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The FUTURE of the US Marine Seafloor and Subseafloor Sampling Capabilities

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Key Points:

- Seafloor and subseafloor sampling via scientific drilling, coring, dredging, seafloor observatories, and deep submergence capabilities
- Science drivers to sustain and improve US Academic Research Fleet, deep submergence, and other oceanographic infrastructure capabilities
- Access to data and sample repositories and improvement of discoverability and archivability of sampling/survey outcomes

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Recent changes in US oceanographic assets are impacting scientists' ability to access seafloor and sub-seafloor materials and thus constraining progress on science critical for societal needs. Here we identify national infrastructure needs to address critical science questions. This commentary reports on community-driven discussions that took place during the 3-day *FUTURE of US Seafloor Sampling Capabilities 2024 Workshop*, which used an “all-hands-on-deck” approach to assess seafloor and sub-seafloor sampling requirements of a broad range of scientific objectives, focusing on capabilities that could be supported through the US Academic Research Fleet (US-ARF) now or in the near future. Cross-cutting issues identified included

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weight and size limitations in the over-boarding capabilities of the US-ARF, a need to access material at depths greater than ∼20 m below the seafloor, sampling capabilities at the full range of ocean depths, technologies required for precise navigation-guided sampling and drilling, resources to capitalize on the research potential of returned materials, and workforce development.

Plain Language Summary The seafloor covers ∼70% of Earth's surface and is the largest interface between the hydrosphere, the lithosphere, and their respective ecosystems. Study of seafloor materials—rock, sediment, fluid, gas, and the biology hosted therein—have transformed our understanding of Earth and ocean processes, addressing vital scientific questions ranging from the driving forces of tectonics and geohazards to natural environmental variability, and more. Unfortunately, recent reductions in US oceanographic assets are limiting scientists' ability to access vital materials in the ocean. The recent *FUTURE of the US Seafloor Sampling Capabilities 2024 Workshop* assessed the current state and future needs for US oceanographic assets, including the evolution and design of multiscale science infrastructure leveraging emerging technologies that will sustain a new generation of oceanographers. Such infrastructure includes the continued availability of scientific deep drilling platforms, infrastructure that enables human access to ice-covered seas in the polar regions, expanded US-Academic Research Fleet capabilities to handle heavy over-the-side shipboard coring, dredging, drilling, and robotic sampling systems; enhanced access to precision mapping and imagery, for example, using autonomous vehicle technology; and increasing the discoverability and accessibility of materials archived in sample repositories.

1. Motivation for Community-Driven Discussion on US (Sub-)Seafloor Sampling Capabilities

Covering ∼70% of Earth's surface, the seafloor is the largest interface between the hydrosphere and lithosphere and hosts some of its largest ecosystems (Bar-On et al., 2018). The first systematic seafloor samples were collected over 150 years ago during the HMS *Challenger* expedition (1872–1876). With increasing sophistication since then, the recovery of seafloor materials—rock, sediment, fluid, gas, and the biology hosted therein—have transformed our knowledge of Earth-ocean interactions and fundamental planetary processes. Examples of paradigm shifts enabled by the study of the seafloor and sub-seafloor include the development of the Theory of Plate Tectonics (e.g., Emiliani, 1981) and Global Meridional Overturning Circulation (e.g., Broecker, 1987). Seafloor samples provide insights into strategic marine mineral resources (e.g., Hein et al., 2013), geologic hazards (e.g., Wang et al., 2024), mechanisms driving our changing climate (e.g., Tierney et al., 2020), global biogeochemical cycles (e.g., D'Hondt et al., 2019), the deep biosphere (e.g., Kallmeyer et al., 2012), and possible origins of life (e.g., Martin et al., 2008). This work continues, but degradation of United States (US) oceanographic infrastructure necessitates community-led initiatives to prioritize science and infrastructure that will sustain future advancement in marine geoscience (Text S1 in Supporting Informations S1). For example, the heavily utilized drilling vessel *JOIDES Resolution* completed its final expedition under the International Ocean Discovery Program (IODP) in Summer 2024, which leaves an unfilled gap in the strategic scientific capabilities of the United States.

Recent planning efforts have identified consensus research priorities that will span the interim between the cessation of *JOIDES Resolution* operations and the development of a future US academic drillship. A series of workshops sponsored by the IODP US Science Support Program (USSSP)/US Advisory Committee for Scientific Ocean Drilling, including NEXT: Scientific Ocean Drilling Beyond 2023, and the 2022 USSSP Science Mission Requirements (SMR), Addressing Future Ocean Drilling in the United States ("FOCUS") prioritize science themes adopted by the FUTURE workshop. A consortium of oceanographic institutions, the US Scientific Ocean Drilling Alliance (US-SODA), has been strongly advocating for a new riser-less drilling vessel. The US National Academies Decadal Survey of Ocean Sciences (hereafter "DSOS," the National Academies of Science, Engineering, and Medicine, 2025) recently published a multidisciplinary report laying out US oceanography priorities over the next decade, including strong emphasis on access to the sub-seafloor (e.g., Progress and Priorities in Ocean Drilling, National Academies of Sciences, Engineering, and Medicine, 2024).

With this scientific prioritization in hand, The FUTURE of the US marine seafloor and subseafloor sampling capabilities workshop (hereafter FUTURE workshop) addresses the next critical planning task: assessing current and emerging seafloor sampling capabilities and envisioning cost-effective infrastructure investments that will

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enable scientific discovery. This assessment starts with the observation that the current US Academic Research Fleet (ARF) has insufficient overboarding capabilities to support the spectrum of desired seafloor and sub-seafloor sampling/coring schemes (Text S1 in Supporting Information S1). There is also an increasing demand for the ARF "Global" class vessels and there are not enough of these large ships to fill well-justified needs; high demand creates scheduling back-logs, which limits the rate of scientific progress (Text S1 in Supporting Information S1).

2. FUTURE 2024 Workshop and Data

Nearly two hundred scientists from >60 institutions contributed to the *FUTURE* workshop, hosted March 26–28, 2024 by the Woods Hole Oceanographic Institution. Over half of the participants were early career scientists, indicating the intellectual capacity for a healthy future of marine science. Participants reviewed state-of-the-art science, facilities, and technologies (https://www.unols.org/event/conference-workshop/2024-future-workshop; Figure 1). Experts-lead breakout sessions addressed six different scientific themes: Ocean-Seafloor Interfaces, Solid Earth Processes, Ridge-Axis Processes, Deep Crust Processes, Climate and Anthropogenic Activities, and High Latitude Science (curated notes in Tominaga et al., 2024). Discussion within these science themes focused on the infrastructure needs critical to advancing the frontiers of US marine seafloor and sub-seafloor science (Figure 1).

3. Cross-Discipline Community Needs and Achievable Technology Advances

A number of cross-disciplinary scientific and infrastructural needs emerged from the discussions. For example, the ability to sample and study sub-seafloor life was noted in almost all the breakout sessions (Text S2 in Supporting Information S1). Challenges in conducting high-latitude (polar) research, including the past and future of ice in warming and glaciating worlds, was also a high priority across disciplines (Table 1; see also Table S3 in Tominaga et al., 2024), suggesting a consensus for additional well-equipped icebreaker assets (National Academies of Sciences, Engineering, and Medicine, 2024). Science in polar regions is somewhat analogous to science in space: if there is no infrastructure to take scientists directly or remotely to the region, there is no other way to access the material.

In parallel with objectives that will require longer timescales and larger investment (e.g., a new scientific drilling platform and lander style robotic drill, highlighted orange and yellow, respectively in Table 1), near-term technological investments must be aligned to the capabilities of the existing ARF to support ongoing US marine seafloor/sub-seafloor science missions. The *FUTURE* workshop delivered the community voice in the following priorities.

3.1. Vessel's Overboarding Capabilities

A critical limitation to both fully utilizing existing resources and implementing new technologies is the ability to safely deploy and recover (sub-)seafloor sampling systems within the current ARF (Table 1). These systems are often large and heavy. With appropriate sensing tools (underway mapping, imaging, and, where appropriate, deep submergence tools, heavy samplers can now be used with great precision (current Facilities summarized in Text S3 in Supporting Information S1). The urgent scientific need to improve current and future ARF overboarding systems demands enhanced deck, winch, wire, and A-frame/crane capabilities, as well as options for lower-weight, larger-diameter synthetic lines. The critical first step is to conduct an engineering study on the largest ARF vessels to assess whether it is possible to modify existing A-frames and winch foundations to safely support higher wire tensions (see Text S1 in Supporting Information S1). Other interim solutions include expanding the support to utilize non-ARF research platforms, including cost-effective leased assets, and/or collaboration with international, commercial, and private non-profit entities. Future (not yet built) ARF Global and Ocean (or equivalent) classes vessels should address the documented overboarding needs in Sections 3.2–3.5 in their science mission requirements.

3.2. Reestablishing Longer Piston Coring Capabilities

Obtaining continuous samples from deep sub-seafloor strata is essential for many paleoenvironment, geohazard and deep biosphere objectives. Our current ability to collect piston cores beyond 20 m length is limited by the ability of ARF vessel handling system's capacity to sustain loading encountered when pulling the corer out of the

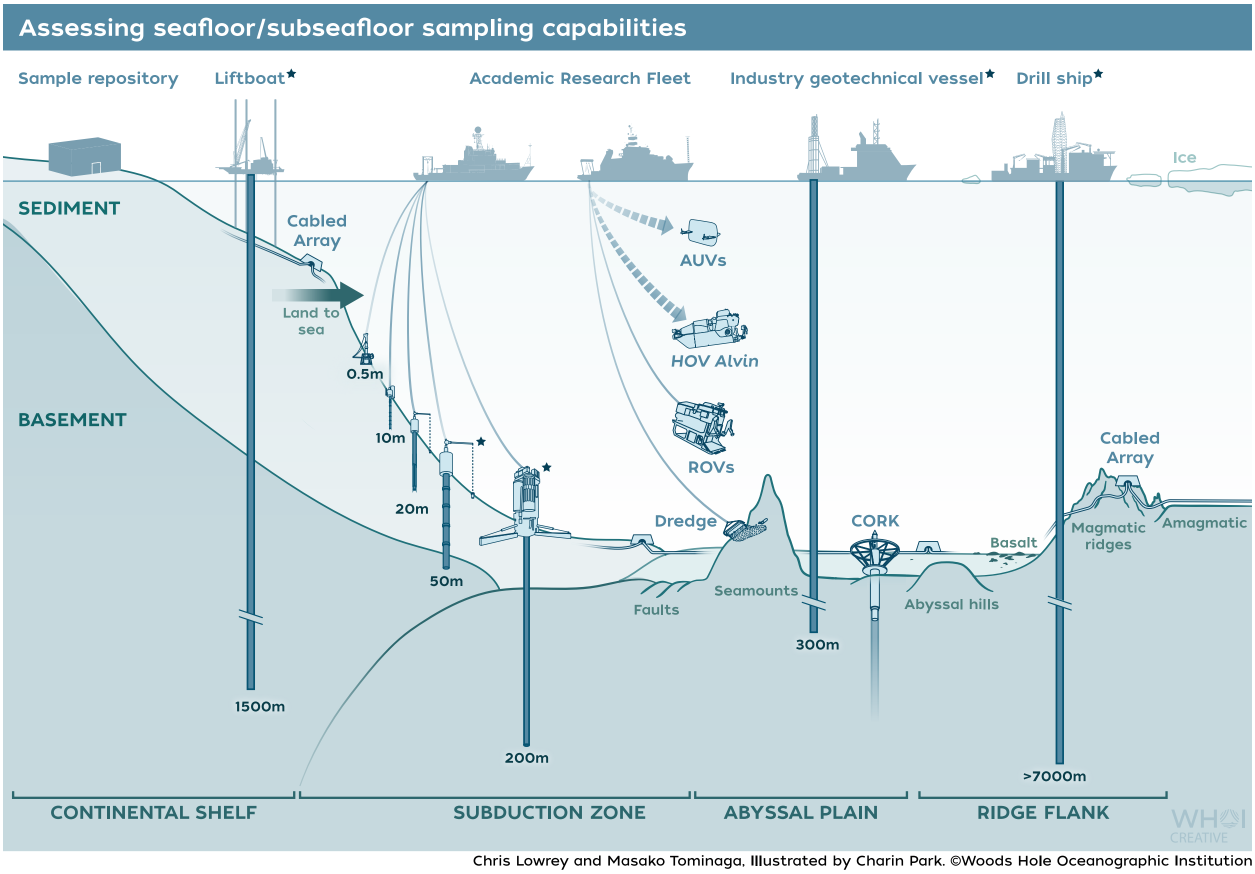

Figure 1. A schematic diagram showing desirable seafloor/sub-seafloor sampling technologies, some of which are presently not readily available within current ARF sampling capabilities (denoted by "*," including 50-m piston coring, lander drill, scientific drill ship, liftboat, and geotechnical vessel). Diagram not to scale. (Chris Lowery and Masako Tominaga, illustrated by Charin Park. ©Woods Hole Oceanographic Institution).

seafloor. The largest wires and ropes in use across the current ARF are typically 9/16″ in diameter, with a Safe Working Load (SWL) of 16,500 lbs. The pullout tensions for piston cores of 10–20 m often exceed this SWL, and require a reduction in safety factor to 1.5x breaking strength (allowing for pullouts of up to 21,667 lb) only permissible aboard the ARF with an exemption given for geological sampling. Longer or "giant" piston coring systems (i.e., cores of 40+ m length) cannot be deployed from this wire. To overcome this limitation, current and future Global vessels will require integrated or deck-mounted winches equipped with larger-diameter synthetic ropes of much greater strength. An ideal piston coring system would have the cross-deck compatible, design flexibility to swap weights and barrel lengths to achieve a wide range of 6–40+ m core lengths and have dedicated handling systems operable from most of the ARF Global and Ocean classes vessels.

3.3. Achieving 5,000 m+ Dredging Capability

Obtaining rock samples from the seafloor is essential to studying surface-to-deep Earth processes. Effective rock dredging requires active wire tension spikes of over 10,000 lbs. Similar to the above coring system discussion, the strength member SWL of the current ARF limits safe deep-sea dredging to less than 5,000 m water depth. The load handling capabilities of the current ARF Global class vessels are not substantially greater than much smaller ARF vessels—for example, the 116″ R/V *Pelican* has a trawl wire diameter of 1/2″ with a maximum SWL of 14,300 lbs. While some ARF vessels are equipped with a synthetic line, most operate with 9/16″ steel wire, the weight of which alone is ~7,000 lbs at 5,000 m payout; coupled with the weight of the dredge, friction from dragging, and heave of the ship, there is only ~4,000–9,000 lbs of pull available for dredging, insufficient for pulling through seabed outcrops. The use of a synthetic line presents an opportunity to extend deep sea dredging capabilities to >5,000 m in the US ARF, and deploying and testing this capability must be set as a near-term, achievable goal (green highlight in Table 1).

Table 1
Synthesis of Cross-Cutting Seafloor/Sub-Seafloor Scientific/Infrastructure Needs Identified in Breakout Session Discussions (See Data in Tominaga et al. (2024))

	FUTURE scientific theme:	Ocean-seafloor interfaces	Climate and anthropogenic activities	Deep crust processes	Ridge axes processes	Solid Earth processes	High-latitude sciences
Research Vessel and Associated Infrastructure Capabilities that Enable Seafloor Sampling	Scientific Drilling platform/vessels (4″+ diameter cores, holes >,1000 m, water depths at least >6,000 m)	A	A	A	A	A	A
	Overboarding capabilities up to 16,500 lb SWL	A	A	A	A	A	A
	Overboarding capabilities up to 100,000 lb SWL	A	A	A	A	A	A
	USBL (ultra short baseline) navigation and dynamic positioning for the widest range of vessel classes	A	A	A	A	A	A
	Seafloor imaging and process characterization (by AUV/ROV/HOV, and TowCam)	A	A		A	A	A
	Shallow subseafloor imaging (<5–~200 m below seafloor)	A	A	A	B	A	A
	Deep subseafloor imaging (>1,000 m below seafloor)		B	A	A	A	A
	Refrigerated laboratory space	A	A	A	A	B	A
	Modular shipboard laboratory vans (e.g., multi-sensor core logger, CT-scanner, radioisotope, etc)	A	A	A	B	B	A
	Trace-metal clean laboratory space	A	B	A	A		B
	Seafloor cabled arrays (sensors, power in focused areas like OOI RCA)	B	A	B	A	B	B
	Ice breaker capabilities (one can be Polar Class 3 in addition to a Polar Class ≥5)	B	A				A
	Polar aircraft		B				A
Seafloor Sampling Capabilities	Dredging/wax coring (seafloor surface rock samples)			A	A	A	B
	Dredging >5,000 m water depths			A	A	A	
	Grab/Bio samplers	B	B				B
	Box/Soutar corers (large volume surface sediments)	B	B				A
	Multi-coring/slow-coring (sediment/water interface)	A	A		B	B	A
	Kasten corers (large volume up to 3 m)	B	A	A	A	A	A
	Gravity corers (2″ or 4″ diameter cores up to 20 m)	A	A	A	A	A	A
	Piston corers (2″ diameter corer up to >30 m)		B	B	B	B	A
	Jumbo piston corers (4″ diameter corer up to 30–40 m)	A	A	B	B	B	A
	Giant piston corers (4″ diameter corer up to 40–50 m)	A	A	A	B	B	A
	Gas/Fluid samplers (H2O, CH4, H2, Oxygen, etc.)	A	B	A	A	B	B
	ROV/HOV-hosted seafloor push corer	A			A	A	A
	ROV/HOV-hosted seafloor (rock) drill	A			A	A	
	CORKs/seals/observatories/sensors			A	A	A	B

Table 1
Continued

FUTURE scientific theme:	Ocean-seafloor interfaces	Climate and anthropogenic activities	Deep crust processes	Ridge axes processes	Solid Earth processes	High-latitude sciences
Logging/geotechnical tools operable from ARF to access legacy holes	B	B	A	A	A	B
Expanded capabilities of AUVs, including efficient access to shallower water (10–4,000 m) depths	A	A	A	A	A	A
Lander-style robotic drills** (3″+ diameter cores, holes up to ~200 m)	A	A	A	A	A	A

Note. A: required, B: desired, blank: non-mission critical. Blue highlights indicate capabilities that exist within the current US Academic Research Fleet. Green highlights indicate workshop priority recommendations achievable within the next funding cycle. Yellow highlights indicate workshop priority recommendations achievable within a typical corporate agreement period, the approximately 5-year cycle over which an NSF-supported facility is funded to maintain operations. Orange highlights indicate community infrastructure needs which will require a longer planning process to implement, over 5 years and likely over a decade. Blue: currently available for NSF research. Green: next emerging needs—low risk and/or low budget) (~1 year funding cycle). Yellow: intermediate—during the corporate agreement period (~5 years funding cycle). Orange: longer term (>~ 5 years funding cycle).

3.4. Establishing US Lander-Style Seafloor Robotic Coring Systems

Lander-style drilling of sub-seafloor strata (hard rocks and sediments) will fulfill key sampling gaps and enable urgent research not currently supported by dedicated drill ships or existing ARF facilities. This includes sampling biogeochemically unique bare hard-rock environments and conducting high-latitude studies in regions accessible only with icebreakers. It is possible to contract lander-style drills from private-sector geotechnical firms; however, industry leasing costs are frequently prohibitive, and scheduling practices are not aligned with academic research and training needs. Establishing a US academic community lander drill facility will better accommodate research objectives, allow for future technological innovation, and grow the workforce via the training of students and skilled technicians. A lander drill will fulfill key sampling gaps between what manipulator-based coring (e.g., ROV based) and deep drilling vessels (e.g., JOIDES Resolution and D/V *Chikyu*) can achieve. While lander style drills are available for academic research outside of the US (e.g., *MARUM*-MeBo, JAMSTEC R/V *Kaimei* Boring Machine System), similar systems cannot currently be deployed from even the largest ARF vessels due to overboarding limitations. Non-US vessels typically have A-frames with 30 Ton or larger SWL for overboarding. Enhancing ARF handling system capabilities would reduce costs relative to the mobilization and deployment of lander style drills from contract vessels.

3.5. Expanding Underwater Robotic Capabilities

Accessing the deep seafloor is essential to expanding our knowledge of the deep biosphere, biogeochemical cycles, and hydrogeology. Many objectives require precision navigation and high-resolution contextual data (e.g., bathymetry, seafloor imagery, and other geophysical and fluid/chemical sensing). Documentation of rates of change and finest-scale processes requires continuous measurements within the seafloor (e.g., via sub-seafloor observatories, utilizing Autonomous Underwater Vehicles (AUVs)). Current oversubscription of national deep submergence assets hampers progress in high-resolution seafloor science. In particular, expanding AUV assets to enhance shallow-intermediate seafloor surveys (water depths <4,000 m to the continental shelf) as well as mapping and increasing accessibility within polar regions is highly desired. Expanding Remotely Operated Vehicles (ROV) manipulator instrumentation such as drilling, oriented coring, handheld rock chemistry, and near-surface physical properties sensing systems is also highly desirable. The workshop participants urge the development of ROV-based capabilities to substitute and supplement drilling-vessel-based downhole sampling and logging operations in legacy holes.

3.6. Maximizing the Value of Returned Samples

Existing seafloor sample repositories and databases preserve materials and enable research beyond the science initially envisioned when they were collected (Text S4 in Supporting Information S1). The workshop identified several areas for enhancing the capabilities provided by sample and data repositories. Repositories can encourage researchers to adopt standardized digital sample descriptions and archival worksheets, facilitating seamless logging of metadata into a ready-made database. Curators could be made available for sampling-intensive campaigns or to train early career chief scientists in addition to providing remote guidance prior to and during sampling programs. Seagoing facilities can work with investigators and repositories to provide operational cruise reports and databases that can be linked to archived samples.

Repositories can further enhance the discoverability of samples and data by improving the functionality of existing databases. Awareness of best practices for sample and data archival in the field can be developed via partnering with relevant UNOLS Facilities (Text S3 in Supporting Informations S1), including providing educational videos for shipboard science parties and convening and participating in community workshops. This will also be established through broader community use of unique sample identifiers (IGSNs) to track samples and resulting publications.

Expanding repository capabilities to include more unconventional seafloor samples (e.g., water, gas, biological) should also be addressed. While some non-US repositories (e.g., Kochi Core Center) can accommodate such needs, there is no similar scale service in the US.

3.7. Maintaining Marine Science Operations Workforce and Advancing Science Through Transfer of Institutional Knowledge

Purposefully passing on institutional knowledge is one of the most efficient mechanisms to prepare early career science, technical, and operations individuals to contribute to scientific progress. The FUTURE workshop emphasized the importance of educational and professional development opportunities, advocating for inclusive workshops that provide opportunities for early career scientists to interface with peers, form collaborations, and gain institutional knowledge from the broader community (e.g., UNOLS early career programs, Crustal Ocean Biosphere Research Accelerator).

Disclaimer

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Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data sets for this research are available in Tominaga et al. (2024), which is publicly findable and accessible via https://doi.org/10.5281/zenodo.13999249.

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