Major Gaps in Fundamental Deep-Sea Science, Assets and Technology, and a Shrinking Pool of Academic Expertise Hamper U.S. Leadership in Deep-Sea Exploration and Management

Executive Summary

The USA does not currently have sufficient data to enable the responsible development of deep seabed mineral extraction. Despite substantial industry investments into scientific research in certain existing mining exploration claim areas, major research gaps remain, even in the best studied areas. Key knowledge gaps include a) resource quantity and quality b) the deep-water column communities c) natural variability in seafloor and water column community structure and biodiversity over space and time– seasonal and interannual scales d) biogeography and vertical connectivity e) animal sensitivity to metals and sediments. If we are to meet the federal goal of responsible development of seabed mining, these research gaps must be filled prior to commencement of commercial mining.

To enable evidence-based and informed decision-making and policy creation around commercial-scale deep sea mining in both domestic and international waters, we must fully understand the potential impacts on the seafloor, the entire water column above it, and the important services those habitats provide including seafood, nutrient regeneration, biodiversity, and natural carbon sequestration. **Additional experimental and ecotoxicological work is urgently needed to evaluate possible impacts on seafood safety and fisheries from deep-sea mining.** The few existing test mining experiments have not provided sufficient data to predict what the full impacts of a mining operation will be. Deep-sea mining will be the largest intentional human impact on the largest habitat on our planet in history, and we must have the scientific knowledge necessary to make informed policy decisions.

The USA has fallen far behind globally in terms of deep-sea scientific capabilities. Action is needed. First, the pool of deep-sea academic expertise has dwindled due largely to limited/shrinking federal funding opportunities, impacting U.S. leadership in deep-sea science and the readiness of the U.S. workforce to serve this potential new industry. Secondly, the USA currently has excellent, but limited numbers of assets capable of sampling at the depths of most seabed resources. Thirdly, US deep-sea research capabilities are limited by an aging, shrinking fleet of global class research vessels.

We can effectively and efficiently fill critical research gaps and restore American leadership in deep sea science through a combination of a) independently administered industry-funded research, b) large, interdisciplinary, federally funded expeditionary campaigns, and c) the creation of smaller funding opportunities to add value to ocean exploration and other existing remote, deep-sea work.

The state of deep-sea science as it relates to the responsible development of deep-sea mineral resources in domestic and international waters.

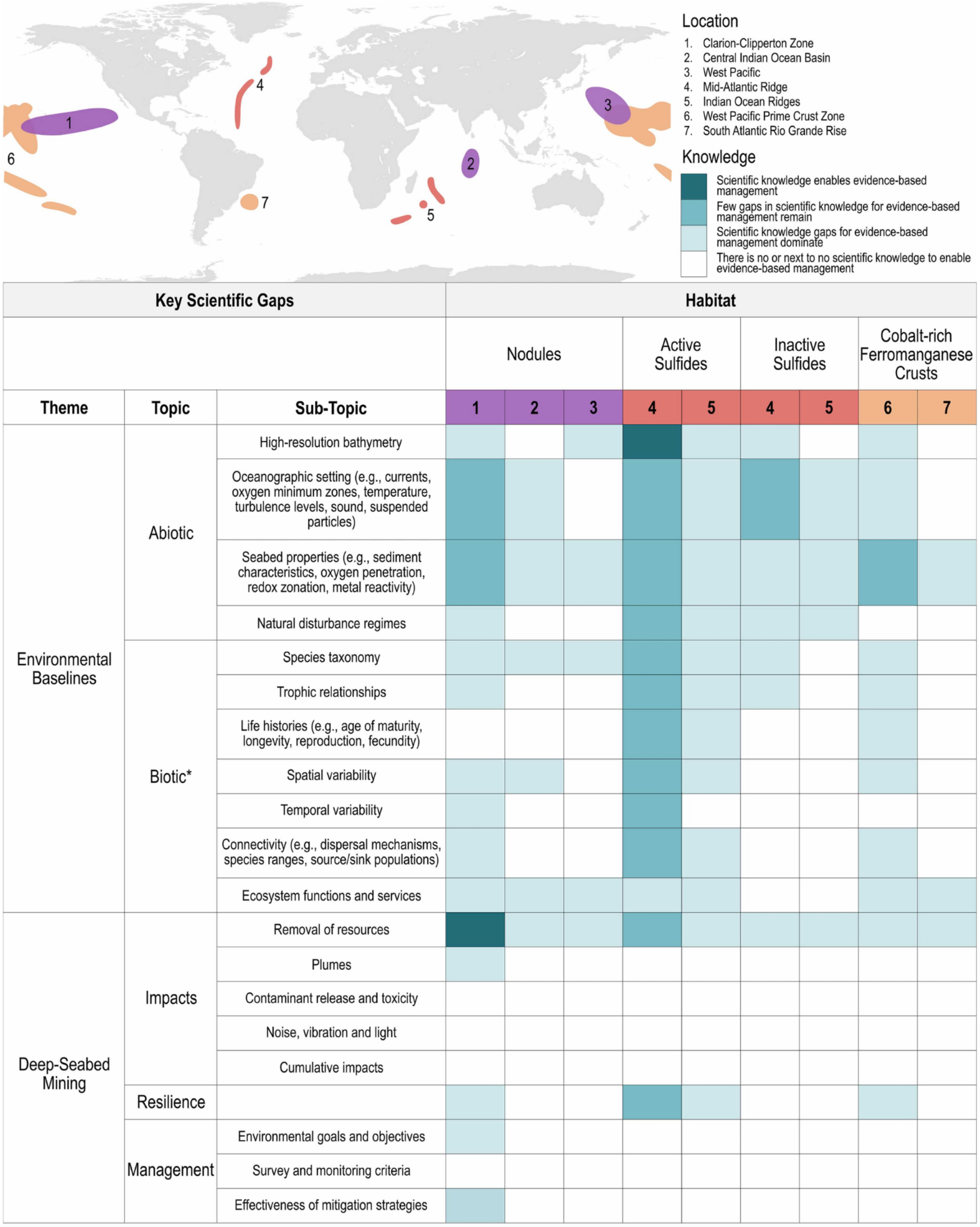
The deep sea is the largest biome on our planet and not only provides more than 90% of living space on Earth but also crucial ecosystem services. It drives the earth system, acts as a large carbon sink, recycles and remineralizes nutrients, provisions commercially important species thereby supporting fisheries and seafood supply, and harbors vast and still largely undescribed biodiversity. In fact, biodiversity levels in the deep sea rival, and sometimes exceed, the most diverse terrestrial habitats (e.g. tropical rainforests) (Washburn et al., 2021). In the CCZ alone, there are an estimated ~7000 species with 90% remaining undescribed (Rabone et al., 2023). While the deep ocean may seem like a remote, alien disconnected world, it is tightly coupled to the surface and to us humans, and despite its enormous size, the deep ocean is not too big for humanity to impact. The abyssal ocean is much less resilient to disturbance than those in shallow water or on land, with fewer or no opportunities for restoration. If we proceed without fully realizing what underwater world we are stepping into, we could lose parts of our planet before we truly know, understand and value them.

Current State of Baseline Data in Potential Deep-Sea Mining Areas

Currently, we do not have sufficient scientific data to enable the responsible development of deep-sea mineral resources. A recent peer-reviewed articles synthesizing 306 studies concluded that there is not enough existing scientific data in any prospective deep-sea mining area in international waters to enable evidence-based decision-making (Amon et al., 2022, full text included in supplementary files). Similarly, recent submissions in response to the Request for Information and Interest for Commercial Leasing for Outer Continental Shelf Seabed Critical Minerals Offshore American Samoa (BOEM-2025-0035) and in response to the Request for Information on Knowledge Gaps Pertaining to Commercial Leasing for Outer Continental Shelf Minerals Offshore Commonwealth of Northern Mariana Islands (90 FR 50872, 2025-19852, BOEM-2025-0351), each compiled by numerous deep-sea experts, all found that there is almost no pertinent environmental baseline data available for either domestic region of interest (full texts included as supplementary). A robust baseline is essential as it establishes a reference point against which impacts can be measured and monitored. This requires data across space and time, covering a range of species (from bacteria to sponges and fishes) and parameters (from seabed to oceanographic parameters) (See Figure 1).

We do not have complete baseline assessments in any prospective deep-sea mining areas, including in the best studied deep-sea mineral contract areas. For example, mining company-funded research in NORI-D, arguably one of the best-studied license areas in the Clarion-Clipperton Zone (CCZ), has resulted in the start of a baseline; however, there are still essential components missing. Seafloor biological data were only collected three times (2020-2022), and baseline water-column data (not collected at all in any other contract area so far) exist only in the spring and fall seasons of a single year (2022), and only down to 1500 m depth, while deeper pelagic samples exist for only one season. This is for a claim roughly the size of the state of New Jersey. **We do not have sufficient data for deep-water column communities for a robust baseline assessment for any prospective deep-sea mining region, domestic or international**. Assessments of seafloor impacts from test mining were conducted only twice, with the second being an incomplete study (e.g. they did not sample macrofauna; Stewart et al., 2026). Biological data from the water column was not also collected post-test. All other expeditions in the area were focused on resource assessment and physical oceanography. Therefore, the biological baseline lacks the temporal resolution required to understand natural variability in abundance, biomass, or community structure and function for both the deep seafloor and the water column. **Thus, even in the best studied areas and certainly in less sampled areas, it remains impossible to distinguish mining induced changes and impacts on the**

ecosystem from natural variability hampering the monitoring and tracking of impacts required for responsible development.



Key Scientific Gaps			Habitat								
			Nodules			Active Sulfides		Inactive Sulfides		Cobalt-rich Ferromanganese Crusts	
Theme	**Topic**	**Sub-Topic**	**1**	**2**	**3**	**4**	**5**	**4**	**5**	**6**	**7**
Environmental Baselines	Abiotic	High-resolution bathymetry	░	□	░	■	░	░	□	░	□
		Oceanographic setting (e.g., currents, oxygen minimum zones, temperature, turbulence levels, sound, suspended particles)	▨	░	□	▨	░	▨	░	░	□
		Seabed properties (e.g., sediment characteristics, oxygen penetration, redox zonation, metal reactivity)	▨	░	░	▨	░	░	░	▨	░
		Natural disturbance regimes	░	□	□	▨	░	░	░	□	□
	Biotic*	Species taxonomy	░	░	░	▨	░	░	□	░	□
		Trophic relationships	░	□	□	▨	░	░	□	░	□
		Life histories (e.g., age of maturity, longevity, reproduction, fecundity)	□	□	□	▨	░	□	□	░	□
		Spatial variability	░	░	□	▨	░	□	□	░	□
		Temporal variability	░	□	□	▨	□	□	□	□	□
		Connectivity (e.g., dispersal mechanisms, species ranges, source/sink populations)	░	□	□	▨	░	□	□	░	□
		Ecosystem functions and services	░	░	░	░	░	□	□	░	░
Deep-Seabed Mining	Impacts	Removal of resources	■	░	░	▨	░	░	░	░	░
		Plumes	░	□	□	□	□	□	□	□	□
		Contaminant release and toxicity	□	□	□	□	□	□	□	□	□
		Noise, vibration and light	□	□	□	□	□	□	□	□	□
		Cumulative impacts	□	□	□	□	□	□	□	□	□
	Resilience		░	□	□	▨	░	□	□	░	□
	Management	Environmental goals and objectives	░	□	□	□	□	□	□	□	□
		Survey and monitoring criteria	□	□	□	□	□	□	□	□	□
		Effectiveness of mitigation strategies	░	□	□	□	□	□	□	□	□

Figure 1. This table shows the current level of scientific knowledge in relation to deep-seabed mining in international waters. Note that there are almost no locations for any of the habitat types that have sufficient knowledge for evidence-based management or decision-making. This has been compiled from a synthesis of the peer-reviewed literature (306 papers) and expert opinion and includes both target and non-target areas within each region. * denotes benthic and pelagic habitats. Reproduced with permission from Amon et al. 2022.

The abyssal ocean is not all the same, so we cannot use data from one area to represent other areas, even adjacent areas within the same prospective mining region. Like on land, we would not expect the same species and ecosystems on the east and west coasts of the USA - the same is true for the deep sea (e.g. Drazen et al., 2021; Leitner et al., 2017; Washburn et al., 2021). From existing data from all over the Clarion-Clipperton Zone (CCZ) and the Pacific, we know that communities change over small scales relative to the scale of individual license areas. This is true for both small (e.g. macrofauna) and large animals (megafauna; Drazen et al., 2021; Simon-Lledó et al., 2023). Even one license area in the CCZ (~75,000 km2) can span different biological communities and habitat types (Park et al., 2026; Uhlenkott et al., 2023), so single-site reference points are not helpful. No deep-sea mining company has yet provided sufficient data to identify a robust reference area for monitoring the impacts of mining. In addition, the reference areas should be studied over decades, along with the mining zones, to capture natural temporal variability.

Only a few empirical studies exist currently that allow for the determination of environmental indicators and thresholds, which are needed to detect change and manage an industry appropriately (Schmidt et al., 2025; Stenvers et al., 2023). Ongoing efforts to determine indicators and thresholds face the challenge of unknown levels of natural variability against which to assess harm. The complex nature of deep-sea ecosystems — including food-web dynamics, species interactions and functional redundancy — limits our ability to select indicators that accurately reflect ecosystem health, which risks selection of less ecologically informative indicators that are easier to measure.

The knowledge gaps, as described above, still exist for the best studied regions in the CCZ and certainly for the much less studied prospective domestic deep-sea mining areas, such as those around Hawai'i, American Samoa, and the Commonwealth of the Northern Mariana Islands (CNMI). See supplementary files for responses to BOEM request for information on these areas. In brief, there are almost no environmental baseline data from the specific regions being considered for mineral leasing. This includes mineralogical data, physical data, chemical data, biological and ecological data, and bathymetric mapping data (Orcutt et al. RFI response). While there has been limited scientific research and exploratory work done in the American Samoan EEZ, almost none of this work has focused on the abyssal seafloor where nodules may be found. Only three ROV dives have been conducted in depths exceeding 3000m, with only 2 AUV dives exceeding 5000m depth, and none of these occurred in the potential lease area. The proposed lease area in CNMI has more available mapping data; however, extensive review of publicly available data found that there are almost no physical, chemical, biological, ecological, or mineralogical baseline data available (Washburn et al. RFI response). Moreover, that review found that there are several existing features within the proposed lease area that likely qualify as vulnerable marine ecosystems (VMEs). Thus, gathering sufficient baseline data, as required for informed decision-making regarding deep sea mining, will require significant investment and independent scientific research. **Major research gaps remain in seafloor and water-column community structure, ecology, connectivity, and biogeography. If we are to meet the federal goal of responsible development of deep-sea mining, these research gaps must be filled prior to the onset of commercial-scale deep-sea mining.**

Current State of Knowledge on Potential Impacts of Deep-Sea Mining

Only a handful of scientific experiments and small-scale mining tests currently inform our understanding of the potential impacts of deep-sea mining, and these are on a much smaller scale compared to commercial-scale mining; more research on impacts is needed. Most experiments cover a few hundred meters to a square kilometer (Jones et al 2017). Commercial-scale deep-sea mining will cover hundreds of square kilometers in a year, with individual contract areas often ~75,000km^2 - close to the land area of the whole state of South Carolina. This scale is unprecedented relative to land-based mining, where, for example, the largest land-based copper mine is ~4.5km (less than 3 miles wide). In addition, the ocean is a highly interconnected dynamic place where ocean currents, storms, and eddies can spread impacts over huge distances. Due to the sheer magnitude and scales involved, and because of the major research gaps in understanding these remote and inaccessible habitats, predicting the impacts of even a single commercial-scale deep-sea mining project is very difficult. Trying to estimate the cumulative impact of multiple mining projects operating simultaneously over many years is even more challenging, especially as mining will create chronic stress in ecosystems. With these caveats in mind, we can use the best available (though far from complete) science to inform our thinking on what potential impacts will be both on the seafloor from nodule removal and the collector vehicle, and the associated seafloor sediment plume and in the waters above where discharge plumes from initial shipboard processing of recovered ore will occur. It must be emphasized that the seafloor plumes will be distinct from the discharge plumes in the water column. If permitted or chosen, discharge in the water column will have distinct and poorly understood impacts. Therefore, seafloor and water-column impacts are described separately below.

Seafloor Impacts

Abyssal seafloor ecosystems provide key ecosystem services such as nutrient regeneration and carbon sequestration, and vast genetic resources. Deep-sea ecosystems are some of the least resilient on Earth, with small-scale experiments showing they do not fully recover, even after 44 years (Jones et al 2025). Though some animals living in the sediments can recover after years, nodule removal will kill nodule associated fauna, with nodules not regrowing on biologically relevant timescales (they form over millions of years). Nodules are critical habitat for small animals living on the nodules and for an estimated 50% of large animals (e.g., corals, octopus) that depend directly on the nodules for survival or reproduction (Amon et al., 2016; Purser et al., 2016, Drennan et al 2021). Depending on the collector type, all sessile or slow animals within the collector tracks will likely be killed. The sediment disturbance caused by nodule mining will create a seafloor sediment plume that will spread as a gravity flow (like an avalanche) along the seabed, eventually settling kilometers away and smothering sessile animals, increasing the area impacted by several times. Deep abyssal waters are amongst the clearest in the world, so animals are anticipated to be extremely sensitive to small changes in turbidity. **The destruction of seafloor fauna in the path of the mining vehicle is undisputed, however more experimental and observational work is needed to test animal sensitivity to elevated turbidity and sediment blanketing.**

Additional population connectivity and biogeography studies are needed to better understand extinction risks. These risks are distinct for each deposit type. All known active hydrothermal vent systems globally could fit on the island of Manhattan, and each region (including at inactive vent fields) has unique species found nowhere else. Thus, extinction risks for polymetallic sulfide mining are extremely high. Seamounts are also relatively small and isolated habitats that host unique species often found nowhere else. Thus, extinction risks posed by ferromanganese or cobalt rich crust mining are likewise high. Although nodule fields are extremely large, communities vary over relatively small ranges (under 200km), and thus species may only exist in a single contract area (Washburn et al., 2021) increasing extinction risks. **Rare species seem to be the rule rather than the exception, further increasing extinction risks, with more research needed.**

Additional research is also needed to evaluate ecosystem services and functioning. For example, measurements of "dark oxygen" production associated with nodules represent a previously unknown ecosystem service provided by nodule fields (Sweetman et al., 2024), highlighting how much remains to be learned.

Water-Column Impacts

The water column, or the part of the ocean between the surface and the seafloor, is of great importance ecologically and for ecosystem services. It plays an important role in connectivity because this is where eggs and larvae of many species occur and where species live that connect deep-sea areas with shallow-water areas (the daily vertical migrators), and it also remains the largest unstudied habitat on the globe. In general, **water-column mining impacts remain the biggest knowledge gap.** Ore will be lifted from the seafloor, separated from unwanted sediment and seawater aboard a ship, and the waste discharged back into the ocean (no current regulation on depth). While mining simulation experiments, collector test trials, and disturbance experiments on the seafloor began decades ago, the first monitored and sampled midwater discharge plume occurred in November 2022, with subsequent peer-reviewed studies starting to be published in 2025. Initial modeling suggests that these plumes may extend ~45km from the discharge point and spread as a layer hundreds of meters thick (Ouillon et al. 2022). Currents and the moving vessel will also continuously bring new water into contact with the discharge pipe thus impacting large volumes of water over time. One estimate is between 1,500 and 15,000km^3 per year; for reference, the volume of Lake Superior is 12,000km^3) (Ouillon et al. 2022). Sediments and bits of ore in the discharged plume may disrupt breathing, vertical migration, and crucial visual communication through bioluminescence. The particles released in that mining trial were the same size as natural organic particles that are fed on by roughly half the deep midwater zooplankton, and thus may dilute their natural food, resulting in starvation, with further effects propagating through the food web (Dowd et al 2025). Only a single study exists that exposed a water column animal to a simulated plume, resulting in intense negative reactions including increased stress (Stenvers et al. 2023). This study did not include the elevated and toxic metal concentrations, microplastics, or organic pollutants in the sediments, which have been measured in test mining discharge (Sackett et al., 2024, Yonkos et al. *in review*). Effects from chronic exposure over weeks to years remain unknown for all deep-sea fauna. **Further experimental trials are needed to better understand the impacts that sediments (in addition to microplastics and metals) will have on diverse and important water column organisms including biogeochemically important microbial processes.**

Water-column communities also provide a critical ecosystem service by feeding many predators, including commercially-important species, such as tunas and billfishes (e.g. Iglesias et al. 2023). Thus, the addition of a combination of metals, microplastics, and sediments will likely affect water column communities on an individual and population scale and may also impact their predators, resulting in potential impacts on regional fisheries. In addition, we still have very little understanding of how additional microplastic and metal concentrations will be incorporated into foodwebs. There is a possibility that, like mercury, metals from discharge plumes could accumulate through the foodweb creating a direct health threat. **Additional experimental and ecotoxicological work is urgently needed to evaluate possible impacts on seafood safety and fisheries from deep-sea mining.**

US position in the global leadership for deep-sea capabilities, expertise, and funding

The U.S.A. has fallen far behind globally in terms of deep-sea scientific capabilities.

State of U.S. deep-sea expertise and state of deep-sea work force

While historically, the USA led in deep-sea research, China, Europe, and other countries have now overtaken the USA especially with regards to deep-sea mining research, as a result of their large-scale, sustained financial investments into scientific and academic institutions, national research facilities, technology development, and international collaborative projects (e.g. EU MiningImpact project;

https://jpi-oceans.eu/en/miningimpact-3). In contrast, due both to retirements and limited/decreasing federal funding opportunities for deep-sea science, the pool of U.S. deep-sea expertise has shrunken over this same period. Only a handful of active U.S. researchers have been involved in deep-sea mining research in the past decade. The current landscape for independent federal funding for deep-sea science generally, and in relation to deep-sea mining, is slim across many science programs that support marine science and oceanography (NSF, ONR, NASA, BOEM, DOE, NOAA). For example, as of last year, NOAA Ocean Exploration no longer offers their annual funding opportunity. Instead, vessels Okeanos Explorer and E/V Nautilus are mapping and visually surveying regions of interest for mining in the US EEZ. Such exploration is an important first step but insufficient to develop regional ecosystem understanding. While the NSF, has traditionally funded considerable deep-sea science, it has not funded deep-sea mining related research on the major scale required to tackle the numerous, large knowledge gaps that remain. **Sustained, substantial investments in industry-independent academic research on deep-sea ecosystems are needed to rectify this situation and bring the USA back into a leadership position globally.**

This shrinking of critical academic expertise likely will negatively affect work force readiness. The deep-sea mining industry and the US federal government will need trained scientific expertise to carry out environmental monitoring and management of activities. Commercial environmental consultants often do not have the specialized training required to work in the deep sea. Even familiar assessment and monitoring tools like boxcores are run and processed very differently (for accurate and quantitative data) in the abyssal environment. More trained scientists, particularly those with higher degrees, shipboard and laboratory experience in the deep sea will be needed. Training of this future workforce can be advanced by funding mining relevant research in the university system. **Thus, the necessary, sustained, substantial investment in U.S. deep-sea research will provide the additional benefit of producing a trained and ready U.S. workforce.**

State of U.S. deep sea assets and technologies

The USA currently has limited assets that are capable of sampling at the depths of many seabed resources (e.g. polymetallic nodules occur at 4000-6000 meter depth both internationally and in domestic waters). The available assets are excellent but are not sufficient to meet the research demand if the U.S. were to aim to fill the critical research gaps. Currently national deep submergence assets Human Occupied Vehicle (HOV) Alvin, Remotely Operated Vehicle (ROV) Jason, and NOAA ROV Deep Discoverer 2, are the only federal assets capable of complex sampling at these depths. National marine coring facilities through the Oregon State University Marine Rock and Sediment Sampling (MARSSAM) group enables collection of seafloor and mineral samples (e.g. boxcores, dredges, etc) at the required depths, which can provide key geological data. Ocean Exploration Trust's (OET) ROV Little Hercules (privately owned, part of the NOAA Oceans Exploration Cooperative Institute) is rated to 6000m depths and can provide excellent imagery of the seafloor but cannot take physical samples and has payload limitations. Autonomous Underwater Vehicle (AUV) Sentry and the National Deep Submergence Facility's TowCam are also depth rated and able to image the seafloor (acoustic and standard imaging) but are not able to collect physical specimens or deploy instruments on the seafloor. Thus, many assets are limited to studying large organisms and visible geological parameters (e.g. abundance/type of nodules, but not quality). These assets miss most of the biology- that which is not visible in photographs or videos taken several meters away (macrofauna, meiofauna) and fundamental abiotic variables (e.g. Figure 1). There are also only two federally owned large multinet systems capable of quantitatively sampling the deep-water column. U.S. deep-sea researchers do have a large set of additional assets at their disposal (e.g. baited cameras, sediment traps, deep larval samplers, additional sensor systems), most of them custom designed and built to purpose. **With sustained,**

substantial investments in U.S. research programs, labs, and institutes, this technology could be expanded and readily deployed to take the required biological, physical, chemical, geological, bathymetric, and biogeochemical data needed to fill research gaps.

State of U.S. research fleet in relation to deep sea capabilities

In addition to asset limitations, deep-sea research capabilities are limited by an aging and shrinking fleet of ocean and global class research vessels. While substantial investment has been made for new regional class vessels, our global and ocean class capabilities are limited and shrinking. The R/V Kilo Moana is the ocean class research vessel currently closest to all prospective mining regions (home port in Hawai'i) and is set to be retired in the next few years with no replacement plan. If I were to receive funding today to conduct a deep-sea research expedition to a potential mining region it would take at least one year if not multiple years before there is availability on a capable research vessel to carry out that research. **In contrast, China has amassed an arsenal of highly capable ships outfitted with 6000m and full ocean depth (11000m) rated vehicles and assets and is rapidly surpassing U.S. deep-sea capabilities and research.** An alternative to using federal research vessels is to contract other ships, which can be adapted for oceanographic expeditions but often lack much of the necessary equipment found on science vessels (e.g. hull mounted multibeam mapping systems, fisheries echosounders, adequate winches and wires for gear deployment, lab spaces to process samples, and clean seawater for metals work). In the short-term, NOAA and OET vessels could be made more available for academics to access through open funding opportunities. For the long term, **strategic investments into new research vessels could restore American leadership in deep-sea capabilities.**

Potential approaches to effectively and efficiently fill critical research gaps and restore American leadership in deep-sea science

To fill research gaps and restore American leadership we firstly need **substantial and sustained federally funded expeditionary scientific campaigns for independent interdisciplinary research in prospective mining regions and in critical mineral habitats generally that go beyond ocean exploration.** While exploration is an important component and has been responsible for incredible and important discoveries and observations, it cannot be the only model because it cannot (in its current form) provide the temporal and spatial sampling required. Going to a never before visited location once with a limited set of tools has limitations. **We need support for sustained sampling through time to build a better understanding of temporal variability in the deep ocean.** This means revisiting a site multiple times on relevant timescales to understand seasonal and interannual variability. This is largely lacking in nearly all deep-sea research including in deep-sea mineral regions. However, the importance of sampling through time is clear. If someone is tasked to sample the biology of a forest outside of DC in the depths of winter one time, even with all the best available technology and tools, they will never be able to tell you what that forest looks like in summer, or in a cold year versus a particularly warm year, and if after some event that person goes back to sample in summer, they would be unable to attribute differences to that event versus to natural seasonal variability. We know from a few, limited time series that the deep ocean experiences variability on both short and long timescales tied to seasonality and interannual cycles at the surface (e.g. Messié et al., 2023). Also, exploratory imaging is not collected in a standardized, quantitative way. We need expeditions doing quantitative sampling in addition to continued ocean exploration to fill knowledge gaps. **Creating new funding avenues for scientists to join ocean exploration expeditions with additional sampling technologies and equipment would allow us to take advantage of ongoing exploration activities in deep-sea minerals regions to conduct complementary, quantitative work.** It must be noted that this kind of "piggyback" funding cannot be limited to covering data collection efforts but must also support the rest of the scientific process: data analysis and peer-reviewed publication.

An alternative structure to funding deep-sea mining related research could also be explored where instead of directly funding science, companies place funds into independent, government-administered accounts or contribute to a general fund for research. To date almost all of the research that has been conducted in prospective mining regions has been funded directly by mining companies. While companies ought to be responsible financially for baseline research and environmental assessments of their contract areas and for the evaluation of the impacts of their mining technology, direct funding presents a conflict of interest and limits data transparency and availability. Also, mining companies only fund research in their lease areas, but biology does not respect these man-made boundaries. Understanding if a given species also lives outside a lease area will require additional sampling, for instance. **We need studies across large areas, over longer timescales, and in future potential mining areas (not leased yet), which is all impossible without sustained, industry-independent funding of science, both fundamental deep-sea research and applied research.**

There are also many additional opportunities to increase the value of other, already funded expeditions. Academics need a program or a pathway to apply for relatively small grants to support piggyback or value-added operations. If millions of taxpayer dollars are going to fund a resource assessment expedition in a critical mineral region for example to map and take samples of the seafloor, why not get a deep-sea ecology team on board? If we are already paying to boxcore, this team should be processing that core for the biology in addition to mineral content. In our current funding models, there are extremely limited options to apply for funding to join other expeditions on relatively short notice (e.g. 6 months) - so called "ships of opportunity"- and then to analyze and publish that data. One potential avenue to enable these quick responses may already exist. NSF has existing models to rapidly fund timely, opportunistic or high-risk work: RAPID and EAGER grants. These are limited to on the order of 200K and are designed for fast response. However, currently these pathways are not being used for this kind of value-added work.

Filling critical research gaps will require a combination of a) independently administered industry funded research, b) large, interdisciplinary, federally funded expeditionary campaigns, and c) the creation of smaller funding opportunities to add value to existing remote and deep-sea work.

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