



Deep Sea Mining and Benthic Recovery: What Decades of Disturbance Experiments Tell Us

Rodrigo Kobayashi^{1*}, Hala Fernandez², Thao Ngo³

¹Department of Geology, Parana Research Institute of Geology, Trinidad and Tobago

²Department of Geology, Chaliyar Graduate Institute of Geology, Slovakia

³Department of Geology, Tamiraparani Academy of Geology, Ethiopia

Article Info

Volume 1, Issue 1, 2026

[doi: 10.62715/ijoms.2026.v1.i1.pp8-13](https://doi.org/10.62715/ijoms.2026.v1.i1.pp8-13)

Received: 31 December 2025

Accepted: 14 February 2026

Published: 05 April 2026

Abstract

Commercial interest in the polymetallic nodules of the abyssal Pacific has returned after a long pause, and regulators are being asked to judge how far the seabed fauna would recover once nodules are removed. The only direct evidence comes from a small set of disturbance experiments and test-mining tracks, the oldest made in the late 1970s, that have been revisited at intervals ever since. This narrative review sets out what those experiments did, how their sites were resampled, and what the published results show for microbes, meiofauna, macrofauna and megafauna. The record is consistent on the main point. Mobile animals and small sediment dwellers return to disturbed ground within years, though rarely to their former composition, while sessile suspension feeders that need hard substrate, sediment microbial activity and food-web carbon flow remain depressed after a quarter of a century. Plough marks themselves are still plainly visible. The review also explains why the experiments understate the effects of real mining: they were small, they left the nodules in place, and they produced modest plumes. It closes with the questions that the next generation of collector trials must answer and with the implications for setting thresholds of harm.

Keywords: Deep-sea mining, Polymetallic nodules, Benthic recovery, DISCOL, Clarion-Clipperton Zone, Abyssal fauna

© 2026 Rodrigo Kobayashi et al. This is an open access article under the CC BY license (<https://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

1. Introduction

Polymetallic nodules are concretions of manganese and iron oxides that lie on the sediment surface of abyssal plains, most densely in the Clarion-Clipperton Zone of the eastern Pacific at depths of four to five kilometres. They grow at rates of millimetres per million years and hold nickel, copper, cobalt and manganese in quantities that compare with land reserves (Hein et al., 2013). Under the United Nations Convention on the Law of the Sea the seabed beyond national jurisdiction and its minerals are the common heritage of mankind, administered by the International Seabed Authority, which is obliged to ensure effective protection of the marine environment from the harmful effects of mining (United Nations, 1982). The Authority has issued exploration contracts and is drafting rules for exploitation.

* Corresponding author: Rodrigo Kobayashi, Department of Geology, Parana Research Institute of Geology, Trinidad and Tobago. E-mail: rodrigo.kobayashi@parana.edu

© 2026 Rodrigo Kobayashi et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Whether protection can be effective depends on a factual question: what happens to the benthos after the nodules have been taken, and over what time. The abyssal seafloor is cold, dark and poor in food, and its communities are diverse, sparse and slow growing (Smith *et al.*, 2008). Glover and Smith (2003) judged nodule mining to be among the largest prospective human disturbances of the deep sea, because a single operation would work over hundreds of square kilometres of seabed each year. Since nobody has mined at commercial scale, the evidence on recovery comes from experiments designed to imitate part of the disturbance. This review examines that evidence.

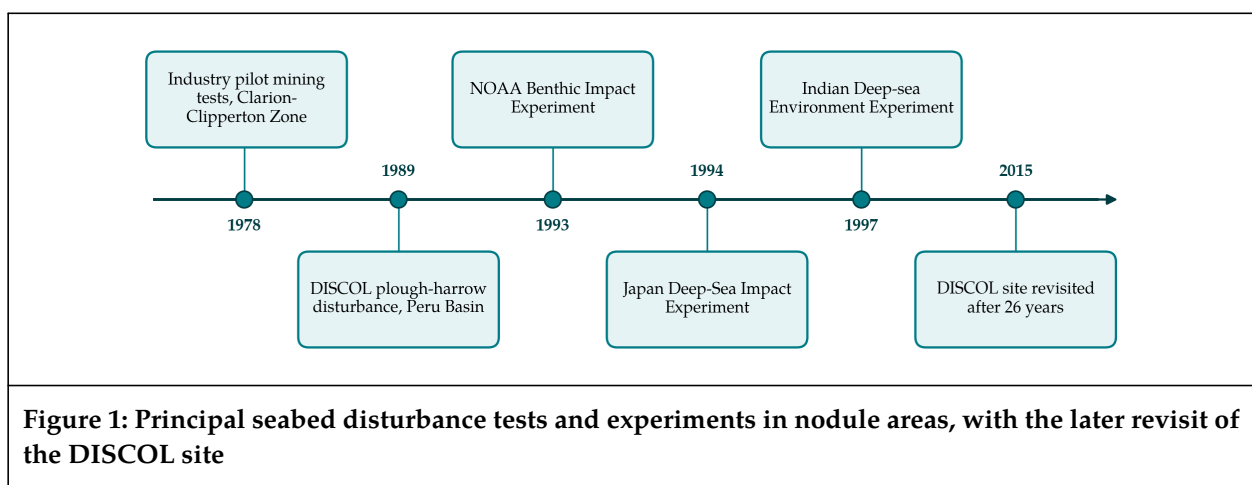
2. Scope and Approach

The article is a narrative review of the published literature on experimental and test-mining disturbance of nodule-bearing abyssal sediments. It concentrates on studies that returned to a disturbed site after a known interval and compared it with undisturbed ground nearby, and on the syntheses that have drawn those studies together. It was not compiled through a formal systematic search and it does not pool effect sizes. Mining of seafloor massive sulphides at hydrothermal vents and of cobalt-rich crusts on seamounts raises related questions but involves different habitats and is mentioned only in passing. General overviews of the industry and its environmental issues are available elsewhere (Miller *et al.*, 2018).

3. The Experiments

The record begins with the pilot mining tests that industrial consortia ran in the Clarion-Clipperton Zone in 1978, which left collector tracks on the seabed that scientists later relocated. The first experiment designed for ecological study was DISCOL, the Disturbance and Recolonization experiment, begun in 1989 in the Peru Basin. A plough-harrow eight metres wide was towed repeatedly across a circular area some two nautical miles in diameter, burying the nodules and turning over the upper sediment, and the site was sampled before, immediately after, and at intervals of months to years (Thiel *et al.*, 2001). Figure 1 places DISCOL among the experiments that followed it.

The experiments of the 1990s took a different approach. Instead of ploughing, they towed a device that fluidised the surface sediment and discharged it a few metres above the bottom, so as to study the blanketing of nearby seabed by resettled material. The Benthic Impact Experiment of the United States National Oceanic and Atmospheric Administration used this design in the Clarion-Clipperton Zone, and the same disturber was then employed by Japanese, eastern European and Indian programmes, the last in the Central Indian Ocean Basin. Results for meiofauna from these resuspension experiments were compared by Radziejewska (2002). Table 1 sets out the main groups of studies, the disturbance each applied and what was later reported.



4. What the Revisits Show

The findings are best taken by size class, since the classes differ in mobility, in generation time and in how they were sampled.

Table 1: Main lines of experimental evidence on benthic recovery in nodule areas

Evidence	Disturbance applied	What revisits reported	Sources
DISCOL, Peru Basin	Repeated ploughing; nodules buried, not removed	Mobile fauna returned; sessile fauna and microbial activity still reduced after 26 years	Thiel <i>et al.</i> , 2001; Simon-Lledó <i>et al.</i> , 2019
Test-mining tracks, Clarion-Clipperton Zone	Collector passes removing nodules and surface sediment	Nematode density and diversity lower inside track after 26 years	Miljutin <i>et al.</i> , 2011
Resuspension experiments	Sediment fluidised and redeposited nearby	Meiofaunal change under redeposited sediment; recovery partial over years	Radziejewska, 2002
Comparative surveys	None; nodule-rich and nodule-free areas compared	Epifaunal density tied to nodule cover	Vanreusel <i>et al.</i> , 2016
Cross-study synthesis	Published responses pooled across sites	Negative effects in most groups; few returned to baseline	Jones <i>et al.</i> , 2017

4.1. Megafauna

Megafauna, the animals large enough to be counted in seabed photographs, were followed at DISCOL from the start. Bluhm (2001) reported that, seven years after ploughing, mobile scavengers and deposit feeders such as holothurians had returned to the disturbed tracks, while sessile forms attached to hard surfaces had not. When the site was photographed again after twenty-six years, the plough marks were still sharply defined and the pattern had persisted: suspension feeders remained scarce in the ploughed ground, and the community there was still distinguishable from that of reference areas (Simon-Lledó *et al.*, 2019). The reason is not obscure. Sponges, anemones, corals and stalked crinoids need something firm to grow on, and in the abyss the nodules are that surface.

Surveys of undisturbed seabed support the inference. In the eastern Clarion-Clipperton Zone much of the megafauna, including many species new to science, lives attached to nodules (Amon *et al.*, 2016). Vanreusel *et al.* (2016) found epifaunal densities to be higher where nodule cover was dense and markedly lower in old experimental tracks from which nodules had been removed. Since nodules take millions of years to form, the loss of this habitat is permanent on any timescale of interest to management.

4.2. Macrofauna and meiofauna

The animals living within the sediment recover faster, in number if not in kind. At DISCOL the macrofauna, dominated by polychaetes, fell sharply after ploughing and had regained much of its abundance within seven years, although the taxonomic make-up and the vertical distribution in the sediment still differed from undisturbed ground (Borowski, 2001). Meiofauna present a less encouraging case where nodules and surface sediment were removed outright. Miljutin *et al.* (2011) sampled a track made by a test collector in the French claim area twenty-six years earlier and found nematode density, biomass and diversity all lower inside the track than beside it. The exposed subsurface sediment was more compact and poorer in food, which suggests that for infauna the removal of the reactive surface layer matters as much as the removal of nodules.

4.3. Microbes and ecosystem function

The most recent work at DISCOL moved from counting animals to measuring processes. Vonnahme *et al.* (2020) reported that microbial cell numbers and metabolic activity in the old plough tracks were still reduced after twenty-six years, most strongly where the organic-rich surface layer had been removed or buried, and estimated that microbially mediated biogeochemical functions need more than fifty years to return. A food-web analysis of the same site reached a matching conclusion: total carbon flow through the

benthic community remained lower in ploughed areas than in reference areas (Stratmann *et al.*, 2018). Recovery of abundance in some groups therefore does not amount to recovery of the system's function.

4.4. The overall pattern

Jones *et al.* (2017) drew the experimental results together in a quantitative synthesis. Effects of disturbance were negative in most faunal groups immediately afterwards, mobile and small organisms tended to recover within a few years, and very few groups returned to baseline or control conditions even after two decades. Effects were more severe where the disturbance was more intense. A broader review of resilience across nodule, vent and seamount systems concluded likewise that recovery in nodule fields is the slowest of the three and, for nodule-dependent fauna, should not be expected (Gollner *et al.*, 2017).

5. Why the Experiments Understate Commercial Mining

All the authors cited above caution against reading the experimental record as a forecast, and their reasons point in one direction. The first is scale. DISCOL disturbed a few square kilometres, of which only a fraction was touched by the plough, so that unploughed strips remained within metres of every track to supply colonists. A mine site would be worked contiguously over an area orders of magnitude larger, and recolonisation from the edges would have much further to travel. The second is the nature of the disturbance. The plough buried nodules but left them in the sediment, and the resuspension experiments left them on the surface. A collector removes them, together with the top few centimetres of sediment in which most of the fauna and most of the labile organic matter are found.

The third is the plume. Collectors will raise fine sediment that settles over ground beyond the mined strips, and the processing vessel will return water and fines to the ocean at some depth. Measurements on experimentally generated plumes indicate that abyssal clay particles aggregate and settle faster than their individual size would suggest, which would concentrate deposition nearer the source (Gillard *et al.*, 2019), though how far this holds at industrial discharge rates is not known. Metals released from crushed nodules and pore water may add a toxic component for which deep-sea dose-response data are almost absent (Hauton *et al.*, 2017). Nor is the seabed the only habitat exposed: Drazen *et al.* (2020) argued that discharge plumes and noise put midwater communities at risk and that these have been left out of most assessments.

6. Implications for Regulation

The experimental evidence bears on three regulatory questions. One is the meaning of serious harm, the threshold at which the Authority must act. Levin *et al.* (2016) proposed that harm be judged against the spatial extent, duration and reversibility of effects, and the revisits supply the duration: decades at least for sediment communities, and geological time for nodule fauna. A second is whether losses can be offset. Van Dover *et al.* (2017) held that biodiversity loss from mining is unavoidable and that restoration at abyssal depths is not feasible at the necessary scale, and Niner *et al.* (2018) concluded that a goal of no net loss cannot be met. The third is spatial planning. If mined areas will not recover, protection has to come from areas left unmined, which is the logic of the network of Areas of Particular Environmental Interest designed for the Clarion-Clipperton Zone (Wedding *et al.*, 2013).

7. Gaps and Future Work

What the old experiments cannot supply defines the agenda for new ones. No published study has yet followed a site after disturbance by a full-scale collector for more than a few years, and trials of prototype collectors are only now producing baseline and early post-impact data. The area over which plume deposition changes the fauna, and the thickness of deposit that does so, are poorly constrained. Connectivity is largely unknown: most abyssal species have been collected only once or twice, so that ranges, larval dispersal and the capacity of distant populations to reseed a mined area cannot be estimated with confidence. Baselines themselves vary from year to year with the supply of sinking food, and separating a mining effect from that variation needs longer reference series than most contractors hold. Finally, almost all the evidence concerns the Peru Basin and the eastern Clarion-Clipperton Zone,

and its transfer to other basins is an assumption.

8. Conclusion

Four decades of experiments give a coherent account. Disturbance of nodule-bearing sediment causes immediate loss across the benthos; mobile and small organisms come back in years, in altered assemblages; and sessile fauna, microbial activity and carbon cycling remain impaired for at least a quarter of a century where the surface layer and its nodules were disturbed. Because the experiments were smaller and gentler than mining would be, these results mark the optimistic end of the range. The sound working assumption for regulators is that mined seabed is lost as habitat for nodule fauna, and that conservation will depend on what is set aside.

Conflict of interest

To be declared by the author(s) before publication.

Funding

To be declared by the author(s) before publication.

References

- Amon, D.J., Ziegler, A.F., Dahlgren, T.G., Glover, A.G., Goineau, A., Gooday, A.J., Wiklund, H. and Smith, C.R. (2016). [Insights into the abundance and diversity of abyssal megafauna in a polymetallic-nodule region in the eastern Clarion-Clipperton Zone. *Scientific Reports*, 6: 30492.](https://doi.org/10.1038/srep30492) <https://doi.org/10.1038/srep30492>
- Bluhm, H. (2001). [Re-establishment of an abyssal megabenthic community after experimental physical disturbance of the seafloor. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 48\(17-18\): 3841-3868.](#)
- Borowski, C. (2001). [Physically disturbed deep-sea macrofauna in the Peru Basin, southeast Pacific, revisited 7 years after the experimental impact. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 48\(17-18\): 3809-3839.](#)
- Drazen, J.C., Smith, C.R., Gjerde, K.M., Haddock, S.H.D., Carter, G.S., Choy, C.A. et al. (2020). [Midwater ecosystems must be considered when evaluating environmental risks of deep-sea mining. *Proceedings of the National Academy of Sciences*, 117\(30\): 17455-17460.](https://doi.org/10.1073/pnas.2011914117) <https://doi.org/10.1073/pnas.2011914117>
- Gillard, B., Purkiani, K., Chatzievangelou, D., Vink, A., Iversen, M.H. and Thomsen, L. (2019). [Physical and hydrodynamic properties of deep sea mining-generated, abyssal sediment plumes in the Clarion Clipperton Fracture Zone \(eastern-central Pacific\). *Elementa: Science of the Anthropocene*, 7: 5.](https://doi.org/10.1525/elementa.343) <https://doi.org/10.1525/elementa.343>
- Glover, A.G. and Smith, C.R. (2003). [The deep-sea floor ecosystem: Current status and prospects of anthropogenic change by the year 2025. *Environmental Conservation*, 30\(3\): 219-241.](https://doi.org/10.1017/S0376892903000225) <https://doi.org/10.1017/S0376892903000225>
- Gollner, S., Kaiser, S., Menzel, L., Jones, D.O.B., Brown, A., Mestre, N.C. et al. (2017). [Resilience of benthic deep-sea fauna to mining activities. *Marine Environmental Research*, 129: 76-101.](https://doi.org/10.1016/j.marenvres.2017.04.010) <https://doi.org/10.1016/j.marenvres.2017.04.010>
- Hauton, C., Brown, A., Thatje, S., Mestre, N.C., Bebianno, M.J., Martins, I. et al. (2017). [Identifying toxic impacts of metals potentially released during deep-sea mining: A synthesis of the challenges to quantifying risk. *Frontiers in Marine Science*, 4: 368.](https://doi.org/10.3389/fmars.2017.00368) <https://doi.org/10.3389/fmars.2017.00368>
- Hein, J.R., Mizell, K., Koschinsky, A. and Conrad, T.A. (2013). [Deep-ocean mineral deposits as a source of critical metals for high- and green-technology applications: Comparison with land-based resources. *Ore Geology Reviews*, 51: 1-14.](https://doi.org/10.1016/j.oregeorev.2012.12.001) <https://doi.org/10.1016/j.oregeorev.2012.12.001>
- Jones, D.O.B., Kaiser, S., Sweetman, A.K., Smith, C.R., Menot, L., Vink, A. et al. (2017). [Biological](#)

- responses to disturbance from simulated deep-sea polymetallic nodule mining. *PLoS ONE*, 12(2): e0171750. <https://doi.org/10.1371/journal.pone.0171750>
- Levin, L.A., Mengerink, K., Gjerde, K.M., Rowden, A.A., Van Dover, C.L., Clark, M.R. et al. (2016). Defining "serious harm" to the marine environment in the context of deep-seabed mining. *Marine Policy*, 74: 245-259. <https://doi.org/10.1016/j.marpol.2016.09.032>
- Miljutin, D.M., Miljutina, M.A., Martínez Arbizu, P. and Galéron, J. (2011). Deep-sea nematode assemblage has not recovered 26 years after experimental mining of polymetallic nodules (Clarion-Clipperton Fracture Zone, Tropical Eastern Pacific). *Deep-Sea Research Part I: Oceanographic Research Papers*, 58(8): 885-897. <https://doi.org/10.1016/j.dsr.2011.06.003>
- Miller, K.A., Thompson, K.F., Johnston, P. and Santillo, D. (2018). An overview of seabed mining including the current state of development, environmental impacts, and knowledge gaps. *Frontiers in Marine Science*, 4: 418. <https://doi.org/10.3389/fmars.2017.00418>
- Niner, H.J., Ardron, J.A., Escobar, E.G., Gianni, M., Jaeckel, A., Jones, D.O.B. et al. (2018). Deep-sea mining with no net loss of biodiversity: An impossible aim. *Frontiers in Marine Science*, 5: 53. <https://doi.org/10.3389/fmars.2018.00053>
- Radziejewska, T. (2002). Responses of deep-sea meiobenthic communities to sediment disturbance simulating effects of polymetallic nodule mining. *International Review of Hydrobiology*, 87(4): 457-477.
- Simon-Lledó, E., Bett, B.J., Huvenne, V.A.I., Köser, K., Schoening, T., Greinert, J. and Jones, D.O.B. (2019). Biological effects 26 years after simulated deep-sea mining. *Scientific Reports*, 9: 8040. <https://doi.org/10.1038/s41598-019-44492-w>
- Smith, C.R., De Leo, F.C., Bernardino, A.F., Sweetman, A.K. and Martinez Arbizu, P. (2008). Abyssal food limitation, ecosystem structure and climate change. *Trends in Ecology & Evolution*, 23(9): 518-528. <https://doi.org/10.1016/j.tree.2008.05.002>
- Stratmann, T., Lins, L., Purser, A., Marcon, Y., Rodrigues, C.F., Ravara, A. et al. (2018). Abyssal plain faunal carbon flows remain depressed 26 years after a simulated deep-sea mining disturbance. *Biogeosciences*, 15(13): 4131-4145. <https://doi.org/10.5194/bg-15-4131-2018>
- Thiel, H., Schriever, G., Ahnert, A., Bluhm, H., Borowski, C. and Vopel, K. (2001). The large-scale environmental impact experiment DISCOL: Reflection and foresight. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 48(17-18): 3869-3882. [https://doi.org/10.1016/S0967-0645\(01\)00071-6](https://doi.org/10.1016/S0967-0645(01)00071-6)
- United Nations (1982). *United Nations Convention on the Law of the Sea*. Montego Bay, 10 December 1982. United Nations Treaty Series, vol. 1833.
- Van Dover, C.L., Ardron, J.A., Escobar, E., Gianni, M., Gjerde, K.M., Jaeckel, A. et al. (2017). Biodiversity loss from deep-sea mining. *Nature Geoscience*, 10: 464-465. <https://doi.org/10.1038/ngeo2983>
- Vanreusel, A., Hilario, A., Ribeiro, P.A., Menot, L. and Martínez Arbizu, P. (2016). Threatened by mining, polymetallic nodules are required to preserve abyssal epifauna. *Scientific Reports*, 6: 26808. <https://doi.org/10.1038/srep26808>
- Vonnahme, T.R., Molari, M., Janssen, F., Wenzhöfer, F., Haeckel, M., Titschack, J. and Boetius, A. (2020). Effects of a deep-sea mining experiment on seafloor microbial communities and functions after 26 years. *Science Advances*, 6(18): eaaz5922. <https://doi.org/10.1126/sciadv.aaz5922>
- Wedding, L.M., Friedlander, A.M., Kittinger, J.N., Watling, L., Gaines, S.D., Bennett, M. et al. (2013). From principles to practice: A spatial approach to systematic conservation planning in the deep sea. *Proceedings of the Royal Society B: Biological Sciences*, 280(1773): 20131684. <https://doi.org/10.1098/rspb.2013.1684>