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The role of sediments in understanding and managing the environmental impacts of deep-sea mining

Zhihan Fan,[1,2] Zhuangcai Tian,[1,*] Xiujun Guo,[1] Xianming Zhu,[1] Hongxian Chu,[2] Dapeng Bai,[2] Tong Li,[3] and Jinran Wu[4]

[1]Shandong Provincial Key Laboratory of Marine Engineering Geology and the Environment, Ocean University of China, Qingdao 266100, China

[2]Yantai Center of Coastal Zone Geological Survey, China Geological Survey, Yantai 264000, China

[3]School of Agriculture and Food Sustainability, The University of Queensland, St Lucia QLD 4072, Australia

[4]School of Mathematics and Physics, The University of Queensland, St Lucia QLD 4072, Australia

*Correspondence: zhuangcaitian@ouc.edu.cn

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Deep-sea sediments cover the vast majority of the Earth's seabed and provide a continuous record of ancient oceanic environmental changes, geological events, and biological evolution over timescales of hundreds of thousands to millions of years. As such, they are regarded as the "memory" of deep-sea environments. Additionally, sediments serve as the active foundation of modern deep-sea ecosystems; their organic matter, microbial communities, and pore water constitute the energy sources for benthic food webs and provide habitat for various benthic organisms. However, deep-sea mining activities directly impact this sensitive medium. This review focuses specifically on polymetallic nodule mining in abyssal plains, which is currently the most advanced commercial target. Regardless of the collection methods, mining inevitably leads to disruption of sediment physical structures and alterations in chemical states. Understanding the responses and feedback mechanisms of sediments is a scientific prerequisite for assessing ecological risks and developing effective conservation measures.

MECHANISM OF SEDIMENT DISTURBANCE: FROM PHYSICAL RESUSPENSION TO CHEMICAL RELEASE

Formation and diffusion of sediment plumes

One of the most apparent environmental disturbances associated with deep-sea mining operations is the generation of sediment plumes.[1] Based on their formation location and underlying mechanisms, these plumes can be categorized into two types: benthic plumes and surface/mid-water plumes.[1,2]

Benthic Plumes: These are generated directly by the disturbance caused by mining vehicle tracks, the suction process during nodule collection, and the movement of equipment. A typical mining vehicle can resuspend hundreds to thousands of tons of fine sediment particles per hour, resulting in the formation of turbid water masses at the seafloor that can disperse tens of kilometers from the operational area due to bottom currents (field observations from trial mining have documented plume extensions exceeding 10 km).

Surface/Mid-Water Plumes: These plumes are formed from tailings discharged from surface support vessels. Their particle size distribution is broad, with fine particles (< 10 μm) settling slowly and remaining suspended for extended periods in water body (at depths of 200-1000 m).

Activation and release of pollutants in sediments

Heavy metals (such as copper, zinc, nickel, and cobalt) in deep-sea sediments primarily exist in stable forms, such as sulfides, which have very low bioavailability. Mining activities can disturb these deep sediments, bringing them to the seafloor surface and exposing them to oxidizing seawater, potentially triggering sulfide oxidation and the release of metal ions. Additionally, historically accumulated persistent organic pollutants may re-enter the water column through resuspended particles and subsequently enter the benthic food chain via trophic transfer. Although current field evidence regarding the actual rates of contaminant migration and transformation under mining disturbances remains limited, laboratory simulations indicate that this risk should not be overlooked. Notably, Sweetman[3] found that the potential effects on the surfaces of polymetallic nodules can electrolyze seawater to produce "dark oxygen", and sediment resuspension and redeposition may alter the electrochemical characteristics at nodule-water interface, thereby indirectly influencing this unique oxygen generation pathway.

ECOLOGICAL CASCADING EFFECTS RESULTING FROM SEDIMENT DISTURBANCE

Habitat loss and alterations in benthic communities

Sediments serve as the primary living substrate for the majority of deep-sea benthic organisms. The removal, agitation, and covering of sediments due to mining activities directly result in the destruction of habitat physical structures.[4,5] Sessile organisms, such as corals and sponges, which depend on surface attachment and growth, are at heightened risk of local extinction as a consequence of habitat loss. Furthermore, in the immediate aftermath of mining disturbances, opportunistic species—characterized by rapid growth and short reproductive cycles—may experience a temporary increase in abundance. However, over time, the community is likely to undergo miniaturization and simplification. Restoration of the original community structure may require hundreds to even thousands of years (based on the slow recolonization rates observed in abyssal environments).

Disruption of biogeochemical cycling at the sediment-water interface

The sediment-water interface is a critical zone for material exchange and energy flow in deep-sea environments. Microorganisms play a pivotal role in driving the biogeochemical cycles of key elements, including carbon, nitrogen, and sulfur, within this interface.[4] Under natural conditions, organic matter in sediments undergoes slow mineralization through microbial processes, thereby providing a sustained energy source for deep-sea ecosystems. Resuspension and subsequent redeposition of sediment particles can disrupt the natural redox stratification: oxygen penetration may increase transiently, oxidizing previously anoxic layers and accelerating sulfide oxidation; this in turn can release dissolved metals and phosphate, while also altering the balance between aerobic and anaerobic decomposition pathways. Moreover, the physical mixing of oxic and anoxic zones can inhibit specialized microbial guilds (e.g., anaerobic methanotrophs), affecting overall carbon and nitrogen cycling. In the short term, disturbance may accelerate mineralization of surface organic matter, leading to a temporary nutrient release. In the long term, this may deplete limited organic matter reserves and diminish overall system productivity. However, long-term consequences for biogeochemical cycles are still largely hypothetical, as long-term field data are lacking.

Mid-water and far-field ecological impacts

Slowly settling fine particle plumes can be transported by the mid-water currents to areas far from the mining site. The mesopelagic zone serves as a critical habitat for many vertically migrating organisms and plays a significant role in the oceanic carbon pump. The introduction of plume particles can dilute natural marine snow, altering the quantity, quality, and sinking rate of organic matter, thereby affecting regional carbon export flux. These mid-water effects are currently inferred from modeling and laboratory studies; direct observational evidence from operational mining is scarce. Although specific mechanisms and scales of the impacts require more investigation, such disturbances may have significant global biogeochemical implications.

SCIENTIFIC MONITORING AND MANAGEMENT STRATEGIES FOR SEDIMENT PROTECTION

Development of intelligent monitoring and prediction technologies

To mitigate sediment disturbance, it is essential to establish a comprehensive intelligent monitoring network that spans the entire mining process. This

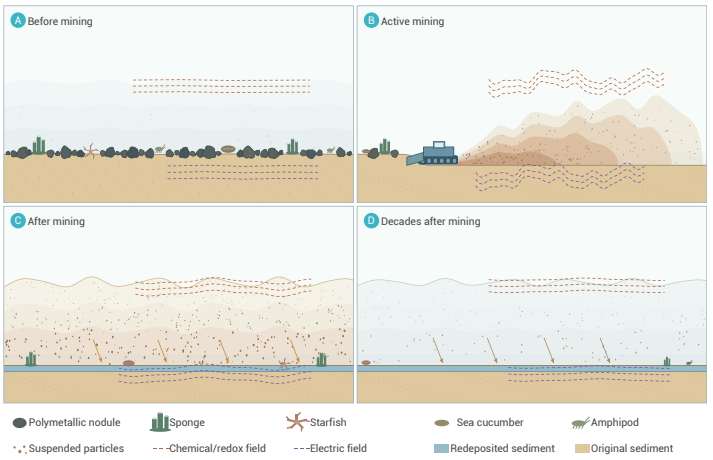

Figure 1. Deep-sea sediment as the memory and regulator of mining-induced environmental responses.

network should facilitate real-time tracking of plume diffusion, settling rates, and chemical changes. The integration of Autonomous Underwater Vehicles (AUVs) will enable the formation of a monitoring network that covers the pre-mining, mining, and post-mining phases. Crucially, monitoring outputs (e.g., turbidity, particle size, dissolved oxygen, and metal concentrations) should be used to adjust operational parameters in real time: for instance, increasing vehicle speed generally reduces the areal intensity of resuspension per unit distance, while adjusting collector suction pressure can limit entrainment of fine particles. Tailings discharge depth and location can be modified based on current direction and stratification to reduce mid-water plume residence time. Additionally, the development of an intelligent predictive model is crucial for forecasting plume diffusion pathways and sediment resuspension under various mining scenarios, thereby providing a foundation for operational planning and environmental impact assessments.

Establishment of environmental standards based on sediment thresholds

The formulation of environmental thresholds must be grounded in the ecological responses to sediment disturbances. The turbidity levels outlined in the five major thresholds established by international seabed management are significantly influenced by sediment characteristics. It is recommended to establish a multiparameter threshold system based on the relationships between sediment resuspension rates, sedimentation flux, and the responses of benthic communities. In setting the maximum permissible turbidity increase in bottom waters, it is imperative to consider physical parameters, including sediment resuspension rates and plume diffusion extents. For practical implementation, these thresholds can be linked to specific management actions: e.g., if turbidity exceeds a predetermined baseline + 10 NTU for more than 1 hour, mining speed should be reduced or collector height adjusted to minimize resuspension.

Implementation of adaptive management

Given the inherent complexity and uncertainty of deep-sea ecosystems, an adaptive management framework is essential for effective sediment management. During the exploration phase, a thorough investigation of the physical properties, chemical composition, and benthic communities of the sediment in the operational area will be conducted to establish a detailed baseline database. Prior to commercial mining, small-scale, controlled experimental mining should be performed to monitor sediment disturbance responses, validate predictive models, and calibrate environmental thresholds. Utilizing real-time monitoring data, adjustments should be made to the operational parameters, including driving speed, collection intensity, and location and method of tailings discharge, to minimize sediment disturbance. Post-mining, continuous monitoring of sediment, pollutant migration and transformation, and recovery of biological communities are necessary to evaluate the extent of ecological damage and the potential for natural recovery.

Enhancement of regional environmental management plans (REMPs)

REMPs serve as critical tools for coordinating mining activities with environmental protection at a regional level. In terms of sediment protection, REMPs should delineate areas requiring special protection based on baseline data, establish mechanisms for assessing the cumulative impacts of regional sediment disturbances, and develop agreements for data sharing and joint monitoring. Contractors should be mandated to share sediment monitoring data, collaborate on cross-regional impact studies, and enhance scientific understanding and management efficiency.

CONCLUSION AND PROSPECT

Sediment plumes are the primary vector of mining disturbance. Ecological recovery is extremely slow. Adaptive management, grounded in real-time monitoring and pre-defined thresholds, is essential.

Deep-sea sediments serve as a repository of Earth's ancient history and play a critical role in maintaining contemporary ecological balance. Each disturbance we impose on these sediments contributes to a new chapter in the Earth's narrative. In the context of deep-sea mining decision-making, it is imperative that we approach this delicate environment with caution. We must ensure that human activities do not exceed the ecological carrying capacity of marine ecosystems, thereby achieving sustainable management and equitable sharing of humanity's common heritage.

Looking ahead, we need to enhance international collaborative research focused on sediment disturbance mechanisms, ecological responses, and restoration processes. This should include long-term observational studies and experimental simulations. It is essential to expedite the development of scientifically grounded sediment environmental thresholds and monitoring standards to ensure their practicality and verifiability. Additionally, we should strive to create more precise monitoring technologies, environmentally friendly mining equipment, and advanced predictive models. Strengthening regulatory capabilities of International Seabed Authority is crucial for effective implementation of regional environmental management plans, as well as for fostering transparency and encouraging multi-stakeholder participation.

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AUTHOR CONTRIBUTIONS

Zhihan Fan: Writing - review & editing, Writing – original draft, Conceptualization. Zhuangcai Tian: Supervision, Conceptualization. Xiujun Guo: Funding acquisition, Conceptualization. Xianming Zhu contributed to the overall review and the Figure. Hongxian Chu was responsible for the review, revision, and approval of Figure 1. Dapeng Bai contributed to the review, revision. Tong Li: Conceptualization. Jinran Wu: Supervision, Writing - review & editing. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.