated container/van deck and the drilling rig floor. Finally, in order to ensure global impact, a new vessel must host the most modern intranet and ship-to-shore communication (via broadband connections) and data management infrastructure available at the time of construction in order to support the technical needs for coring operations, operational decision-making, and off-ship science participation and outreach.

The community also recognized that a successful program includes more than just the vessel and its operations. Past experience demonstrates the critical need for support of other pre- and post-expedition activities. These activities include site surveys to identify the best possible drilling locations (and alternates), which significantly increase the probability of achieving the science goals while providing data to meet safety and environmental impact requirements. A successful program also must be capable of implementing innovative and nimble missions (including rapid-response operations), archiving and distributing data and core materials with open access and request policies, defining the standard measurements needed to ensure long-term continuity, and supporting development, design, and testing of new technologies. Collectively, such a successful program will have widespread impact on the United States through:

1. Advancing our understanding of the interconnected Earth system.
2. Developing a diverse, skilled workforce.
3. Training the next generation of global scientific leaders.
4. Developing novel technologies.
5. Disseminating results through educational materials; high-quality, open access (FAIR) databases; shipboard telepresence; high impact scientific publications; and communication to policymakers.

NSF's investment in a new globally ranging, riserless drilling vessel will have a powerful economic multiplier effect. This includes the infusion of additional science support funds in the United States for training and research, the development of new techniques and tools, and the associated scientific and technical workforce development. The skills and knowledge gained through scientific ocean drilling are translatable to careers in fields such as sustainable energy development (e.g., geothermal and offshore wind), carbon sequestration, data management and infrastructure, biotechnology, communications, science education, policy, hazard mitigation, and environmental management.

The United States is currently a leader in a well-established and internationally collaborative scientific ocean drilling community. A new riserless drilling vessel will allow the United States to retain and grow its leadership position and to cultivate equitable international, multidisciplinary collaborations that will enhance scientific ocean drilling's future success.

Science Mission Requirements

The U.S. community established two classes of SMRs—Foundational Science Mission Requirements and Primary Science Mission Requirements—based on the criteria for success and on what a future riserless drilling vessel must provide to support a program that will benefit both the Untied States and scientists worldwide. Foundational SMRs define minimum criteria for a new riserless drilling vessel that can address significant portions of the *2050 Science Framework*. Primary SMRs build upon the Foundational SMRs to create more robust science opportunities and data collection capabilities, to increase the impact on the *2050 Science Framework*, and to provide more real-time ship-to-shore interaction to improve science engagement and outreach.

Foundational Science Mission Requirements

Any new globally ranging, riserless drilling vessel must provide the following base-level capabilities to achieve success in scientific ocean drilling and to address significant portions of the *2050 Science Framework*.

1. MODERN SAFETY AND ENVIRONMENTAL STANDARDS

Design criteria should meet the highest safety and environmental standards in order to provide global access and to be prepared for governmental regulation changes. Meeting these standards will be required to access protected waters such as exclusive economic zones (EEZs), extended continental shelves (ECSs), or high latitudes (>60°). A modern riserless drilling vessel and associated program should also be cognizant of its environmental footprint. Footprint improvements could include increasing virtual participation, continuing the practice of optimizing ship tracks, and ensuring the vessel can pass through the Panama Canal. Alternative power and propulsion systems and hull designs, which could significantly reduce the environmental impact, should be investigated.

2. LOCATIONS AND WATER DEPTHS

The diverse environments identified in the *2050 Science Framework* require a vessel that can operate safely and efficiently in water depths ranging from 70 m to 6000 m, with total drill string length of at least 7000 m (addresses NSF Question 2 in Appendix 3). Operations in ice-impacted waters (either icebergs or sea ice) are critical to U.S. science goals, with the ability to at least come in contact with seasonal ice. Actual ice-breaking capabilities are not required (e.g., Lloyd's Ice Class of 1D or potentially 1C, or a Polar Vessel Class 6) (addresses NSF Question 1 in Appendix 3).

3. COLLECTING HIGH-QUALITY CORE FROM KEY ENVIRONMENTS

Samples that preserve in situ formation characteristics will advance our understanding of fundamental questions in key geological environments. Geological formations that pose recovery challenges include soft sediment-hard rock boundaries, unconsolidated sands, glacial sediments, fractured fault zones, and high-resolution stratigraphic units spanning critical time intervals of the past. Drilling-disturbed cores (e.g., biscuiting, suction, gas-expansion cracking) often make it challenging to interpret stratigraphy and natural deformation and to accurately quantify some physical/mechanical properties. Wireline coring will be the primary coring approach, but the capability to do non-wireline coring should be available for specific drilling environments. Additionally, new coring technologies should be investigated and tested as they emerge. The capability to deploy larger diameter drillpipe should be explored, even if large diameter drillpipe is only used on an as-needed basis (addresses NSF Questions 5 & 6 in Appendix 3). Potential advantages of larger-diameter drillpipe include more core recovered for scientific analysis and the ability to use industry-standard downhole tools; potential disadvantages include heavier drill string and core-size effects which impact lab equipment and core storage.

Life

Scientific, technological, and coring advancements provide an opportunity to better understand habitability and life on Earth. Drilling and sampling deep sediments and crust in ocean basins worldwide allows exploration of the distribution of life in extreme environments and their significant impact on subsurface biogeochemical cycles. A modern riserless vessel is necessary to further characterize the phylogenetic and functional diversity of life at and beneath the seafloor, to test microbial activity, to track and quantify biogeochemical reactions, and to explore the limits and survival strategies of life on Earth. To achieve these scientific goals, a new riserless drilling vessel must be able to: (1) collect continuous, intact cores that reduce contamination (e.g., gel coring) and retain in situ conditions (e.g., pressure coring); (2) provide a contamination-free laboratory work space for sample collection and preservation; (3) collect and store cores and samples at in situ or other appropriate pressures and temperatures; and (4) capture the sediment-water interface with over-the-side coring technology.

4. HEAVE COMPENSATION, DYNAMIC POSITIONING, AND DRILLPIPE STABILITY

Minimizing the effects of heave on drilling parameters will improve quality of recovered cores, downhole logs, and in situ measurements. It will also facilitate successful, efficient observatory installations. Data from several recent high-latitude expeditions suggest that improved compensation when maximum heave exceeds ~13 feet (~4 meters)—whether achieved by capabilities in the derrick, on the rig floor, or below the waterline—has the potential to significantly reduce time lost to waiting on weather, and thereby significantly increase scientific productivity (addresses NSF Question 4 in Appendix 3). Advanced dynamic positioning (DP) systems, capable of maintaining drillship position within drilling system tolerances under challenging weather or current conditions, also will be required (addresses NSF Question 3 in Appendix 3). Some of the systems that improve heave compensation, together with modern DP capabilities, will enhance drillpipe stability, which will support scientific advances through more efficient drilling operations and the recovery of better quality core.

5. MODERN MUD AND CEMENT/CASING SYSTEMS

Greater use of drilling muds will be important to maintain borehole stability and successfully reach deep (e.g., 1500+ mbsf) and challenging scientific targets (e.g., fault zones, sands). More extensive use of weighted drilling mud will improve borehole mechanical stability and the removal of drill cuttings, which in turn will improve core and log quality and will make downhole measurements and observatory installations more efficient. Increased mud use, however, requires having an appropriate mud pump and mud storage system. Mud/cement systems also will be instrumental in the installation of observatories for long-term, time-series measurements. Optimizing mud/cement systems requires monitoring the drilling and coring parameters at the drill bit, at the seabed, and at the rig floor, which in turn will require implementing advanced rig information systems (RIS). Integrating RIS data with science data will provide new approaches to investigating the Earth system.

6. CRITICAL ONBOARD MEASUREMENTS

Critical onboard measurements are essential for safety, operational decision-making, mission-specific science, and long-term science goals that extend beyond a single expedition. Shipboard measurements fall within the categories of physical, lithologic, petrologic, micropaleontologic, microbiologic, and geochemical characterization of geological and fluid properties. Real-time 3D imaging capabilities at core-to-grain scales will significantly advance scientific discovery. Critical onboard measurements must be modernized to allow efficient core flow and processing and to accommodate the diverse array of science outlined in the *2050 Science Framework*. These critical measurements are essential for safe operations, and are the foundation for future science projects and for integration of data across science missions.

7. APPROPRIATE SPACE FOR SAMPLE AND DATA PRESERVATION

A hallmark of scientific ocean drilling has always been, and should remain, the ability to provide data to the community, specifically, data collected in a consistent and comparable format and published in a format appropriate for community use. Community access to samples that have been appropriately collected, curated, and stored also should continue to be a hallmark of scientific ocean drilling; this begins with providing the shipboard space needed to collect and store samples under appropriate conditions (e.g., clean, sterile, anoxic, constant temperature). Emphasis should be placed on accommodating both standard and specialized sample storage, with redundancy for special conditions. Digital data should also have redundant preservation, including near-real-time, cloud-based storage.

8. PERSONNEL

Onboard and shore-based science discoveries require technical staff that include, but are not limited to, the minimum technical staff for supporting: curation and core handling; safe operations; time-sensitive and critical shipboard measurements; computer assistance; equipment and instrument repair; applications; and data assurance. Science staff and its levels of experience change with every expedition, so technical staff with appropriate background and training is essential for working with scientists to ensure cross-expedition continuity and data quality. The science party must be responsible for addressing the science questions of any expedition, which then requires sufficient science staff to oversee, evaluate, and interpret safety measurements that support operational decision-making in a timely manner. Sufficient shipboard scientists also are needed to complete, analyze, and interpret time-sensitive measurements of ephemeral properties, as well as other critical measurements that impact drilling and coring strategies. The science party should include a broad spectrum of backgrounds and expertise to ensure a diverse community for posing and testing new hypotheses based on data returned, and for converging on appropriate interpretations. A new program should use the unique opportunities provided by a globally ranging, riserless drilling vessel to facilitate immersive STEM workforce development training. Undergraduate or graduate students should be supported on every project—at sea and onshore—as a training opportunity to enhance their education and experience. For the development of new scientists, the value of the learning environment during an extended research project on a scientific ocean drilling vessel should not be underestimated.

Carbon Cycling

Improved understanding of large-scale geological processes, including energy cycling and microbial productivity, requires detailed characterization of the global carbon cycle. To make progress, these studies need data that will place robust constraints on the carbon cycle at multiple scales (e.g., changes in atmospheric carbon dioxide and ocean carbon storage; gas hydrate dynamics, geological carbon dioxide sequestration). To provide data necessary to investigate the carbon cycle in the vast and diverse regions of interest, including high latitudes, in shallow and deep water, and from the seafloor to 1500+ mbsf, requires a riserless drilling vessel with: (1) an ice-strengthened hull capable of touching first season ice, likely polar class 5 or 6; (2) an ability to maintain position and recover core in a range of sea states, including those commonly (80% of the time) encountered in the high latitude Southern Ocean; (3) critical onboard measurement and sampling capabilities for future analyses; (4) flexibility in lab and rig floor space to accommodate specialty equipment (e.g., pressure coring); and (5) modern mud and cementing/casing systems (e.g., for sequestration experiments).

These eight Foundational SMRs define the minimum requirements for a new riserless drilling vessel. They build upon each other to provide the capabilities for the science community to implement the majority of the science defined in the *2050 Science Framework* (Figure 3). A vessel that provides access to sites globally, can operate in diverse subseafloor settings, and can control some aspects of the downhole conditions will give scientists entry to key geological and biological environments and enable the collection of high-quality cores. Technical and scientific personnel are critical to the enterprise, performing and interpreting onboard measurements and preserving samples and data for future research.

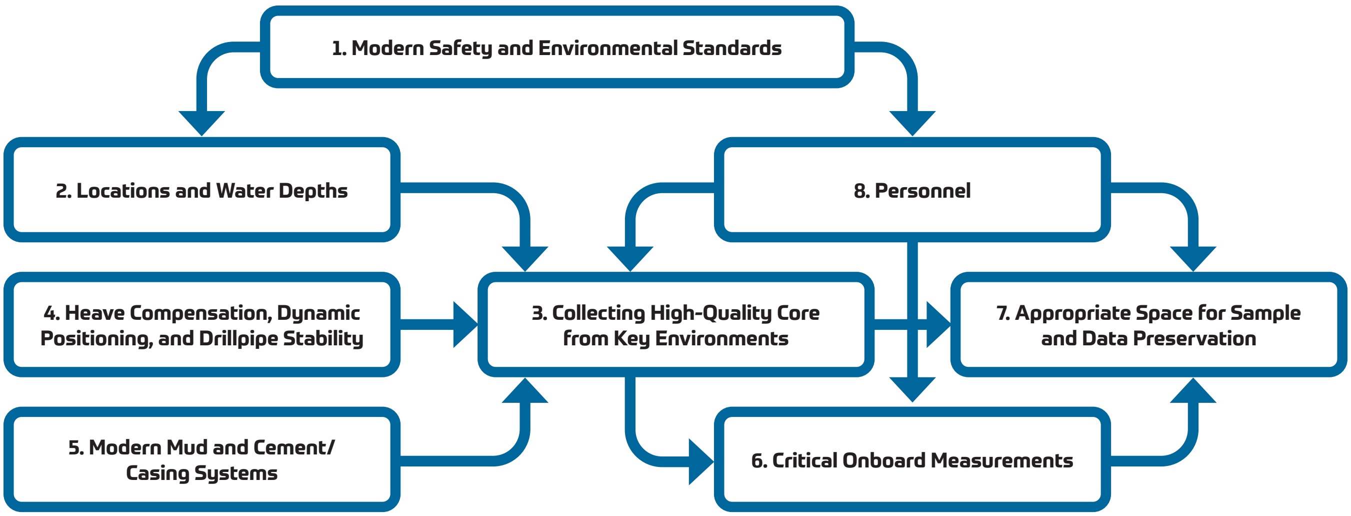


FIGURE 3. Dependencies and relationships of Foundational Science Mission Requirements.

Primary Science Mission Requirements

The following Primary SMRs add substantial scientific value to the Foundational SMRs by enabling robust data generation and the capability to appropriately work with the generated data. A future riserless drilling vessel that incorporates the Foundational and Primary SMRs will be capable of completing a significant portion of the *2050 Science Framework*.

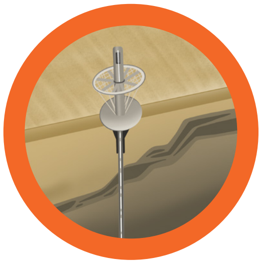
1. FLEXIBILITY IN SHIPBOARD SPACE

A new riserless drilling vessel will need suitable shipboard space to ensure safe, successful implementation of science objectives and operations. It will also house personnel and facilitate communications for science, education, and personal purposes. Notably, demands on space are likely to change over time on a vessel designed for long-term (30+ years), high-level operations. Such diverse and evolving applications spotlight the importance of designing spaces—laboratory, deck, and rig floor—for flexible and adaptable usage. A modular design would allow rapid conversion and effective use of deck space for vans containing sampling equipment and dedicated workspaces that will be required on expeditions using non-standard, expedition-critical applications (e.g., constant temperature conditions, pressure coring, isotope use). The ability to accommodate different classes of remotely operated vehicles (ROVs; e.g., working-class vs eyes-only) or autonomous underwater vehicles (AUVs) will allow for versatility based on the science need. Given the overwhelming desire for flexibility as well as a push toward more complex operations, we estimate that space for six standard container vans is needed (addresses NSF Question 7 in Appendix 3). Power, water, ventilation, and other special requirements must be considered for all spaces. Moonpool size and rig floor layout must be adaptable for observatory preparation and installation; limited space and clearances have proven problematic during prior installation operations. Modular design of interior spaces will also facilitate the adaptation of new/improved measurement strategies, allowing the upgrade of laboratory facilities without a full renovation of permanent structures. Modular space also can support the Enabling Elements of the *2050 Science Framework* by providing outreach video/audio production capabilities for public engagement. Adaptable space will also help support partnerships with other agencies (e.g., DOE, NASA) or industry (e.g., geothermal, carbon sequestration, offshore wind) when special tools or lab capabilities are required.

Remotely Operated Vehicles

Tools available for probing the interconnections among the Earth system components are improving rapidly. The potential to collect real-time, in situ observations, measurements, and samples while drilling is an exciting development that will increase our ability to understand cause-and-effect phenomena near and at the seafloor, such as drilling-related perturbations of pore fluids, hydrothermal systems, and associated communities; destabilization of gas hydrate systems; and initiation of slope failures all may occur near a drill site. Without over-the-side operations, these phenomena remain undetected by shipboard scientists. Documenting and investigating such phenomena would be scalable to regional biomes, would have implications for natural hazard assessments, and would be advantageous for outreach activities. ROV observations could also improve safe, efficient drilling operations, especially in areas of complex and dynamic local terrain (e.g., mid-ocean ridges, continental slopes, deep-sea trenches). Specific regions of scientific interest, such as the US EEZ, may only be accessible for scientific ocean drilling if an ROV is available on site. To take advantage of these opportunities and to meet regulatory criteria, a new riserless drilling vessel requires: (1) the capability for over-the-side deployments; (2) sufficient onboard and onshore support and outreach personnel and infrastructure to support these deployments; and (3) full integration of any video recorded, samples collected, or measurements taken into the standard curatorial and data streams.

Observatories



Earth system processes are active at timescales ranging from seconds to millions of years and occur over a range of temperatures and pressures. Observatories deployed in scientific ocean drilling boreholes provide the capability to monitor changes in subseafloor temperature, pressure, chemistry, and biological activity over human timescales. The acquisition of in situ stress, pressure, and temperature data—at different points in the earthquake cycle—will help us better understand earthquake behavior from episodic tremor and slip to megaquakes. Geotechnical experiments coupled with observatory data will provide constraints for earthquake models, including tsunami risk assessment. In situ time-series data on fluid, heat, and chemical fluxes combined with microbial activity monitoring will provide new insights on nutrient fluxes between the crust and the ocean and on biogeochemical cycling, which will improve our understanding Earth-life interactions and ocean health. Successful observatory science will require an integrated approach that includes: (1) modern heave and dynamic positioning capability for working in shallow and deep water; (2) collecting, imaging, and preserving high-quality cores above, within, and below key intervals (e.g., fault zone, high-microbial activity layer); (3) installation of observatories to monitor in situ pore pressure, temperature, strain, chemistry, and/or microbial activity in/near key intervals; and (4) the ability to confirm sensor functionality before leaving a site, which could be accomplished with over-the-side capability (e.g., ROVs).

2. MINIMIZING CONTAMINATION OF RECOVERED SAMPLES

Accurate microbiological and geochemical assessment is essential for addressing many parts of the *2050 Science Framework*. The most compelling scientific impact can only be made when the microbiological and geochemical signals are not significantly influenced by contamination. Technologies such as gel coring, sidewall coring, and Shelby-tube samplers should be explored as ways to minimize contamination. Development and testing of novel coring techniques to minimize contamination of cored samples should be included. In addition, routine contamination testing on the ship is necessary to quantitatively assess contamination and thus ensure high-quality science.

3. OVER-THE-SIDE CAPABILITIES

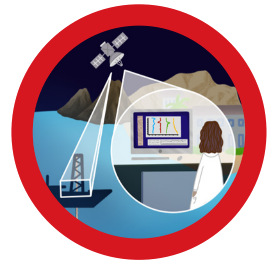
In support of coring and drilling, ROVs could help identify the most favorable location to spud-in a hole (e.g., between pillows in exposed basalt); make borehole reentries more efficient (working-class ROVs) by manipulating drillpipe at the seafloor; save operational time because ROV deployments are independent of the drillpipe; and provide seafloor monitoring for environmental assessments. In facilitating observatory science, ROVs would provide visualization of the site or manipulation of the observatory into the borehole. Post-installation, ROVs can connect to and test a borehole observatory installation to ensure the system is functional before the vessel leaves the site. At sites near seafloor cables, ROVs can connect observatories to the cables, allowing for real-time data delivery. Collection of water, fluids, and near-seafloor sediments by AUVs, autonomous underwater gliders (AUGs), ROVs, and/or other over-the-side sampling capabilities would permit complementary scientific efforts when measurements are time sensitive (e.g., microbiological and geochemical evaluation of ephemeral properties). ROVs can provide improved safety and environmental monitoring and may be required in the future for specific operations in U.S. and some international EEZs or along ECSs.

4. DOWNHOLE LOGGING AND MEASUREMENTS

Downhole logging and downhole measurements of in situ formation and fluid composition, temperature, and pressure are critical for understanding natural hazards (e.g., submarine landslide evolution, earthquake initiation and propagation), carbon cycling (e.g., natural gas hydrate

Data Analytics

Future scientific ocean drilling researchers will be able to use existing data and big data analytics to develop new scientific insights, provide operational efficiencies, and inform drilling decisions. For example, correlating drilling parameter data with rock strength can expand earthquake research by providing more details on strong and weak zones. Additionally, rapid investigation of drilling parameters and lithologic variability from prior expeditions could provide information for real-time drilling and mud parameter adjustments to improve core recovery. Data validation against existing databases could also help provide information on when target stratigraphic horizons have been reached and thus may provide data for making operational decisions. Key requirements to allow for near-real-time data analytics that can grow the impact of riserless scientific ocean drilling include: (1) reliable and consistent communications capabilities with access to cloud-based computing; (2) input of critical onboard measurements and standard scientific measurements in open-access (FAIR) databases; and (3) real-time integration of science data and rig instrumentation data.



dynamics), and habitability and functionality of life in the deep biosphere. Log data can also fill important gaps when core recovery is compromised. Slimline wireline logging tools will provide the petrophysical data needed by many expeditions, but we must have the capability to accommodate specialty, larger-diameter tools (e.g., formation pressure testing, downhole fluid sampling, logging while drilling) on an as-needed basis. A key gap to address in future operations is the current inability to collect logging data in the upper 50–100 mbsf with standard wireline logging tools. In addition, there is a need to accommodate a broader range of downhole measurement and sampling tools for in situ pressure and temperature characterization and for taking specialty samples (e.g., geotechnical cores, pressure cores) to depths of 1500+ mbsf.

5. EXPANDED OBSERVATORY CAPABILITIES

Time-series downhole/in situ measurements will help us gain important insights into dynamics in the shallow subsurface. A new riserless drilling vessel should be capable of installing and testing in situ measurement systems that include more types of measurements and different (sub) seafloor infrastructure than historical scientific ocean drilling borehole observation technologies (i.e., Circulation Obviation Retrofit Kits [CORKs]). Enhanced installation capabilities will support implementation of new in situ sensors and observatories in different environments (e.g., outer continental shelf vs abyssal plain). Example options range from push-in penetrometer-based monitoring systems to SCIMPI (Simple Cabled Instruments for Measuring Parameters In situ) to multi-packer pumping wells. New technologies will optimize power use, expand data storage capacity, and simplify data retrieval. Faster, easier installation and testing of sensors during installation will significantly improve our return on the investment of vessel operational time.

6. RELIABLE AND CONSISTENT SHIP-TO-SHORE COMMUNICATIONS

The capability to operate seamlessly at sea and on shore—including the abilities to pass large data sets from ship to shore for real-time evaluation and to collaborate with experts on shore—will enhance scientific output and improve operational decision-making related to both safety and science. For example, rapid processing of sonar data might identify safe landing sites for seabed equipment. Efficient data processing by onshore data centers could also reduce the time required to repeat certain offshore measurements and thus reduce ship-time pressure for multiple, multiyear operations. Reliable communication also will expand the community of scientists involved in scientific ocean drilling missions and will facilitate hands-on training and development of a STEM workforce by enabling virtual engagement and mentoring. The same capabilities can increase options for science participation by persons historically unable to participate in seagoing missions. A robust communications system will also enable global outreach, including engaging the audience through real-time access to cutting-edge research conducted in some of the most remote areas on Earth. The use of true telepresence—the suite of technologies that enable people to feel as if they are in a different environment—should also be explored. These technologies have the potential to remove financial, cultural, and geographical barriers to participation on science ocean drilling expeditions, which increases the potential for more cross-disciplinary and inclusive science parties. This could have a powerful effect on workforce development by preparing a wider range of people for careers in science, engineering, and computer technology.

Implementing these six Primary SMRs on a new U.S. riserless drilling vessel will maximize the scientific return. It is imperative that the vessel include appropriate and flexible space that facilitates improved and expanded coring and science operations and allows and encourages more extensive ship-to-shore science participation, education, and outreach (Figure 4). The combined impact of Primary and Foundational SMRs will be the generation of more science opportunities aided by increased data collection and dissemination, in support of the *2050 Science Framework*.

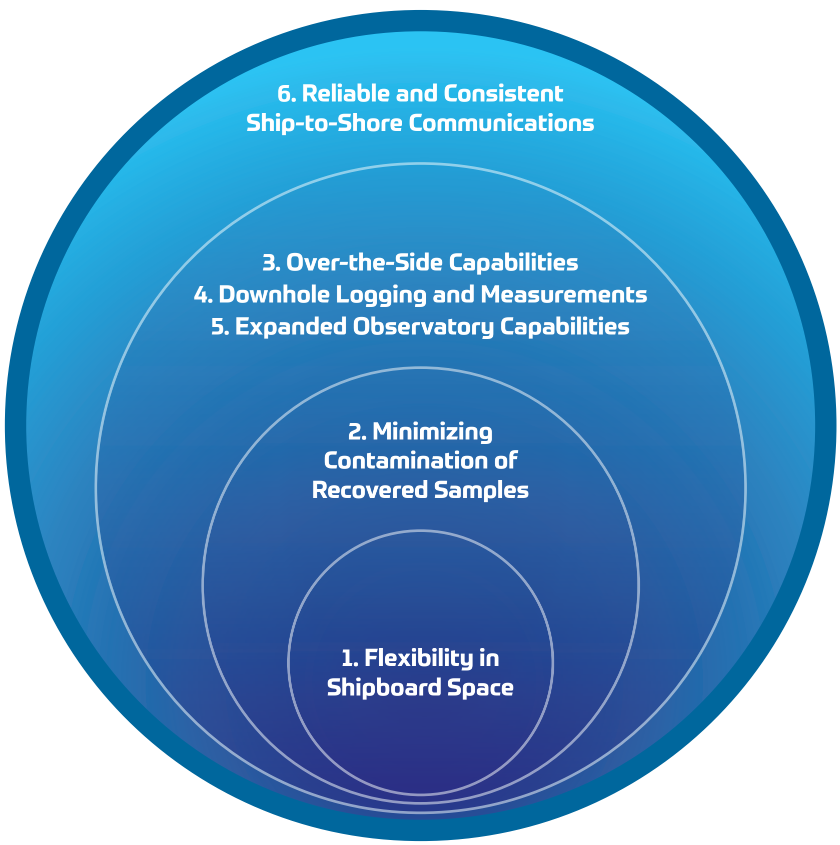


FIGURE 4. Structural relation of Primary Science Mission Requirements showing priority of appropriate and flexible space upon which additional SMRs can be developed to add capability.

Regional Priorities

The cryosphere, including polar ice sheets and smaller mountain glaciers, modulates global sea level. It responds to changes in various forcings, whether natural or anthropogenic, including ongoing climate change today. A clear way to understand the sensitivity of the cryosphere, and thus modern-day risk, is to study how the cryosphere behaved during past climate change events. Some portions of Earth's ice cover are showing clear trends toward retreat and ice-mass loss; researchers believe some glaciers may have already passed their tipping points, entering a phase of sustained retreat. It is becoming clear that not all regions respond similarly. Despite this variability, very few detailed direct records of past ice behavior have yet been recovered from the ocean floor.

Obtaining scientific drill cores proximal to a variety of glacial catchments that are currently responding to climate warming will provide records of ice advance and retreat at high temporal and spatial scales. Such records will provide the resolution needed to determine ice behavior during past warm intervals and the forcings and feedbacks that influence ice dynamics, thus improving the ability of models to forecast future rates of sea level rise. Without access to polar regions, including icy waters, we will not have the ability to access ice-proximal sites at "ground zero" of ice-sheet collapse. Polar and ice-proximal locations are currently the biggest gap in the existing scientific drill core collections (including all current platforms, not just D/V *JOIDES Resolution*). Thus, an ice-strengthened hull is a high-priority capability for the next riserless drilling vessel (addresses NSF Question 1 in Appendix 3).

In addition to needing access to icy water, high-latitude drilling is also likely to encounter difficult-to-recover lithologies related to alternating layers of vastly different properties, such as layers of glacial diamicton with pebbles and cobbles mixed throughout mud and sand, and layers with high shear strength due to overcompaction from overriding ice. For example, recovering pristine soft interglacial sediments between stiff glacial layers is of critical importance for defining the timing and extent of cryosphere changes. To recover high-quality core from sediment with such properties requires improved core recovery techniques, and these techniques will be beneficial beyond drilling in high latitudes. Lastly, operational flexibility is required when working in icy waters; it can be enabled by efficient pipe-handling, which allows the vessel to move onto and off of a site with greater speed with a clear benefit to safety.

Climate

While it is becoming clear that the world is quickly transitioning into a new climate state, there still are large uncertainties in climate projections, such as to how much warming will occur as a result of a given increase in the amount of carbon dioxide in the atmosphere. The likely consequences of this warming also are poorly understood, such as its effects on sea level rise, precipitation, flooding, droughts, and ocean acidification and deoxygenation. Paleoclimate records of warmer periods can offer insights into these issues and, potentially, help us reduce uncertainties through direct proxy observations and validation of climate models. For example, variations in ice sheet size and stability are subject to internal feedbacks within the Earth system, and models may not accurately predict potential tipping points. This presents an urgent need for observational data from ice-proximal locations, such as around Antarctica, as well as from distal locations experiencing sea level rise. This data-model combination lends confidence to future projections. Continuous climate records with high temporal and spatial resolution are primarily accessible through deep ocean drilling. No other platform offers the possibility of recovering sediments from warm periods that are considered analogs for future warming, such as the middle Pliocene (~ 3 Ma) and the Miocene climate optimum (~ 14 Ma), in sufficiently high resolution to provide meaningful data. To help advance climate science, a new drilling vessel must be able to work globally from the tropics to the poles, including at sites with sea ice, iceberg hazards, and adverse sea states, and it must be able to core deep into sediment sequences to recover the time intervals of interest. This requires: (1) an ice-strengthened hull capable of touching first season ice, likely polar class 5 or 6; (2) rapid pipe deployment and recovery operations (e.g., vertical pipe racking); (3) the ability to maintain position and recover core in a range of sea states, including those commonly (80% of the time) encountered in the high-latitude Southern Ocean; (4) improved weight-on-bit and coring methods to recover interbedded hard and soft lithologies.

Hotspots and Large Igneous Provinces

The study of volcanic hotspots and large igneous provinces (LIPs) is fundamentally important to our understanding of the cycles of tectonic plates and geological hazards, as well as long-term climate and ocean health. The rapid emplacement of magma during LIP development has been implicated in the geologically rapid addition of carbon dioxide to Earth's ocean and atmosphere, with subsequent warming, decreased ocean oxygen, and a range of extinctions in the deep sea and elsewhere. Deep crustal samples are needed to address the origin and evolution of hotspots and LIPs, including cores that encompass multiple flow units from multiple locations. Recovery of interbedded sediments and igneous rocks deposited together is required to assess environmental impacts of hotspot/LIP formation. In addition, deep crustal holes must be logged to collect in situ data to better characterize the complete geological sequence. A new drilling vessel must be able to core precisely, with excellent hard rock recovery (i.e., >65%) from deep into the crust, requiring: (1) drill pipe and hole stability controls that permit greater core recovery and rate of penetration (e.g., seabed frame, weighted mud use); (2) faster coring in order to penetrate deep into the crust; (3) the ability to characterize the subseafloor and precisely locate the core site in order to access "tectonic windows" where deep crust has been moved closer to the seafloor; and (4) global access to hotspots and LIPs.

Deep Water and Deep Coring

The ability of a new riserless drilling vessel to operate in deep waters and to collect cores deep beneath the seafloor is critical to achieving many of the objectives in the *2050 Science Framework*. Deep coring targets include oceanic large igneous provinces, convergent margins, underthrust plates, earthquake rupture zones, pristine mantle sections through oceanic crust, and areas of interest deep in the oceanic crust where observatories can be installed, all of which are out of reach of conventional drilling. For example, to address Habitability and Life on Earth, recovering high-quality cores from extreme pressure and temperature conditions will require deep operations (e.g., 6500+ meters below sea level). Continuous and undisturbed cores through expanded sedimentary sections that record specific time intervals will be required to address questions related to Earth's Climate System and Tipping Points in Earth's History. Deep drilling may be required to understand seafloor-breaching fault rupture, and deep coring will be required to access fault zones at different states of stress and at different phases of the earthquake cycle. Such an approach will be necessary to improve our understanding of Natural Hazards Impacting Society. Deep hard rock drilling and coring will be an integral component to probing the Oceanic Life Cycle of Tectonic Plates by providing compositional and age information in a range of environments.

Because deep drilling, in terms of water depth, depth below seafloor, and their combination, is integral to broad swaths of the *2050 Science Framework*, it is important that the vessel incorporates the technology to meet these operational requirements. The offshore oil industry drives tool, technology, and drilling strategy and practice for offshore drilling in ocean basins. This industry defines deep water as >300 m water depth (mwd) and ultra-deep water as >1500 mwd. Of all the targets ever approached during the history of scientific ocean drilling, >95% have been deeper than 300 m and >70% have been beyond the industry-defined ultra-deep water level of 1500 m. Without deep water capability and holding capacity for redundant drillstrings, few of the historic and future targets of scientific ocean drilling would have been or would be achievable. Specifically, the new riserless vessel should be able to drill with 7000 m of total drillpipe. Given riserless operations with modern mud control, the vessel should be able to drill and collect high-quality core to 1500+ mbsf in favorable formations. Success of these operations will require an appropriate mud circulation system, storage space for mud, and space for casing construction and deployment. For expedition-specific needs, efficiencies could be gained through over-the-side operations such as ROV support for borehole reentry.

Interdependencies and Trade-Offs Between Vessel Capabilities

Throughout the SMR process, the scientific community has repeatedly noted that their ongoing input is necessary to assess the interdependencies of many ship capabilities and the associated science trade-offs. For example, insufficient heave compensation would result in poorer drillpipe stability, that in turn would negatively impact the collection of high-quality deep cores, increase the possible contamination of samples, and render the installation of observatories for monitoring of Earth processes more difficult or impossible. As another example, not having an ice-strengthened hull would limit the regional capabilities of the vessel and would greatly impact our ability to investigate Earth's climate system and to more accurately predict the impact of a warming climate on the United States and globally. Thus, it is critical that the community continue to have input throughout the design process to appropriately address how different vessel options would impact the execution of the *2050 Science Framework*.

Programmatic Considerations Beyond a Riserless Drilling Vessel

In addition to describing the capabilities for the riserless drilling vessel, the community also discussed additional considerations that will influence the long-term success of the facility and affiliated programs. These considerations generally can be parsed into three categories: before an expedition, after an expedition, and technology development. Keys to success before a project include identifying drilling locations and having the capability for nimble operations, such as rapid-response operations and projects of variable and appropriate duration. In terms of identifying drilling locations, success of a facility will require high-quality site and environmental survey data. Support for collecting such data must be a priority to avoid delaying, or potentially missing, opportunities to address components of the *2050 Science Framework*. The community also noted that any program should have mechanisms to support innovative and nimble implementation. While the majority of operations will follow a standard schedule building off the current ship track model, there could be events (e.g., earthquakes) or opportunities (e.g., cooperative drilling with a partner agency) that would require adapting and/or mobilizing on short timescales (i.e., rapid-response operations) to maximize the return to the science community and to broader society. After an expedition, it is crucial that all data and cores are archived with open access and open request policies. Mechanisms for adding time-series or real-time data to scientific databases will also be essential. Data planning should also include a focused effort on defining standard measurements, both shipboard and shore-based. As an innovative drilling facility, support mechanisms should be developed to promote advanced tool development (e.g., new coring technologies, redesigned extended core barrel), including design and at-sea testing. With the ambitious and diverse goals of the *2050 Science Framework*, the need to develop and improve technology will be integral to success. To accommodate new technologies, protocols will be needed for tool testing and approval for use. Industry collaborations also should be pursued when exploring technology and tool development or advancement.

The U.S. scientific community collaborated to develop Foundational and Primary SMRs that would ensure the value of a future U.S.-led, globally ranging, riserless drilling vessel is maximized. The U.S. community also worked cooperatively with its international colleagues to develop the *2050 Scientific Framework*. It is now collaborating with international partners on Mission Specific Platform (MSP) drilling proposals that address the *Framework*, is eager to develop scientific ocean drilling proposals for a U.S. vessel that will do the same, and is ready to advance scientific ocean drilling beyond IODP. The acquisition and deployment of a new globally ranging, riserless vessel is essential for the United States to continue its leadership in ocean drilling science and technology, to develop new research partnerships, and to increase societal interest in Earth science all while working on problems that have direct applications to U.S. and global interests and goals.

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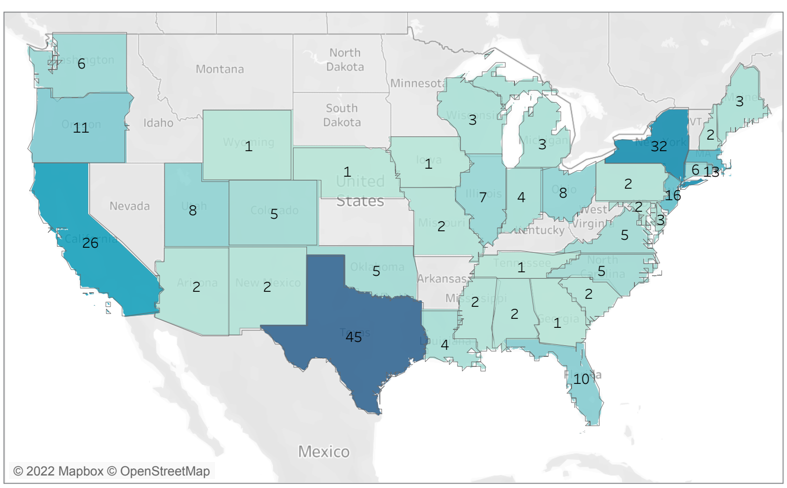
APPENDIX 1

Approach to Developing Science Mission Requirements

NSF's formal Request for Assistance to USSSP emphasized the importance of ensuring the broadest possible input into the SMR process from the U.S. science community. To achieve this broad input, the SMR Steering Committee adopted a three-step approach: (1) conduct an online, community-wide survey; (2) conduct virtual workshops; and (3) conduct and in-person workshop.

The first step involved creating and issuing a community-wide survey to elicit the relative degree of interest among community members in the various Strategic Objectives, Flagship Initiatives, and Enabling Elements of the *2050 Science Framework*, and obtaining a first look at the specific operational and technical capabilities identified by community members as critical to addressing their interests. The survey also asked respondents to identify the specific oceans/seas they were most interested in, as well as the types of ocean environments (e.g., ridges, margins, arc systems, abyssal plains). Finally, respondents were asked to assess the priority level of various initial vessel recommendations that emerged in the report from the 2019 NEXT Workshop. During the open survey period, SMR steering committee chairs participated in two online community town halls to answer specific questions and provide information on the SMR process and opportunities for participation.

The community survey was released on February 1, 2022, and was open for approximately six weeks. Because NSF's Request for Assistance indicated that the Foundation was interested in the priorities of the U.S. scientific ocean drilling community specifically, the few responses received from outside the United States were not included in the survey report. (The survey instructions made it clear that only U.S. responses would be counted, and that comments from the non-U.S. community would be solicited when the draft report was posted online. Nevertheless, a few responses from non-U.S. scientists were received.) Overall, 278 survey responses were received from U.S. community members, representing 104 unique institutions from 39 states and the District of Columbia (Figure A1). The three states with the most survey respondents were Texas, New York, and California. Thirty-two percent of respondents self-characterized as senior scientists (defined as 20 or more years post-PhD), while 62% were students, postdocs, early career (less than 10 years post-PhD) or mid-career (10–20 years post-PhD). These demographics are encouraging, as they indicate that most respondents are at career stages where they are potential users of the new drilling vessel. Full survey results can be found in here.



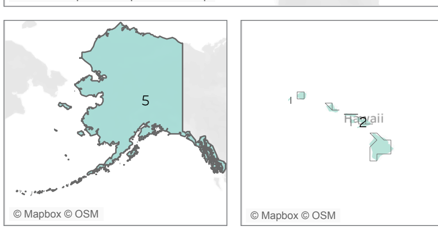


Figure A1. Number of SMR survey respondents by state.

The survey results informed the next step in the SMR process—a group of online workshops in April that were organized around five general categories: Coring Capabilities; Mission-Critical/Time-Sensitive Measurements; Downhole, Observatory and Near-Seafloor Capabilities; Vessel Operations; and Shipboard and Ship-to-Shore Communications. These "virtual workshops" were held in order to make a first pass at clarifying and expanding on the survey results, and to facilitate the participation and contributions of community members who were unable to attend the later in-person workshop (see below). The virtual workshops also provided the first opportunity for experts from industry, or with a long history of participation in the operations of *JOIDES Resolution*, to share their expertise on technical matters, guide the discussions on engineering capabilities, and provide a "reality check" on community aspirations.

During the first week of April 2022, the Coring Capabilities group met twice, for two hours each time, over a three-day period, and this pattern was repeated over the next three weeks by groups for the virtual workshops on Mission-Critical/Time-Sensitive Measurements; Downhole, Observatory and Near-Seafloor Capabilities; and Vessel Operations. The number of registrants in each virtual workshop group ranged from 35 to 61, and more than 100 individuals participated in one or more of the virtual workshop sessions. Attendees at these workshops skewed toward more senior than the pool of survey respondents, probably reflecting both greater confidence among the participants in "open" interactions over Zoom as well as more familiarity and experience with the specific technical capabilities under discussion. The fifth virtual workshop group (computer and satellite communication capabilities) met once, and was a smaller workshop of experts who focused on present best technologies.

The Virtual Workshop discussions and outcomes were then summarized and distributed prior to the third stage of the SMR process: the in-person workshop, which was held in Chicago on May 17–18, 2022. Despite ongoing concerns about the COVID pandemic, a total of 89 people attended the workshop, including 47 early- and mid-career researchers (including graduate students) and seven who were not from academia.

On the first day of the workshop, the summaries from the five virtual workshop groups were presented, and two breakout sessions were then convened. Workshop presentations can be found here. The first breakout session focused on key scientific priorities and the gains envisioned in addressing them with a modern, globally ranging, riserless drilling vessel. Attendees were randomly assigned to one of four breakout groups. With a series of guiding questions, each group was asked to map Strategic Objectives and Enabling Elements from the *2050 Science Framework* to enabling capabilities provided by a new riserless drilling vessel, and to develop vignettes that illustrated the science gains of specific capabilities. These vignettes were the basis of the sidebars presented in this report. The groups in the second breakout session were asked to address the same questions and issues, but were organized by career stage. Working notes from breakout sessions one and two can be found here. An aggregated, semi-quantitative compilation of the science objectives and vessel capabilities can be found here. Please note that this spreadsheet is based on partial completion by multiple breakout groups during two breakout sessions so they are reflective of the community discussions and provide guidance but do not provide objective, quantified ranking or assessment.

Two breakout sessions were also held during the second day. In the first, participants were organized by self-selected affiliation with one of four general science themes and asked to determine what would constitute success in addressing the science goals discussed in the first two breakout groups. The four themes were:

1. Habitability and Life; Diagnosing Ocean Health; and Exploring Life and Its Origins
2. Earth's Climate System; Feedbacks; and Ground Truthing Future Climate Change
3. Natural Hazards Impacting Society; Assessing Earthquake and Tsunami Hazards; and Tipping Points
4. Oceanic Life Cycle of Plates; Probing Deep Earth; and Global Cycles of Energy and Matter

To define success, each group provided significant information on the criteria required to achieve significant portions of the *2050 Science Framework* and some information for final prioritization. Groups were specifically tasked to define the criteria for three levels of achievement: minimum acceptable achievement, meets objectives achievement, and exceeds expectations achievement. Working notes from the discussions can be found here.

In the final breakout session, participants were organized by the SMR steering committee to ensure a range of career stages and expertise within each breakout group. Each group was then asked to begin the process of finalizing the prioritization of science goals while also considering tradeoffs that might be associated with prioritizing specific science goals and/or enabling technologies. Working notes from the discussions can be found here. These outcomes were then reviewed in a plenary session during the afternoon of the second day.

APPENDIX 2

Unique Participants in the Virtual and In-Person SMR Workshops

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APPENDIX 3

Questions from NSF to be Considered for Determining SMR Priorities

Q1 Do priority regions of operations require an ice-strengthened hull (as opposed to an ice breaking hull)?

Q2 What are the critical water depths where the vessel will need to operate to support priority strategic objectives and flagship initiatives?

Q3 Dynamic positioning requirements- is International Maritime Organization (IMO) DP Class/Level 2 (completely redundant systems) or DP Class/Level 3 (multiply redundant systems) required? What level of station-keeping is required (the *JOIDES Resolution* can generally keep position within 2% of the water depth)? To what Sea State should routine drilling operations be possible?

Q4 What drill string diameters and other characteristics are required to support coring and logging capabilities needed to achieve priority strategic objectives and flagship initiatives? Is the current core size adequate for the proposed science?

Q5 Research vessels commonly accommodate International Standards Organization (ISO) shipping containers used as removable and transportable science laboratories. The *JOIDES Resolution* currently has space for two removable 20-foot Standard Containers (one is used as the isotope lab). What capability for removable containers is required?

Q6 What communication facilities and capabilities are required to meet the 2050 Science Framework Enabling Elements?

Q7 What are the laboratory power, water, analytical gas supply and ventilation requirements, as well as unallocated flexible space requirements?

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