

Environmental Impacts of Polymetallic Nodule Collection: What does the data tell us?

Prepared by TMC Environment Team

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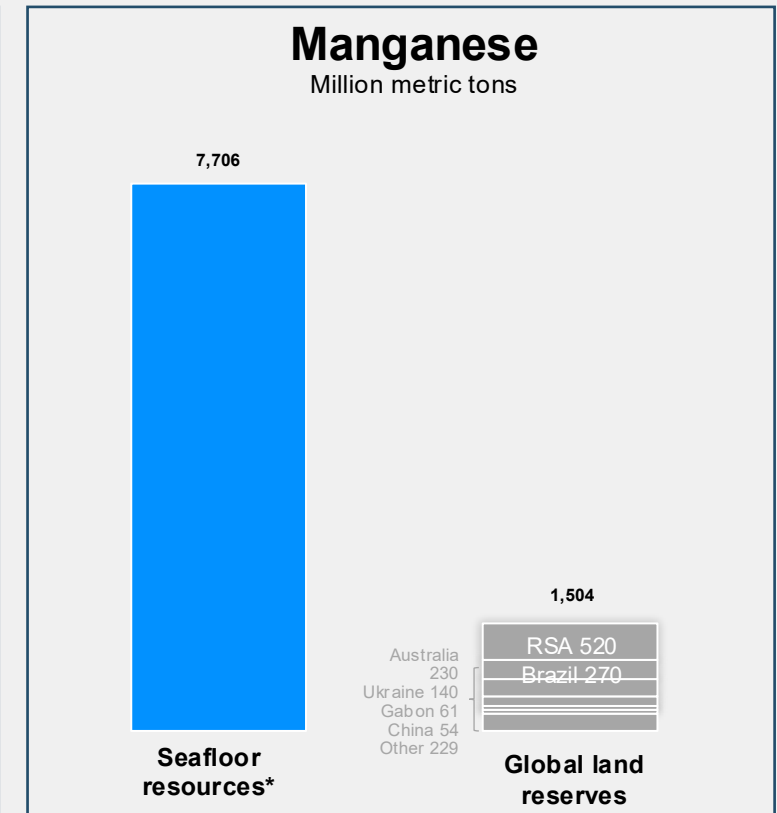
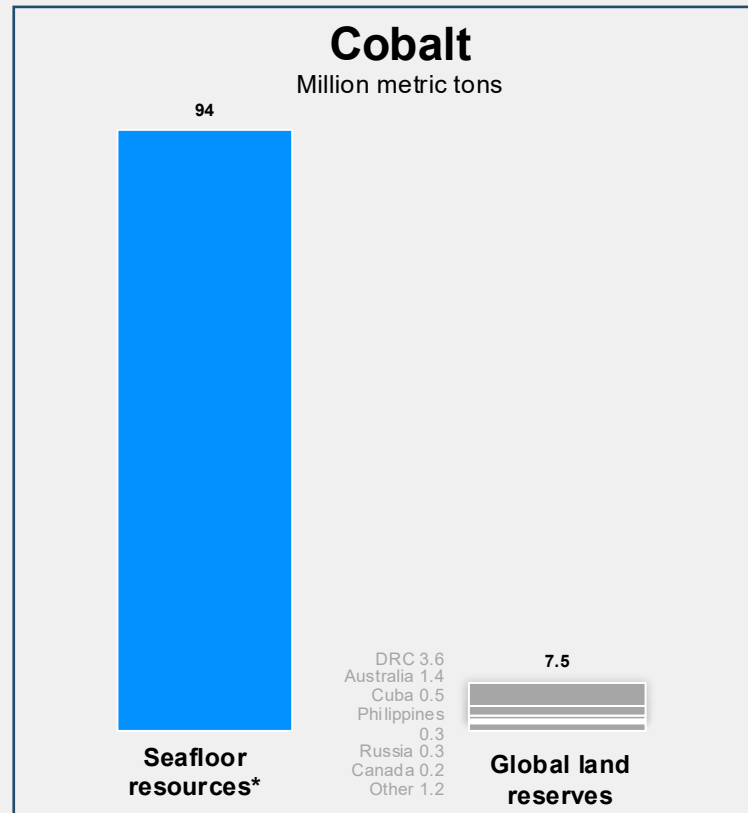
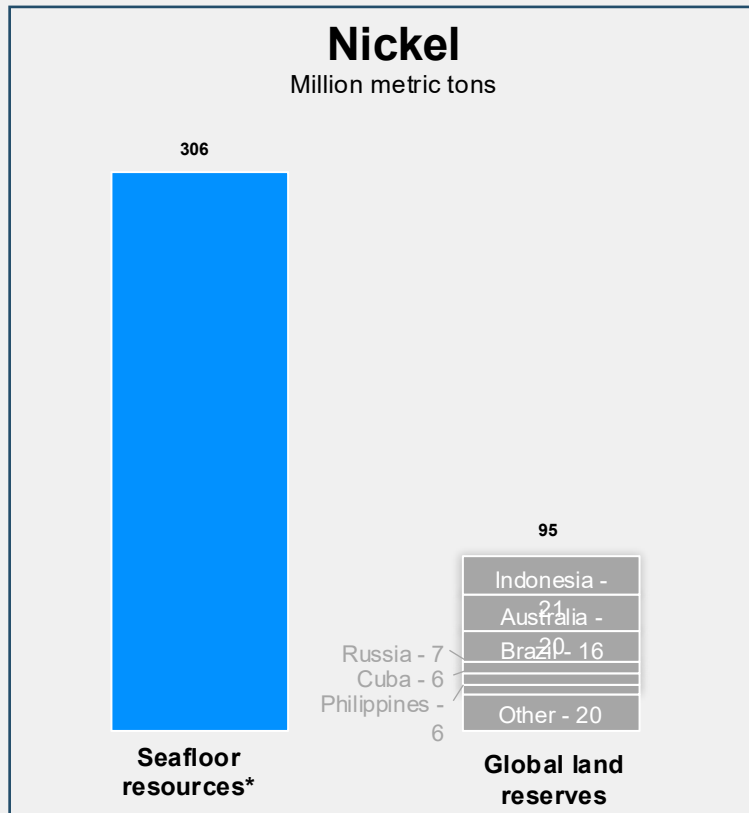
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Why explore the seafloor? That's where most of the planet's nickel, cobalt & manganese is.



*Combined estimates for Clarion-Clipperton Zone polymetallic nodules and Prime Crust Zone cobalt crusts

Source: USGS 2021 commodity summaries for terrestrial resources; James R. Hein, Kira Mizell, Andrea Koschinsky, Tracey A. Conrad, Deepocean mineral deposits as a source of critical metals for high- and green-technology applications: Comparison with land-based resources, Ore Geology Reviews, Volume 51, 2013, Pages 1-14, ISSN 0169-1368, doi.org/10.1016/j.oregeorev.2012.12.001 for CCZ nodules and PCZ crusts

Oceans—despite covering a much larger area than land—host much less life.

3%

of biomass lives
in the ocean

97%

of biomass lives
on land

Note: Ocean life is defined as marine life and deep-subsurface life but excluding 1.5GtC of life inside oceanic crusts as that life will not be impacted by nodule collection operations.
Source: Bar-On et al, The Biomass Distribution on Earth, PNAS, June 2018, www.pnas.org/cgi/doi/10.1073/pnas.1711842115

And the deeper you go, the less life you find.

Abyssal plain is a vast sedimentary seabed, oxic to 2m. It has gentle depressions, troughs and ridges. There is intense pressure (5,700-8,500 psi) and no sound or light except the ones made by animals. This environment is food-poor and stable.



“Deep-sea mining” usually covers three types of resources.

Polymetallic nodules



3,800-5,500m depth

The Abyssal Plains

2-30 cm diameter discrete rocks formed by dissolved metal compounds precipitating around a nucleus
Growth: 10-100mm per million years

Unattached to the seafloor
Can be collected using gentle water jets directed at nodules in parallel with the seafloor

Low-food, low-energy environment

10 grams of biomass / m²

Cobalt crusts



800-2,500m depth

Seamounts

2-26 cm thick, rock-hard, metallic layers that precipitate on the flanks of submarine volcanoes
Growth: 1-5mm per million years

Integral part of the seafloor that requires hard-rock cutting to break the ore from the substrate

Abundant food supply due to nutrient-rich water upwelling from near-bottom currents
High frequency destination for tuna and sharks
10-100x biomass vs. Abyssal Plain

Seafloor massive sulfides



1,000-4,000m depth

Hydrothermal vents

Tall chimney-like structures that form at hot vents where sulfide-enriched water flows out of the seabed, causing dissolved metals to bind into minute sulfide particles and sink as fine precipitants to the bottom

Integral part of the seafloor that requires hard-rock cutting to break the ore from the substrate

Abundant food supplied by chemoautotrophic bacteria which exploit energy-rich chemical compounds from the vents

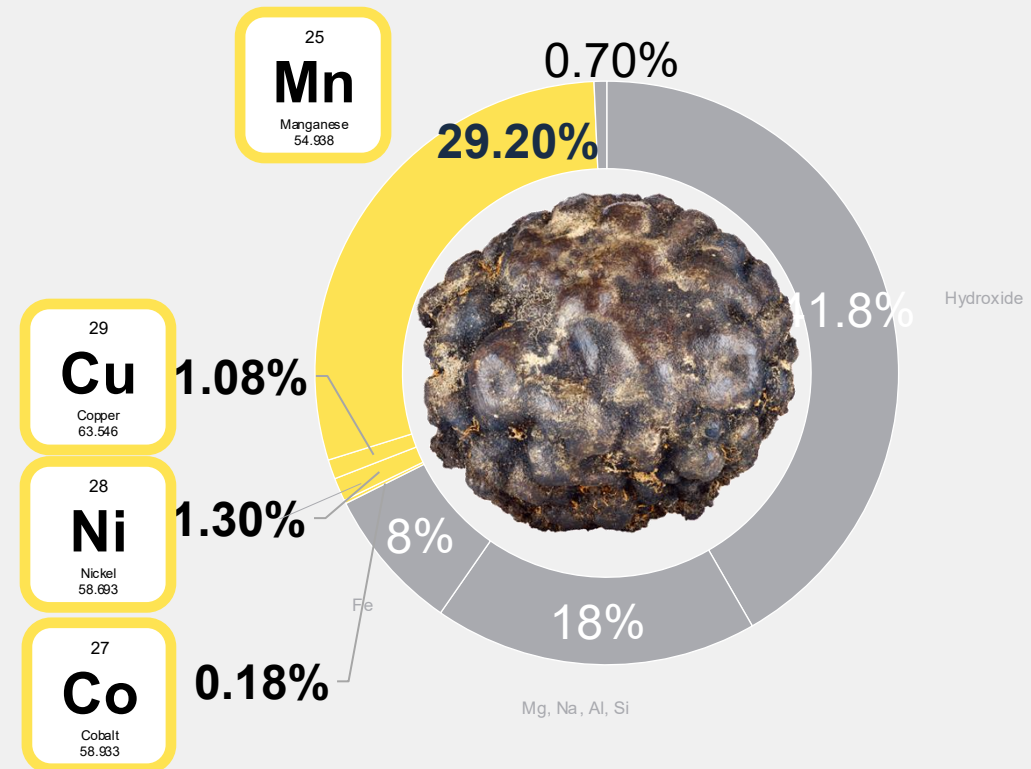
100x biomass vs. Abyssal Plain

**This is what a nodule
field looks like.**

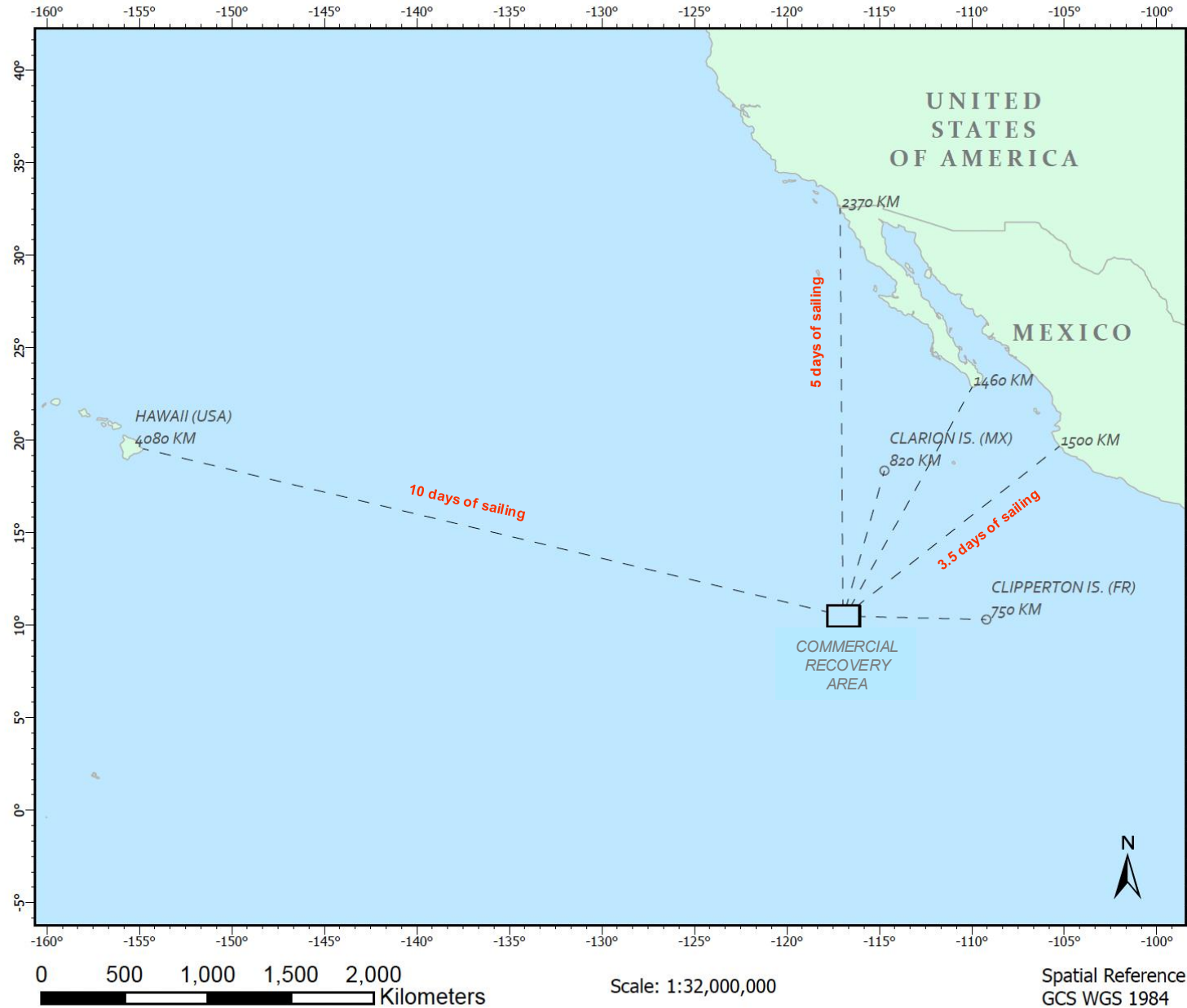


Polymetallic: One new nodule project can replace three new mines on land.

Dry nodule mass composition breakdown



Far offshore:
far away from
people and
physical
impacts on
communities.



The distance between
Commercial Recovery Area
and selected territories

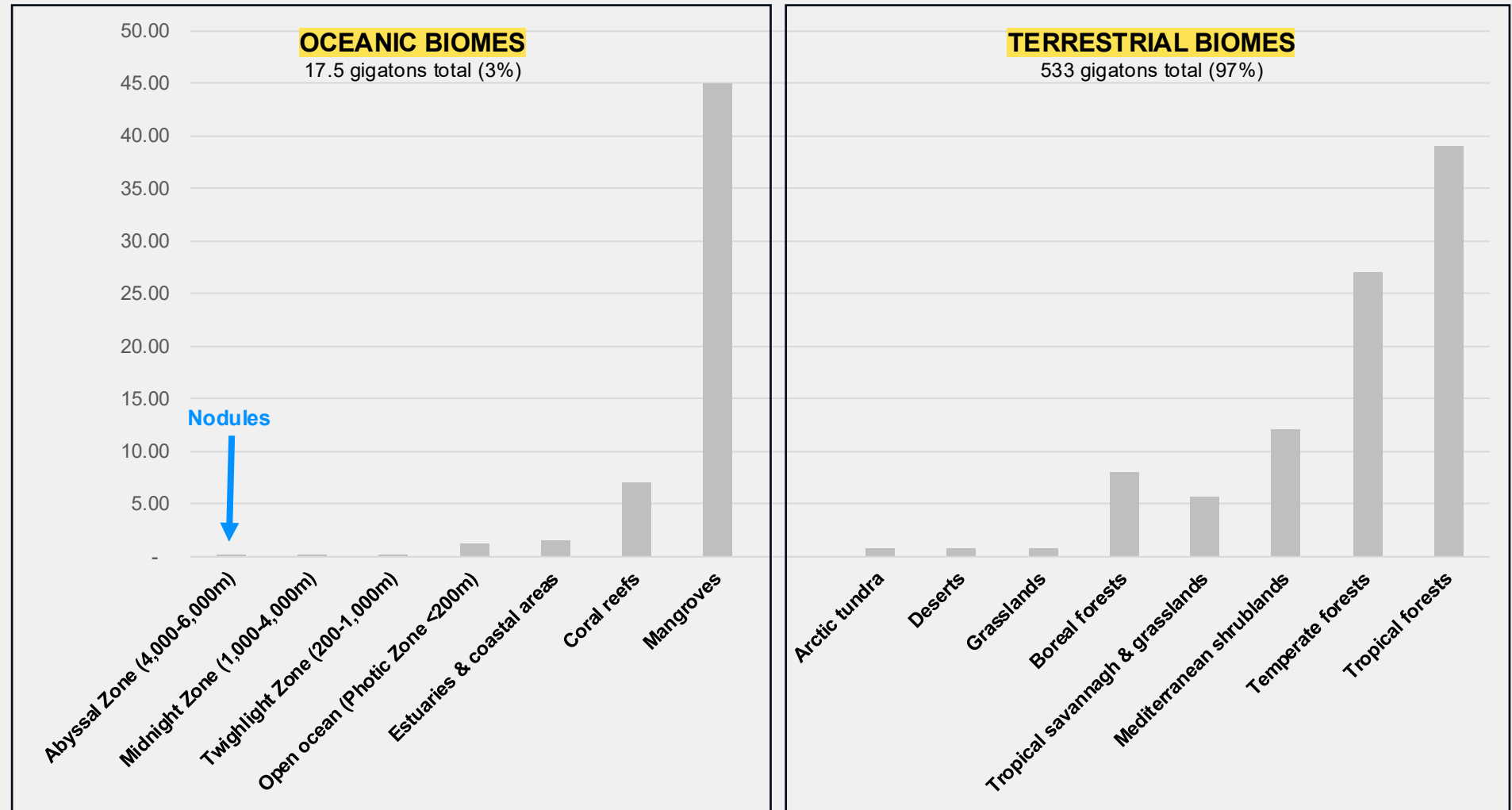
Legend

- Islands
- - - Distances
- ▭ Commercial Recovery Area
- Administrative Boundaries



Very deep: an ecosystem with least life...

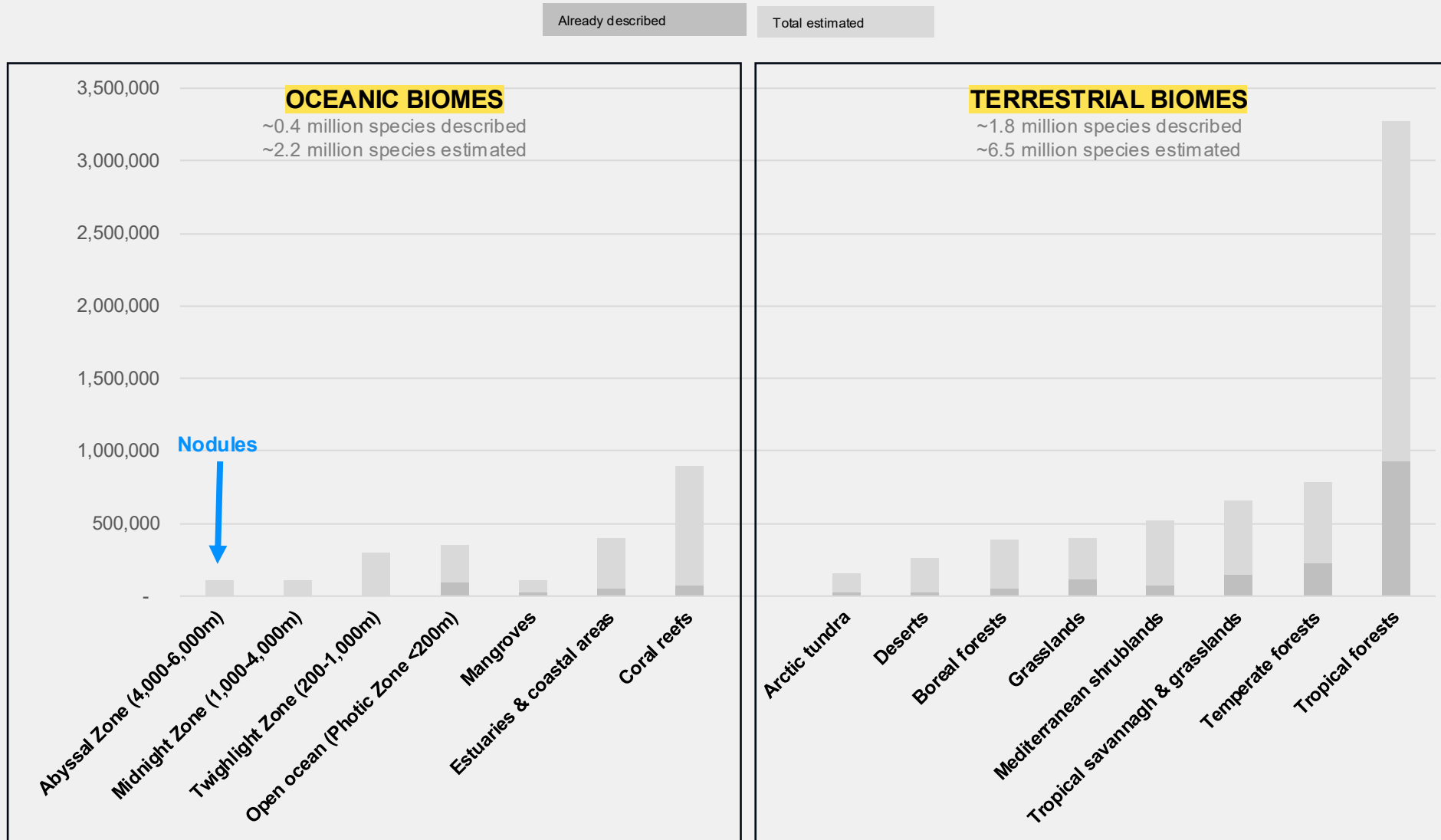
Living biomass density by biome
Mean kg of contained carbon / m²



...and relatively low levels of biodiversity.

Species richness by biome

Estimated number of species, excluding microbial life



Source: Described species based on [Dec 2022 IUCN Red List table](#); total species estimates based on [Mora, C., Tittensor, D. P., Adl, S., Simpson, A. G., & Worm, B. \(2011\). How many species are there on Earth and in the ocean? PLoS Biol. 9\(8\), e1001127.](#) Ballpark estimates for how described and total species break down by biome generated using Open AI's GPT-4 based on review of sources that included peer-reviewed literature, WWF's Global Ecoregions, IUCN Red List, scientific literature, GBIF, field guides, and conservation organizations

Over more than a decade, we've put together one of the largest deep-sea datasets ever compiled.

100+ studies

Seabed-to-surface ocean research program

Surface biology

Surface fauna logbook (PelagOS)
Remote Sensing, Hydrophone Acousitcs



Pelagic biology

Microbial Community Characterization
Phytoplankton Community Characterization
Zooplankton Community Characterization
Gelatinous Zooplankton Characterization
Micronekton Characterization
Trophic Analysis (Stable Isotopes)
Temporal Variability of Pelagic Communities
Trace Element Profiles In Water Column
Particulate Profiles in Water Column
Discharge Plume Characterization (Physical)
Discharge Plume Characterization (Biological)
Midwater Discharge (food webs particle composition)



Benthic biology

Megafauna Characterization (Photo transects)
Megafauna Characterization (Time Lapse)
Macro Fauna Characterization
Micro Fauna Characterization
Meso Fauna Characterization
Macro Fauna Characterization

Sediment analysis

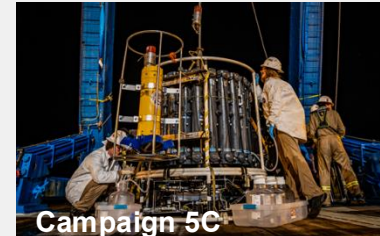
Baited camera and traps
Benthic respiration and nutrient cycling
Seafloor metabolic activities
Bioturbation, sediment characteristics
Porewater sampling
Exposure toxicology studies
Metals determination by ICP analysis
Induction of gene transcripts (metals)

Collector impact studies

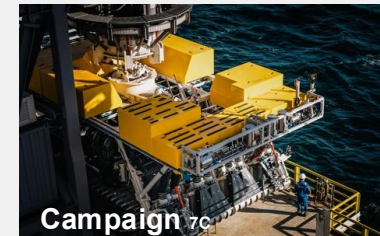
Met ocean studies
Bathymetry (seabed mapping)
Habitat mapping
Database development
Digital twin development
Collector test nearfield studies
Collector test far-field modeling
Plume modeling
Existing Resource Utilization Study
Noise & Light Study
Meteorology & Air Quality Study
Hazard & Risk Assessment
Emergency Response Planning
Cultural & Historical Resources
Waste Management
Cumulative Impacts



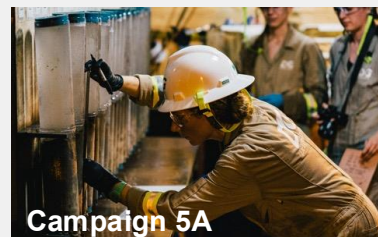
Campaign 4D



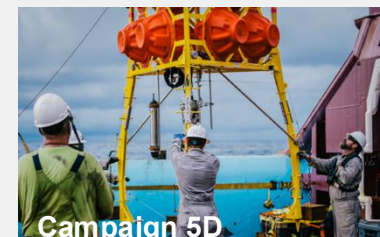
Campaign 5C



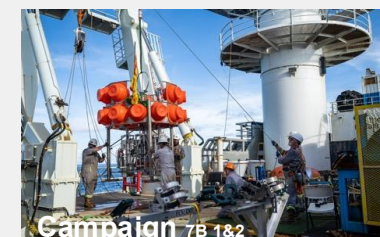
Campaign 7C



Campaign 5A



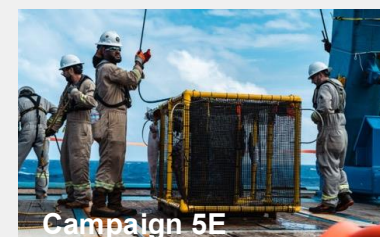
Campaign 5D



Campaign 7B 1&2



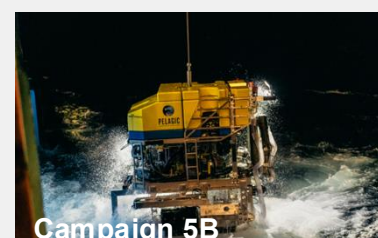
Campaign 4E



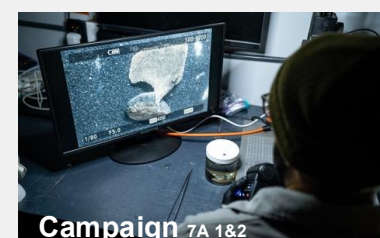
Campaign 5E



Campaign 8A



Campaign 5B



Campaign 7A 1&2



Campaign 8B

* Assuming the average length of a campaign to be 35-40 days, this represents over 4000 days.

Working with the world's leading marine research organizations to gather over a petabyte of data.



This is what nodule collection looks like.

PATENTED TECHNOLOGY

Video available at: <https://vimeo.com/653068330/7f4d928878?fl=tl&fe=ec>

In 2022, we conducted the first collection system test in the CCZ since the 1970s.



Video available at: <https://www.youtube.com/watch?v=iydMJToa2iU>

But while the data we've gathered over more than a decade show the impacts are minimal and manageable, media coverage paints a very different picture.

Race to the bottom: the disastrous, blindfolded rush to mine the deep sea

**DEEP SEABED MINING
WOULD DESTROY
BIODIVERSITY — AND WE
DON'T NEED IT**

Seafood industry joins chorus of groups calling for halt to deep-sea mining plans

Sediment plumes from deep-sea mining could pollute vast swaths of the ocean, scientists say

If marine noise pollution is bad, deep-sea mining could add to the cacophony

Oxygen discovery defies knowledge of the deep ocean

22 July 2024

Victoria Gill Science correspondent, BBC News

Share Save

Deep-Sea Mining Could Cause 25x the Biodiversity Loss of Land-Based Mining, Report Warns

By: Cristen Hemingway-Jaymes | Published: June 20, 2023 | Edited by Chris McDermott



The Climate Myth of Deep Sea Mining

Deep-sea mining test site shows 'little sign of life' 40 years later

Deep-sea mining will cause irreversible damage to the oceans, Greenpeace warns

AUG 5, 2019

This article is published in collaboration with Thomson Reuters Foundation trust.org.



Our EIS addresses six **key concerns** and two **extraordinary claims**.

Seafloor plumes

“Seafloor plumes could travel 1,000s km from mining site.”

Midwater plumes

“Midwater plumes could travel over a 1,000 km and poison tuna fisheries.”

Noise & light

“Noise and light from operations could disrupt wildlife.”

Dark oxygen

“Nodules produce oxygen through electrolysis”

Carbon sequestration

“Planet’s biggest carbon sink could be disturbed.”

Biodiversity loss

“Mining could lead to the extinction of species unknown to science.”

Habitat destruction

“Mining could irreversibly destroy ancient deep-sea habitats.”

Radioactivity

“Alpha radiation from nodules is a health hazard.”



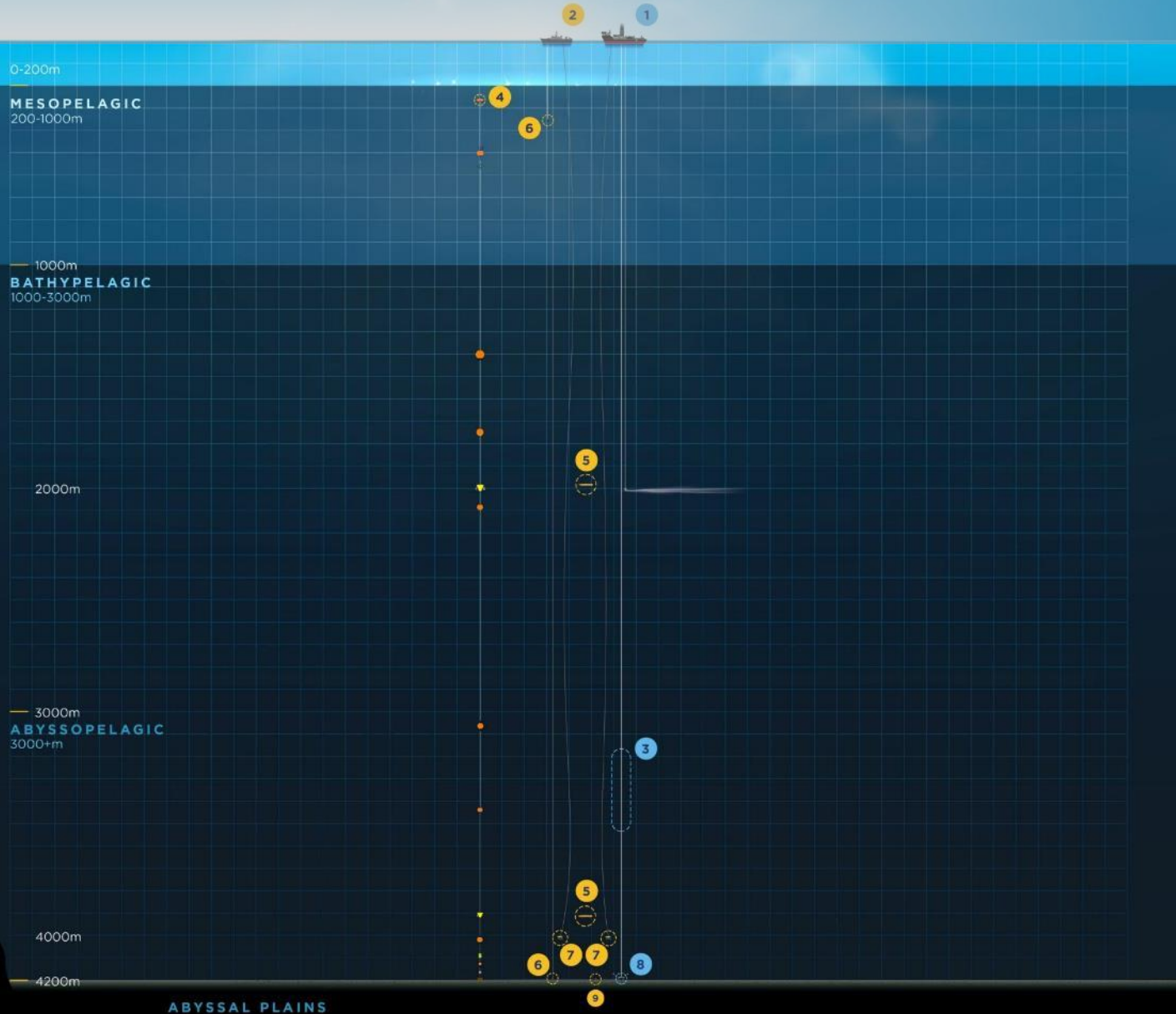
Key Concern:

**“Seafloor plumes could spread
10,000s km² beyond mining sites.”**

Seafloor plumes: evidence shows that the sediment forms a gravity-driven turbidity current that hugs the seafloor.

Video available at: <https://www.youtube.com/watch?v=8gYJJjxY8g0>

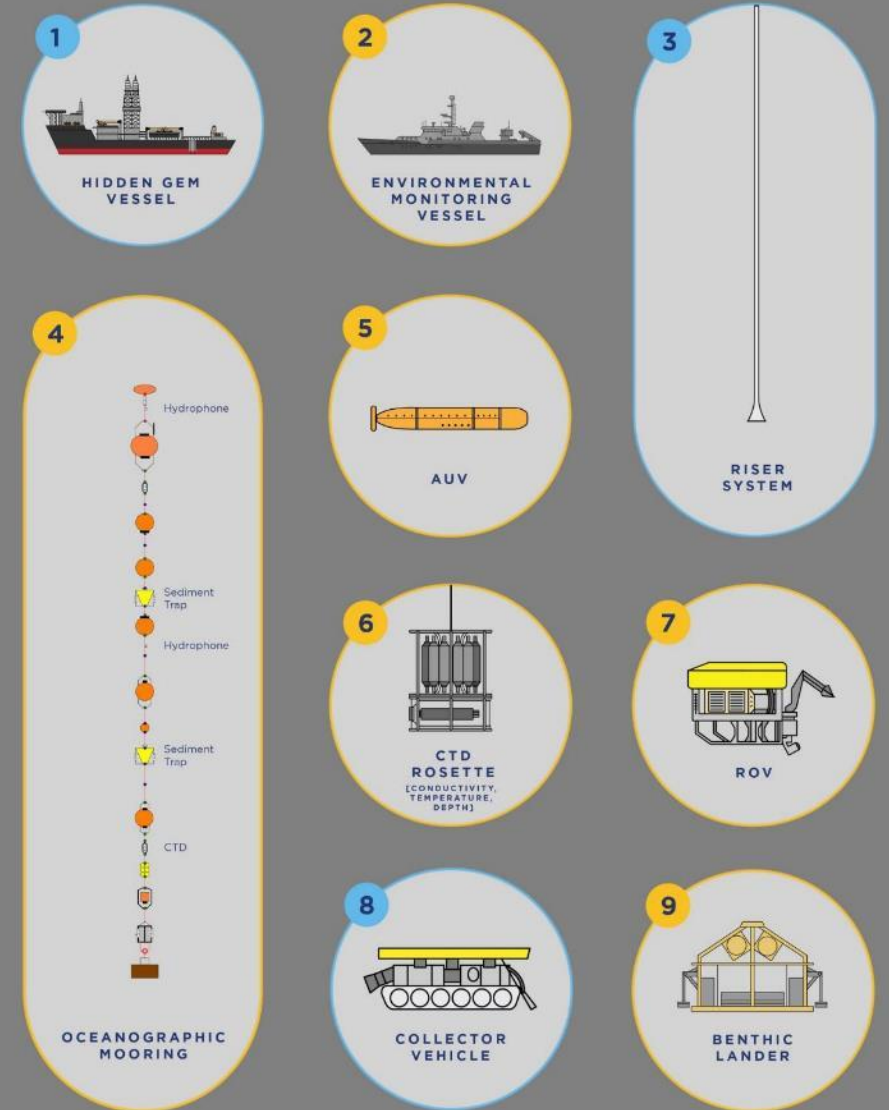
Seafloor plumes: successfully monitored during our pilot collection system test.



- PRODUCTION EQUIPMENT
- MONITORING EQUIPMENT

NORI
NAURU OCEAN RESOURCES INC.

A subsidiary of
the metals company



Seafloor plumes: in-field observed data and modeling are contradicting prior speculation by opposition groups.

FTS-006

FTS-002

FTS-001

FTS-005

FTS-004

FTS-007

FTS-003

Good enough for swimming

Good enough for drinking if it were freshwater

Natural sedimentation level

≥ 100

50

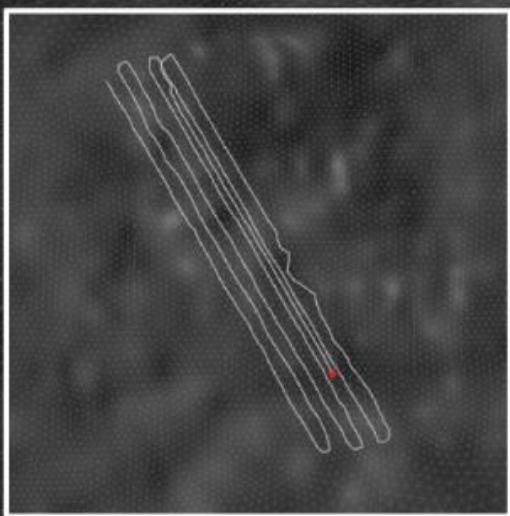
25

10

5

≤ 1

Total SSC [mg/L]



2022-10-23 00:45:00

Video available at: <https://vimeo.com/851319010/79c7c9ff18>

Seafloor plumes will not travel 1,000s of km — most mass resettles within 1 km.

Near field

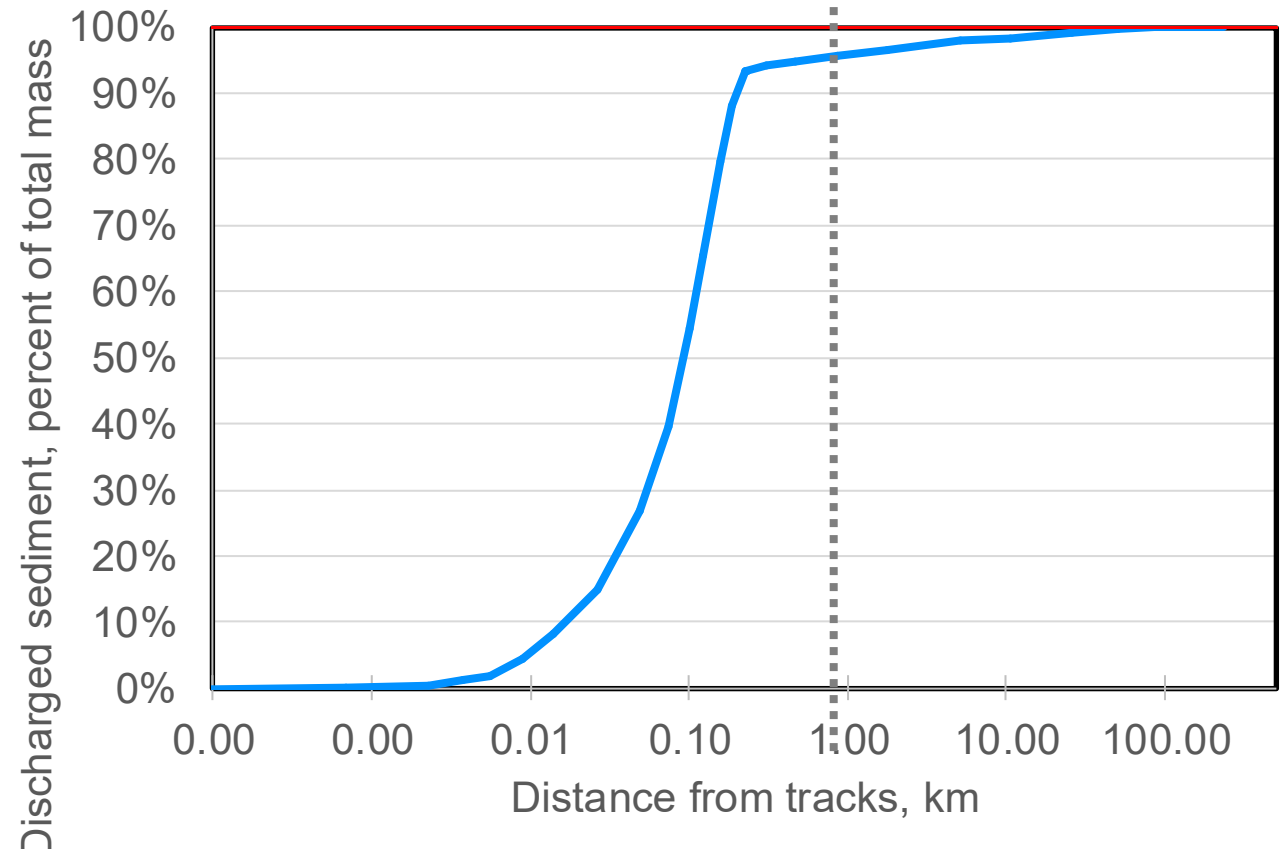
- Vast majority of sediment (>95%) resettles within 1 km of the collector tracks
- Mobilized sediment is a density-driven flow, redeposition is aided by flocculation

Far field

- Mobilized sediment is colloidal material that didn't flocculate, redeposition is characterized by extremely low thickness (micron scale or thinner than human hair)

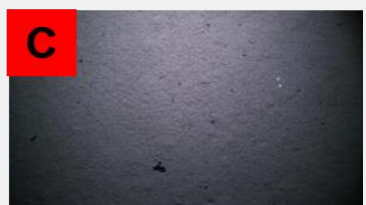
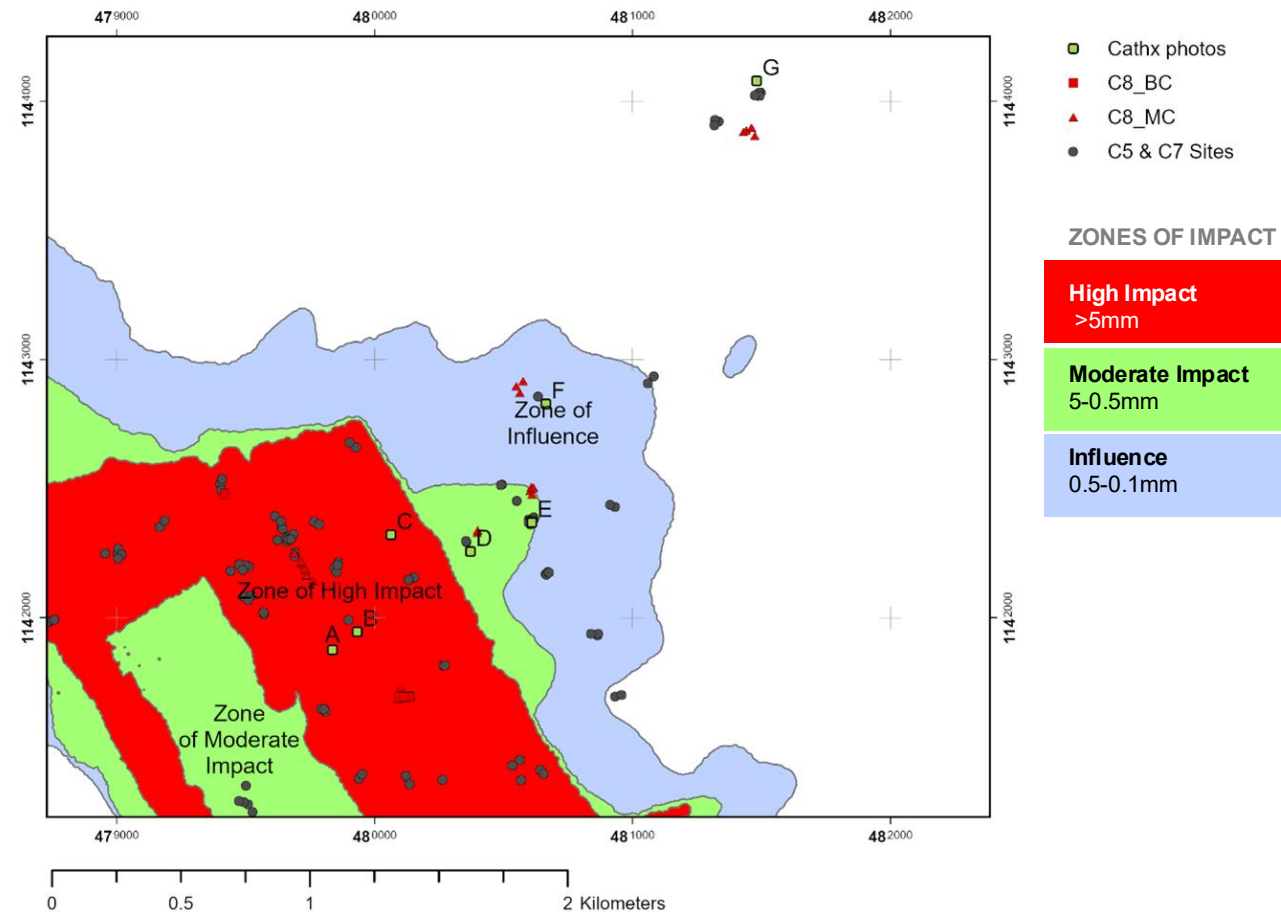
Redeposition of seafloor plumes by distance

Cumulative distribution based on DHI seafloor plume model developed for Project Zero and validated based on in-field measurements during NORI pilot trial

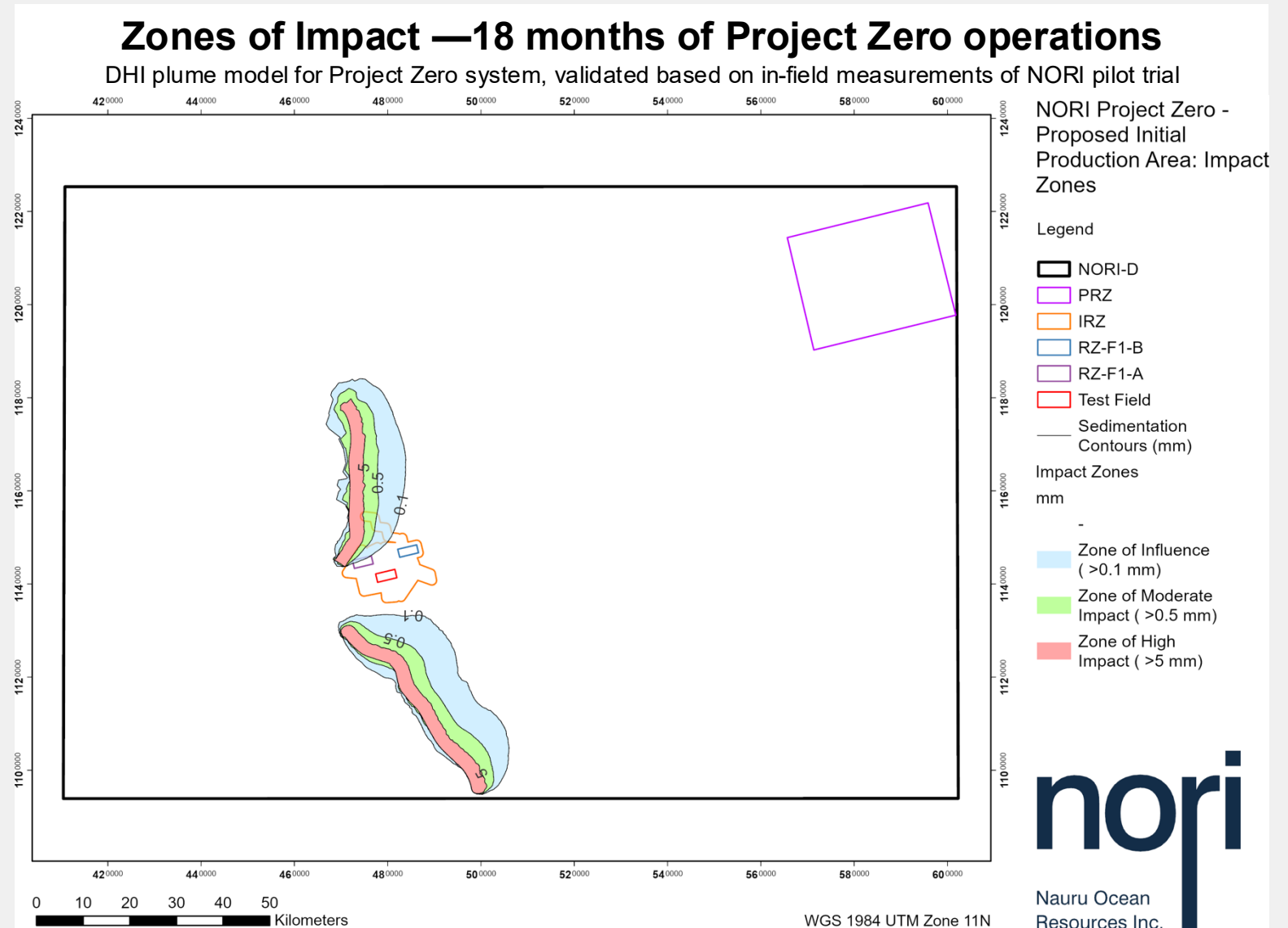


Seafloor plume blanketing
with high impact (>5mm) is
limited to 100s of meters.

Zones of Impact measured during NORI pilot trial



Seafloor plumes' zones of impact (red and green) are constrained to several kms after 18 months of operations.





Full video: <https://www.youtube.com/watch?v=f9Hi1ks5EyE>



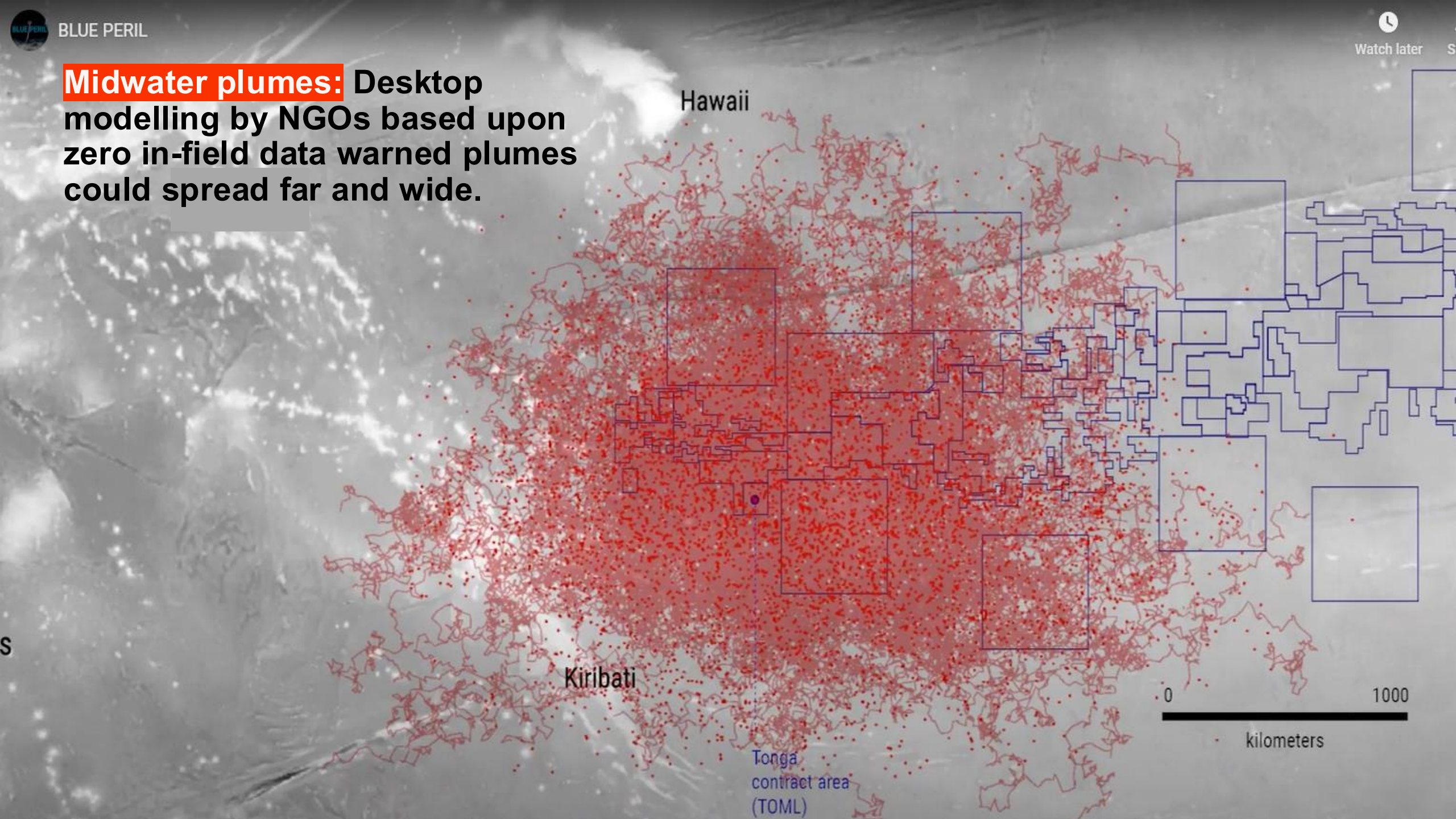


Key Concern:

“Midwater plumes could travel over a 1,000 km and poison tuna fisheries.”



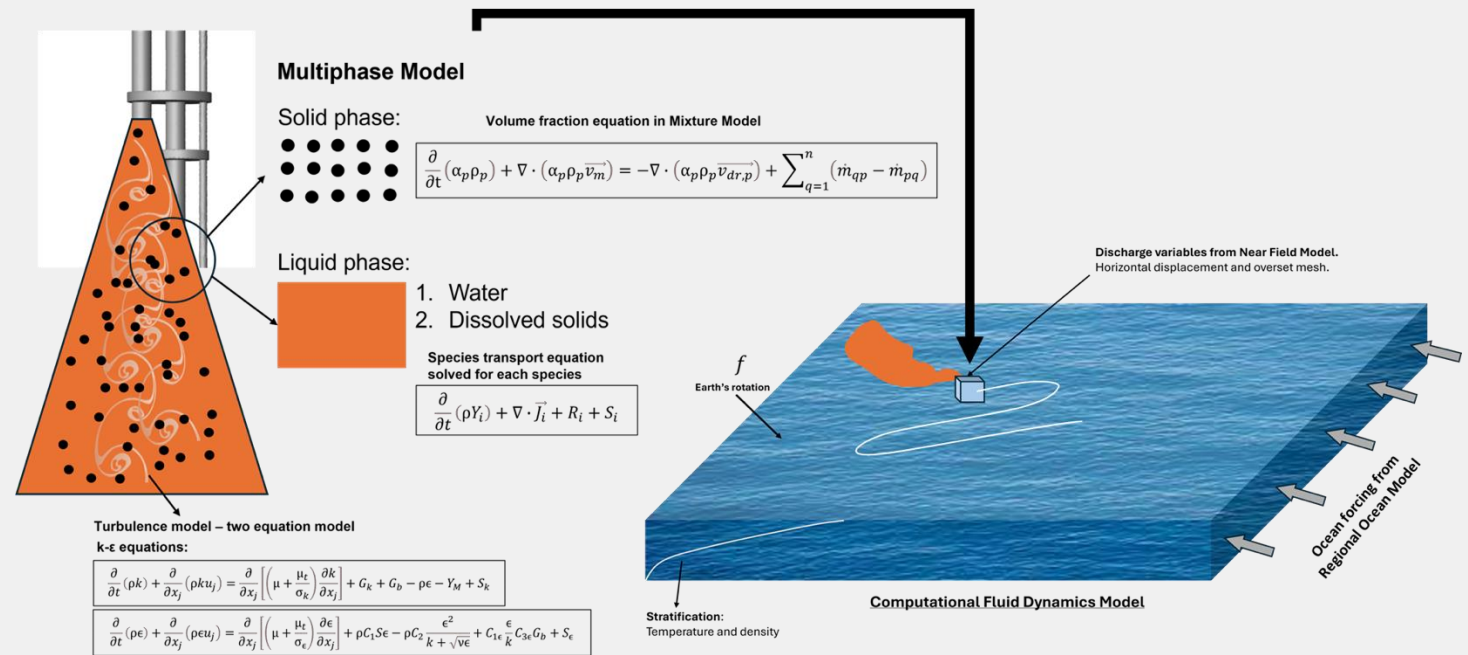
Midwater plumes: Desktop modelling by NGOs based upon zero in-field data warned plumes could spread far and wide.



We modelled **midwater plumes** based upon actual test mining data using a multiphase model.

NORI Multiphase Sediment Plume Model

- **Solid Phase:** Includes equations for specific sediment volume fractions
- **Liquid Phase:** Consists of water and dissolved solids
- Incorporates Earth's rotation effects
- Includes ocean stratification
- Accounts for ocean currents, temperature, and salinity, using NORI empirical data and General Ocean Global Models
- All models have been validated using field data from NORI test mining and exhibit high levels of fidelity

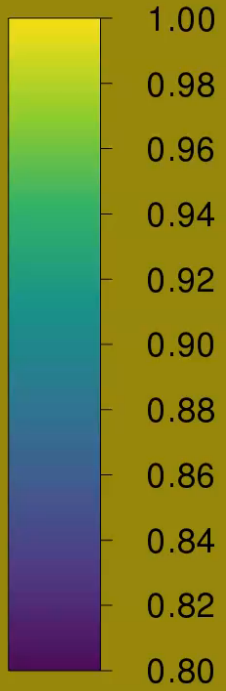


Midwater plumes:
Here's what the sediment and seawater looks like as it leaves the return outlet.



Midwater plumes: disks attached to the return outlet accelerate dilution.

Mass fraction of h2o



contour-1

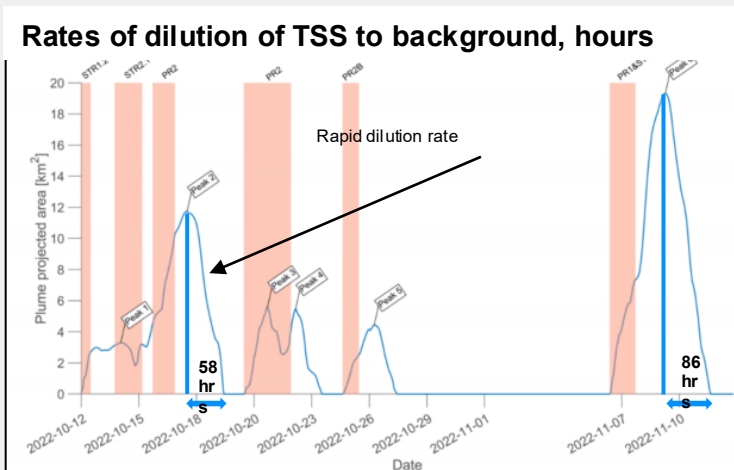


Midwater plumes will not travel 1,000s of km — but rapidly dilute to within natural range of background variation within 10s of km.

Speed of dilution

In-field measurements of how quickly midwater plume diluted to background during NORI pilot trial.

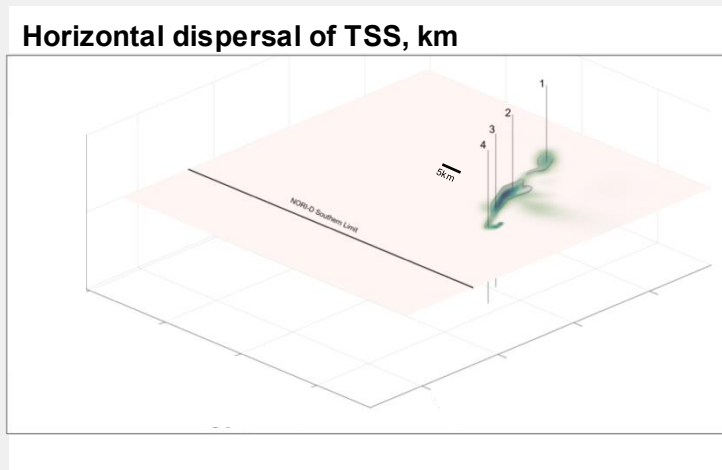
During pilot, plumes diluted to background within 2-4 days.



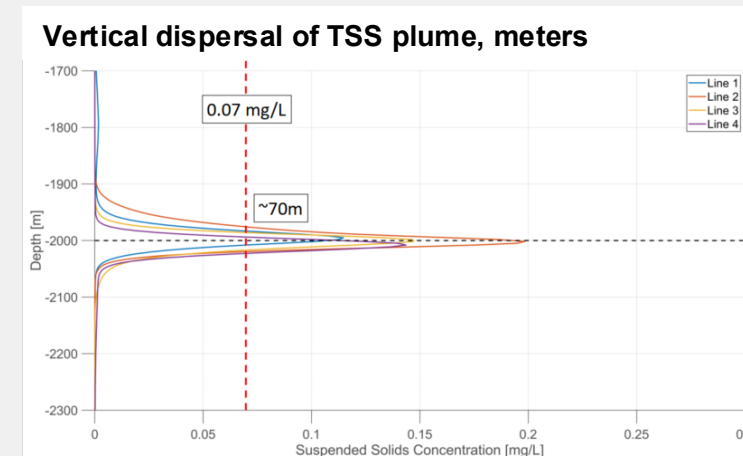
Dispersal distance

Plume model developed for Project Zero and validated based on in-field measurements of NORI pilot trial. The cut-off selected for mid-water plume modelling is the upper limit of natural range of Total Suspended Solids (TSS) variation of 0.07 mg/l. For reference, permissible TSS in drinking water as per Australian drinking water guidelines is 500 mg/l or >7,000x higher.

Horizontally, plumes dispersed several kms before reaching natural background variation.



Vertically, plumes dispersed 10s-100s of meters before reaching natural background variation.



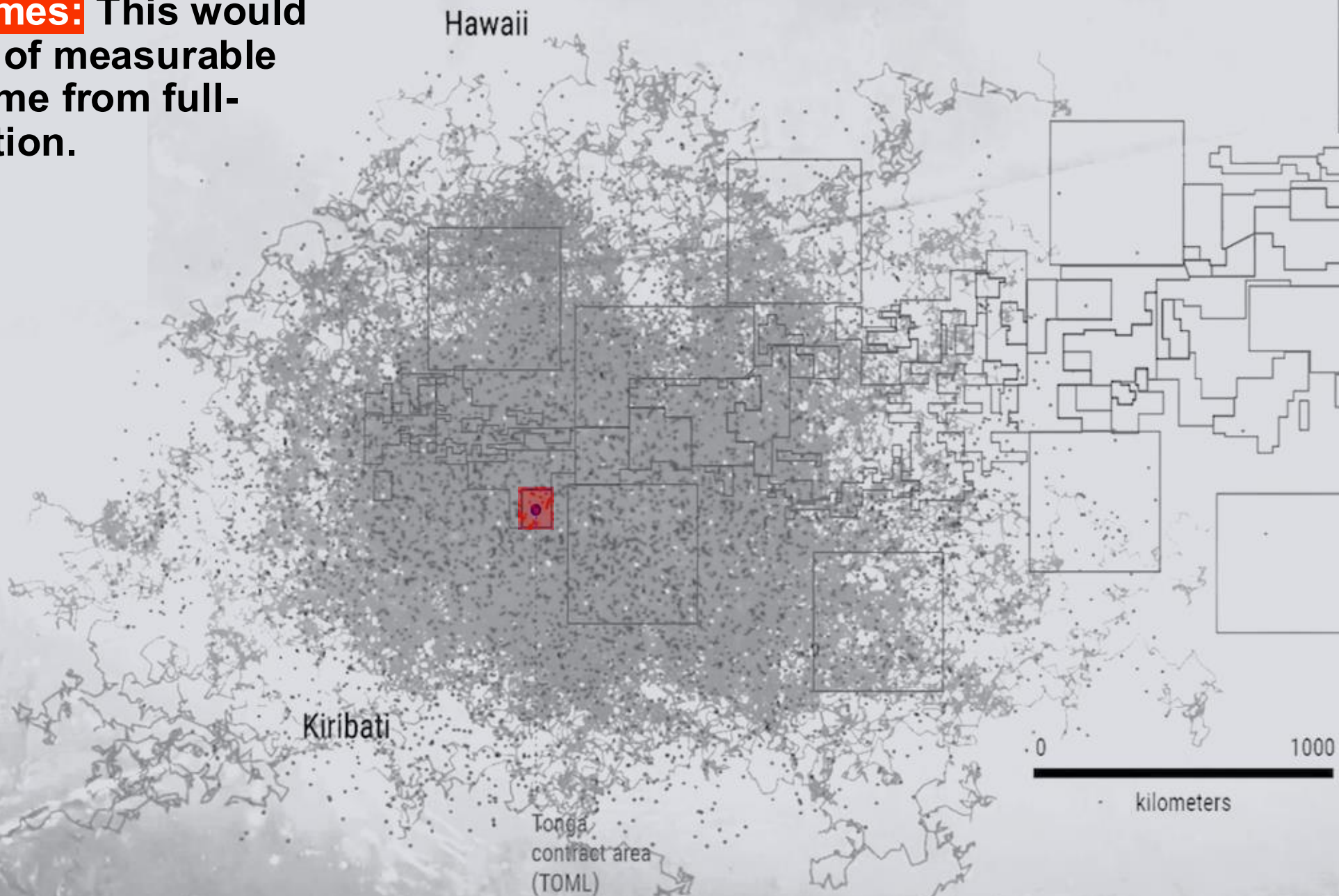
The volume of water impacted by the **midwater plume** is negligible in the vast Pacific Ocean.



Video available: <https://www.youtube.com/watch?v=Fb9qAytaT-M>



Midwater plumes: This would be the extent of measurable midwater plume from full-scale production.



Midwater plumes released at 2,000m depth are unlikely to impact tuna fisheries.

Vertical biomass migration during day-night cycle Acoustic measurements in the upper 1,000m at a reference site in December 2015

Key takeaways:

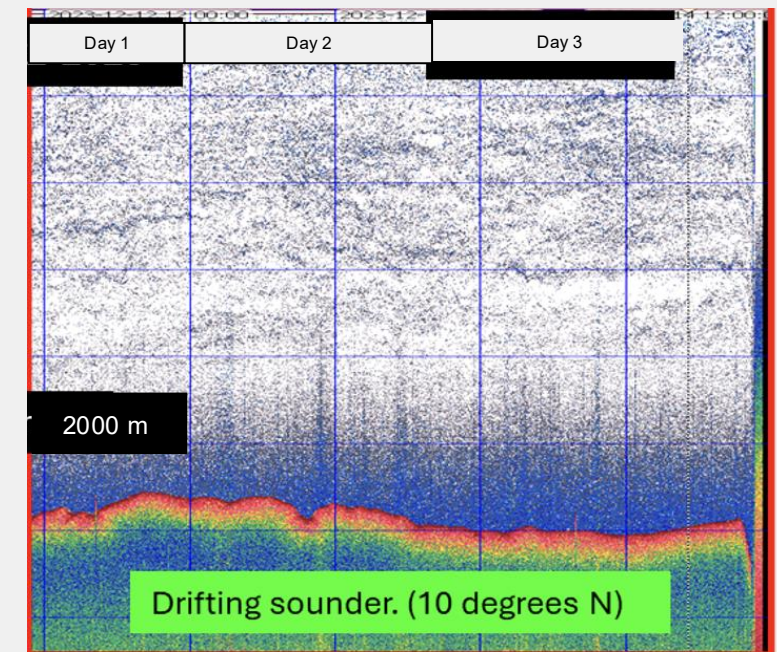
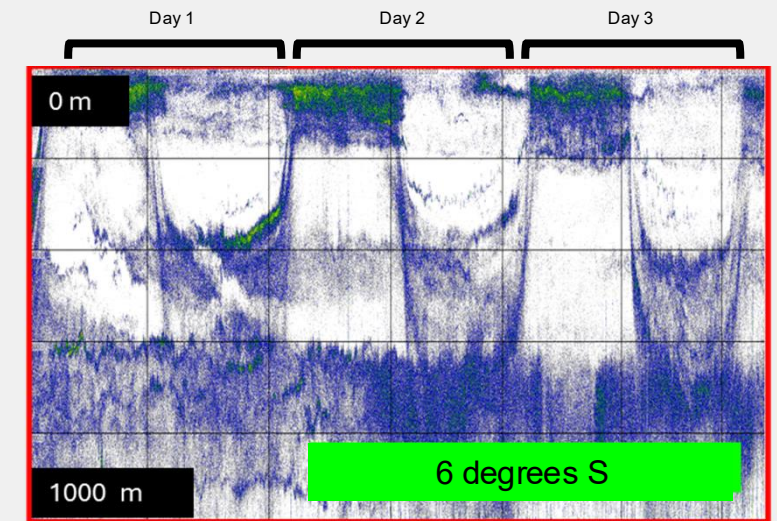
- Most vertical migration of mesopelagic organisms takes place in the top 500 m, with some biomass migrating as far down as 800-900 m
- Very limited biomass is found below 1,000m as most lives above the Oxygen Minimum Layer

Observed biomass concentrations

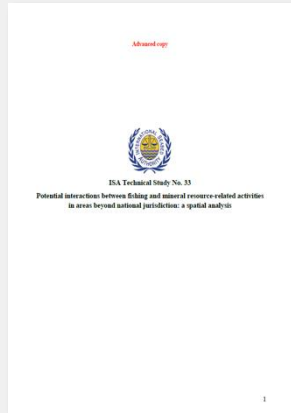
Acoustic measurements using drifting sounder at 2,000m in NORI-D site, December 2023

Key takeaways:

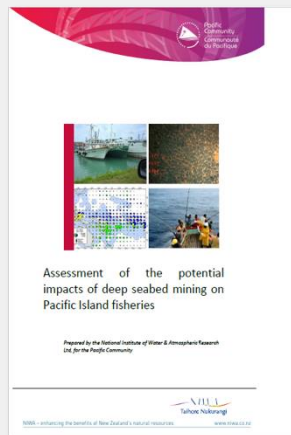
- No day-night biomass migration observed at 2,000 m
- Releasing midwater plume at 2,000m below the layers with high biomass and below the lower limit of day-night migration will minimise the risk of bioaccumulation of metals in the food web
- Dissolved metal concentrations dilute to background within 1,500 m. Model for bioaccumulation in commercial fish species is currently under development by CSIRO



Midwater plumes: Multiple papers point to low risks to fisheries due to operational depth.

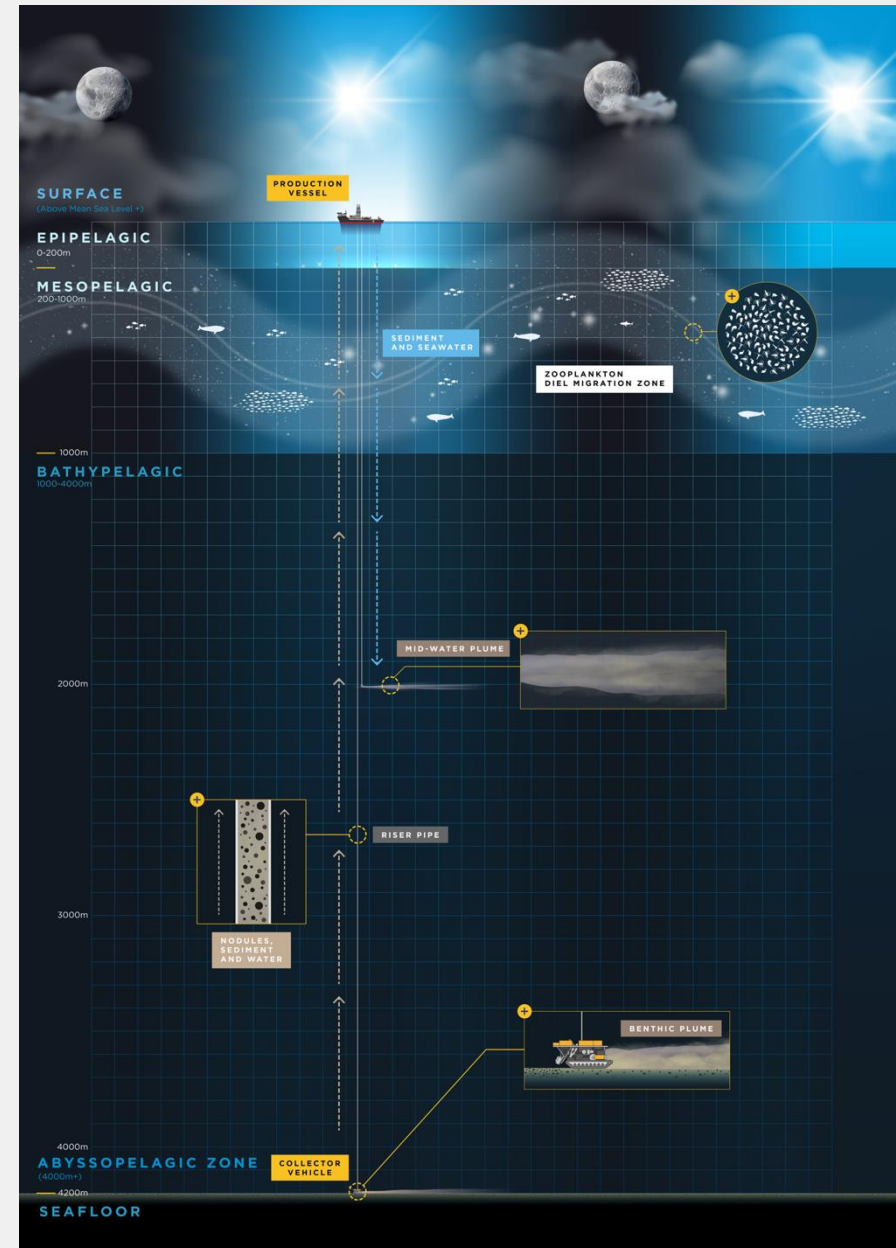


“Tuna fisheries were classified as low risk during both exploration and mining phases for the three mineral types. This was largely due to a depth separation of most mining operations from the tuna fisheries, with DSM activities deeper than the fisheries, as well as the widespread distribution and mobility of most tuna stocks. There could be localised effects, but it was judged none would have substantial effects at the population or stock level.”



“Overall, the analyses document a negligible overlap between the occurrence of fishing with gears that operate at or near the seafloor in ABNJ and areas allocated as contract areas or reserved areas for deep-sea mineral resource exploration.”

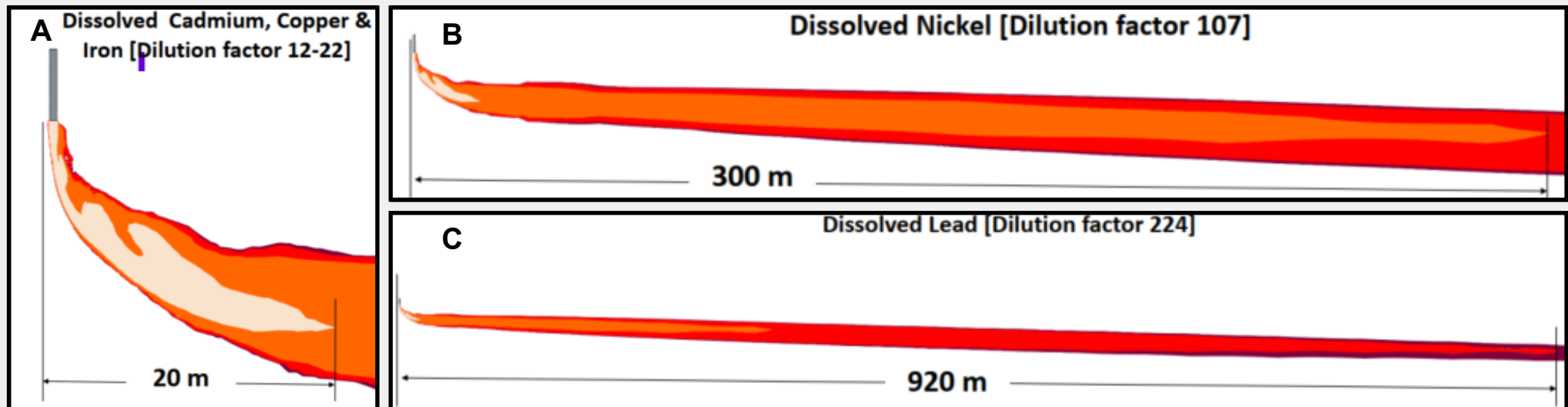
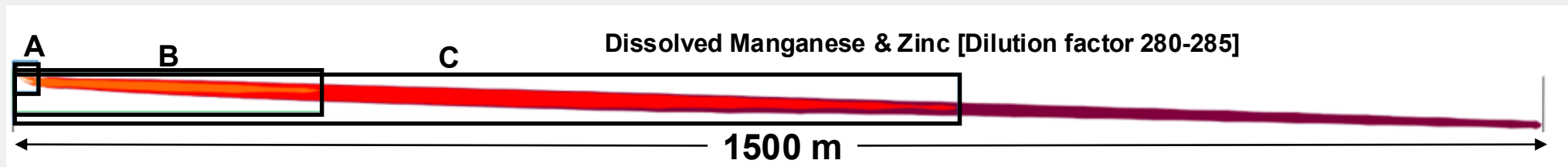
“These findings suggest that direct conflicts for operating space between fisheries and deep-sea mineral exploration and exploitation are expected to be infrequent and readily managed.”



Dissolved metals in **midwater plumes** dilute to background within 1.5 km of source.

Dissolved Metal Fraction	*Source Concentration [mg/L]	**Background Concentrations [mg/L]	***Dilution Fraction [%]
Dissolved Iron	0.004042941	0.00041300	21.63
Dissolved Zinc	0.033787371	0.00000000	284.48
Dissolved Nickel	0.027864648	0.00000000	106.89
Dissolved Copper	0.011814123	0.00032000	20.12
Dissolved Cadmium (114)	0.000390544	0.00011100	11.53
Dissolved Lead	0.000084952	0.00000212	223.26
Dissolved Manganese	0.060401914	0.00070700	279.68

*, ** References are in progress; *** Dilution factor required for the source concentration to return to background levels.

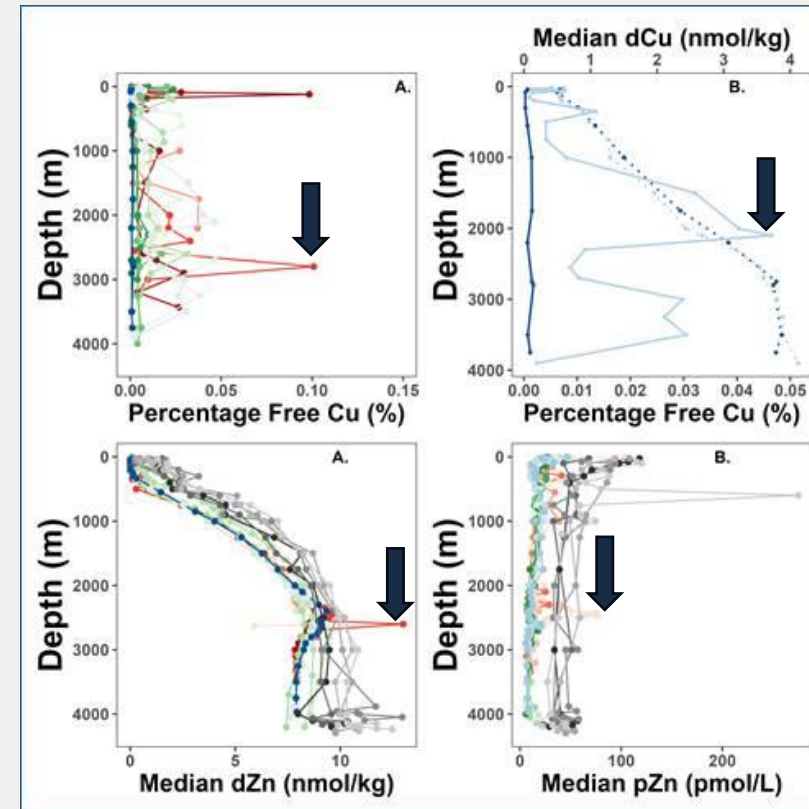


Pelagic organisms impacted by **midwater plumes** already experience spikes in metal concentrations from the nearby East Pacific Rise (EPR).

The EPR is a linear submarine volcanic chain on the floor of the southeastern Pacific Ocean, roughly paralleling the west coast of South America.



The volcanic activity of the EPR appears to be the source of periodic spikes in heavy metal concentrations at NORI-D at 2000 – 3000 m depth.



Midwater plumes: Research by Australia's national science agency and universities found that metals are highly unlikely to bioaccumulate in fish.



MUSEUMSVICTORIA
RESEARCH INSTITUTE

GRIFFITH
UNIVERSITY



Modelling ecological impacts of metal bioaccumulation from mid-water plume discharges

Project: Integrated Ecosystem Assessment and Ecosystem-Based Management Framework for Polymetallic Nodule Collection Activities

June 2025

Pethybridge H, Fulton EA, Parr JM, Dunstan PK, Rowden AA, Dambacher JM

	Mesopelagic (200 – 1,000 m)				Bathypelagic (1,000 – 3,000 m)			
	+5%	+10%	+20%	+50%	+5%	+10%	+20%	+50%
Marlins	Low	Low	Low	Medium	Low	Low	Low	Low
Sharks	Low	Low	Low	Medium	Low	Low	Low	Low
Toothed Whales	Low	Low	Low	Low	Low	Low	Low	Low
Dolphins	Low	Low	Low	Low	Low	Low	Low	Low
Swordfish	Low	Low	Low	Medium	Low	Low	Low	Low
Bigeye	Low	Low	Low	Low	Low	Low	Low	Low
Other tuna	Low	Low	Low	Low	Low	Low	Low	Low
Large Yellowfin	Low	Low	Low	Low	Low	Low	Low	Low
Seabirds	Low	Low	Low	Low	Low	Low	Low	Low
Cephalopods	Low	Low	Low	Low	Low	Low	Low	Low
Bathypelagic fish	Low	Low	Low	Low	Low	Low	Low	Low
Rays	Low	Low	Low	Low	Low	Low	Low	Low
Sea Turtles	Low	Low	Low	Low	Low	Low	Low	Low
Mesopelagic fish	Low	Low	Low	Low	Low	Low	Low	Low
Crabs	Low	Low	Low	Low	Low	Low	Low	Low
Epipelagic fish	Low	Low	Low	Low	Low	Low	Low	Low
Zooplankton deep	Low	Low	Low	Low	Low	Low	Low	Low
Zooplankton meso	Low	Low	Low	Low	Low	Low	Low	Low
Zooplankton epi	Low	Low	Low	Low	Low	Low	Low	Low

Classification of bioaccumulation on model simulated increased in metal group 1 concentration for functional groups under discharge exposure scenarios at mesopelagic and bathypelagic depths.

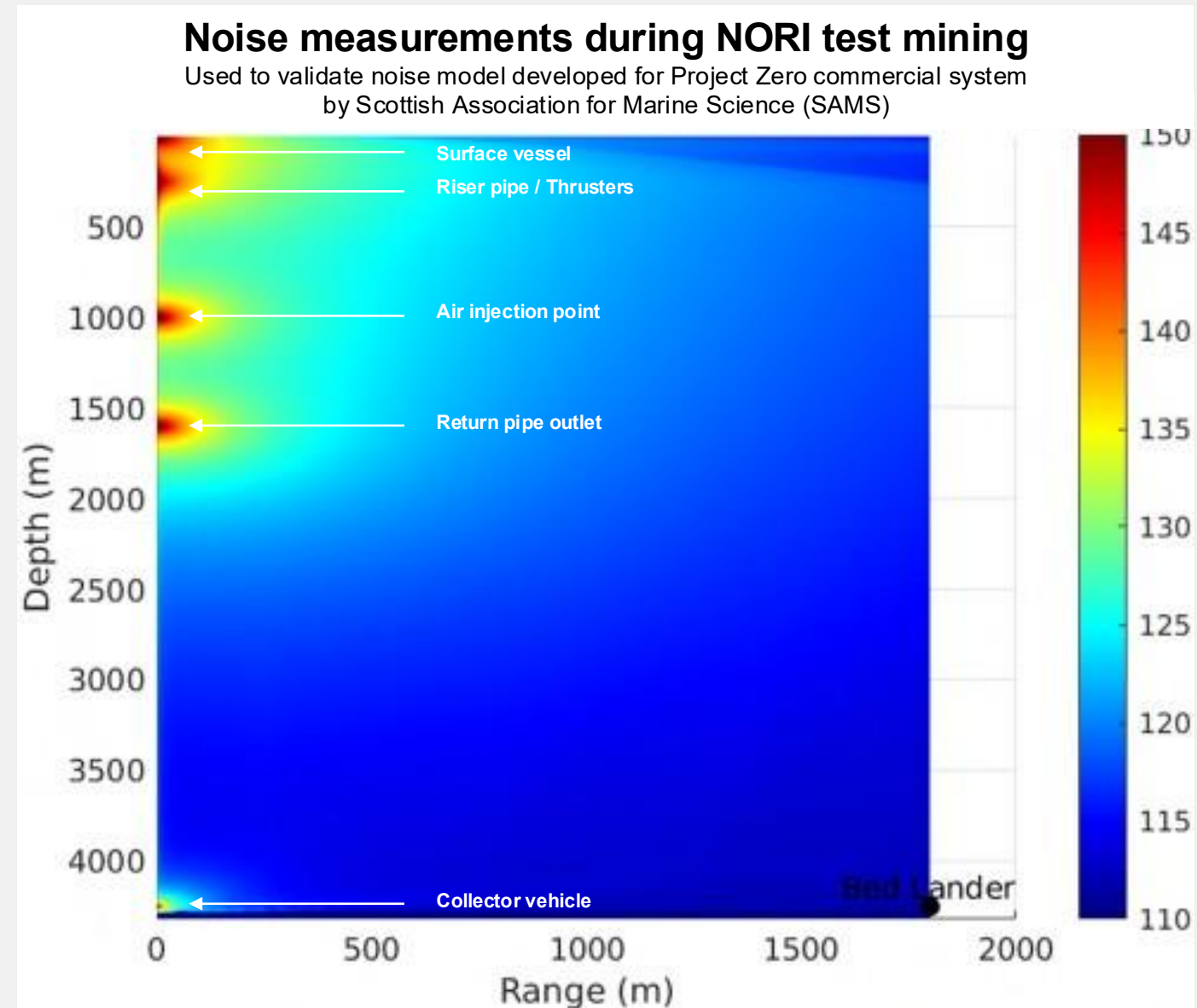


Key Concern:

**“Noise and light from operations
could disrupt wildlife.”**

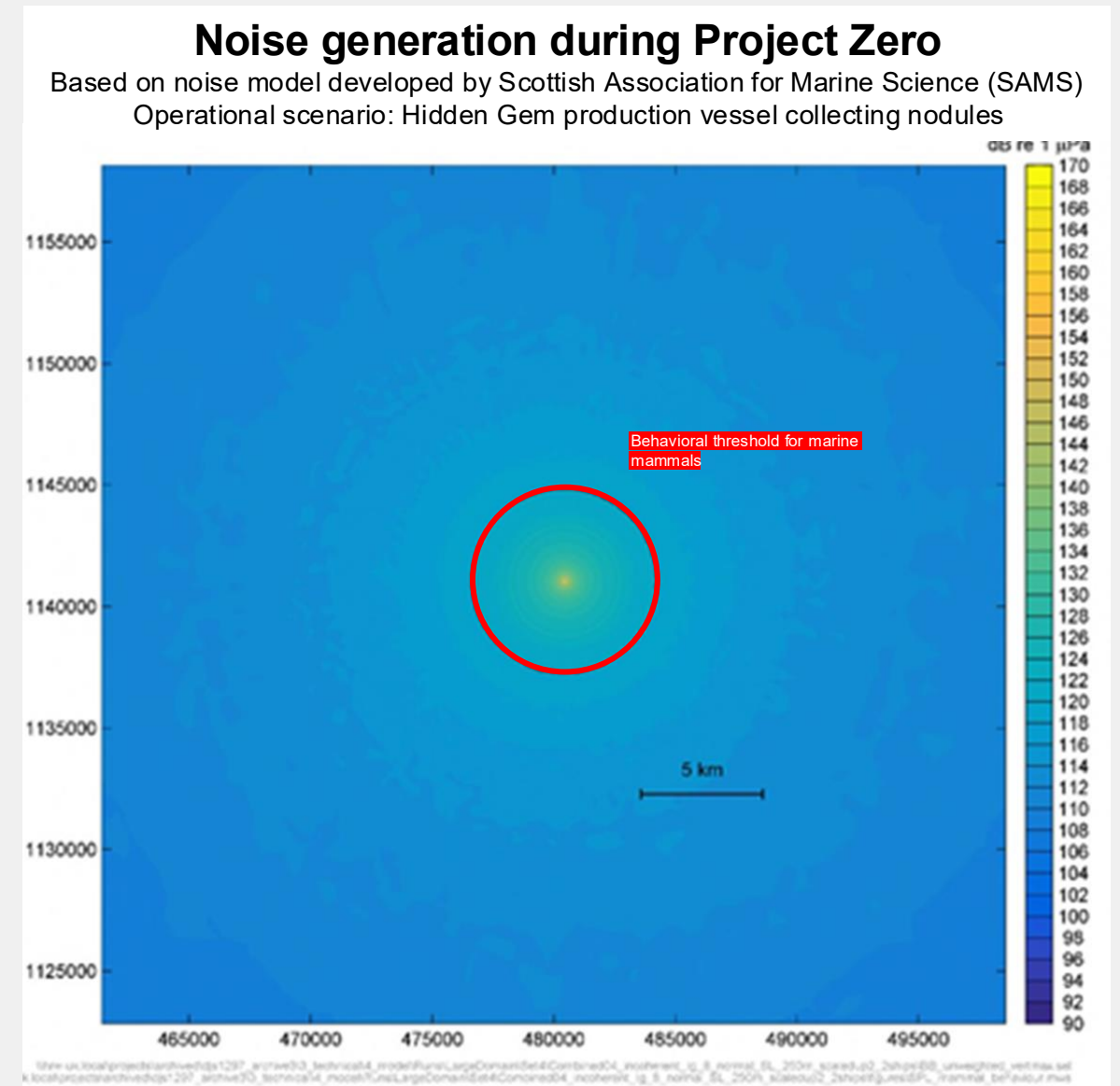
Noise measured during pilot was highest from the surface vessel.

- Empirical noise data was collected during test mining using an array of hydrophones
- Results show that the main noise source is from the diesel engines and dynamic positioning (DP) thrusters of the Hidden Gem during transits and repositioning



For initial production, the **noise footprint above NOAA behavioral threshold for marine mammals is constrained to 3.8 km radius.**

- A noise model was developed by the Scottish Association for Marine Science (SAMS) to assess the likely noise impacts of our first commercial project, Project Zero
- Noise model was developed using data from test mining
- In line with NOAA thresholds, behavioral effects on marine mammals were assumed to occur above a threshold of 120 dB re 1 μ Pa for continuous sources (NMFS, 2018)
- Modelling predicts that noise levels > 120 dB will be experienced within a 3.8 km radius of the production vessel



Light is generated by the surface vessel, collector and ROVs/AUVs.

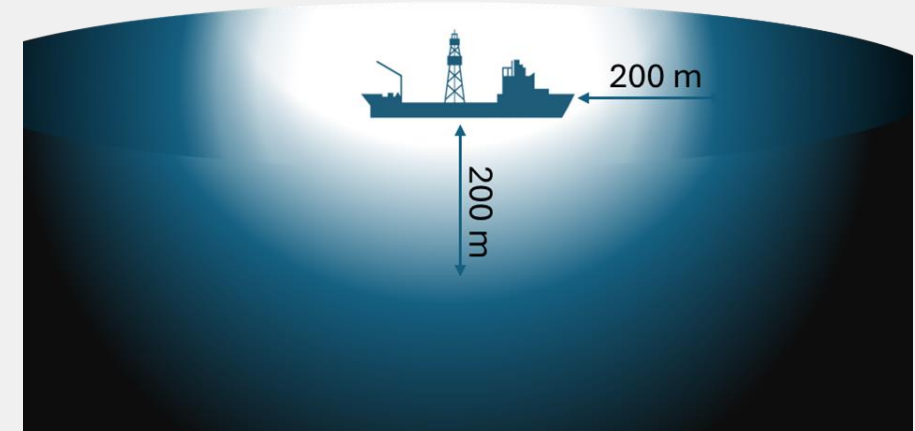
- Sources of light at the surface and in the epipelagic zone will be from production vessels. The Hidden Gem is the primary source of Artificial Light at Night (ALAN)
- ROVs, AUVs, and the collector vehicle are equipped with lights to illuminate video feeds for the operators. As the vehicles descend through the water column, they temporarily introduce light into the mesopelagic and bathypelagic zones
- The collector vehicle is the primary source of light at the seafloor



Light footprint will be constrained to 200m radius on the surface and 11m on the seafloor.

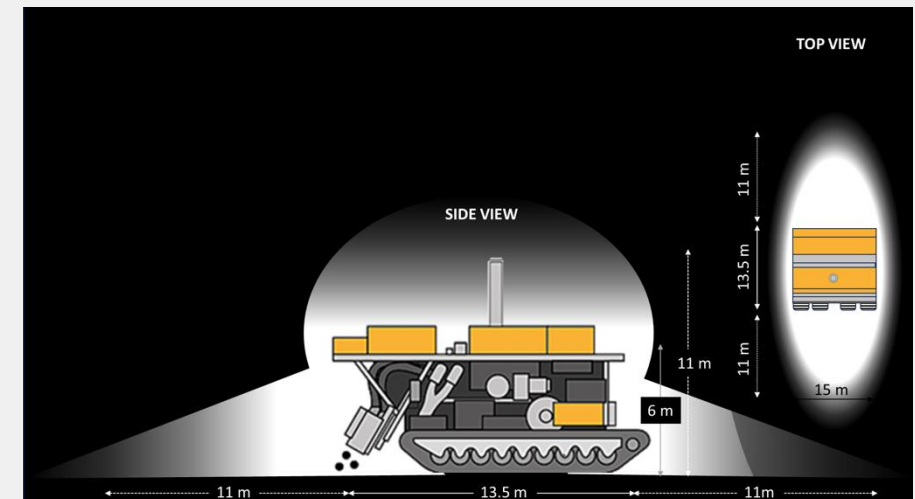
Light from the surface vessel

Normal working light from a vessel may disrupt fish and zooplankton behaviour down to at least 200m depth across an area of $> 0.125 \text{ km}^2$ around the ship (Berge et al., 2020). This equates to a circular pool of light around the vessel with a radius of approximately 200m extending to a 200m depth.



Light from seafloor collector

During test mining, the lighting system on the prototype collector vehicle emitted a 10m-long horizontal cone of light at the front and back of the vehicle, which lofted approximately 4m into the water column. Light spill from the sides of the collector was low as the lighting systems are directed to the front and rear only. Applying these metrics to the full-scale commercial vehicle, a pool of light measuring 11 m to the front and rear with 5 m of loft is anticipated.



A wide-angle photograph of the ocean under an overcast sky. In the foreground, two large red spherical buoys with black bases are visible. A yellow and black triangular marker is also present. In the distance, a white buoy with a red top is visible. A blue text box is overlaid on the left side of the image.

Key Concern:

“Planet’s biggest carbon sink could be disturbed.”

Carbon sequestration will not be materially impacted.

“Proposed mining of these nodule-bearing sediments and resulting resuspension of particles and organic matter will have a **trivial impact** on the ecosystem service of carbon sequestration.” *Orcutt, B.N., et al. (2020)*

“...the localized nature and relatively small scale of potential disturbances make a substantial impact on the global carbon cycle **unlikely.**”

ISA Fact-check 2024/1

LIMNOLOGY and OCEANOGRAPHY

ASLO

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doi: 10.1002/lno.11403

Impacts of deep-sea mining on microbial ecosystem services²

Beth N. Orcutt^{1,*}, James A. Bradley,² William J. Brazelton³, Emily R. Estes,⁴ Jacqueline M. Goordial^{1,5}, Julie A. Huber⁶, Rose M. Jones^{7,1,7}, Nagissa Mahmoudi⁸, Jeffrey J. Marlow,⁹ Sheryl Murdock¹⁰, Maria Pachiadaki⁶

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Abstract

Interest in extracting mineral resources from the seafloor through deep-sea mining has accelerated in the past decade, driven by consumer demand for various metals like zinc, cobalt, and rare earth elements. While there are ongoing studies evaluating potential environmental impacts of deep-sea mining activities, these focus primarily on impacts to animal biodiversity. The microscopic spectrum of seafloor life and the services that this life provides in the deep sea are rarely considered explicitly. In April 2018, scientists met to define the microbial ecosystem services that should be considered when assessing potential impacts of deep-sea mining, and to provide recommendations for how to evaluate and safeguard these services. Here, we indicate that the potential impacts of mining on microbial ecosystem services in the deep sea vary substantially, from minimal expected impact to loss of services that cannot be remedied by protected area offsets. For example, we (1) describe potential major losses of microbial ecosystem services at active hydrothermal vent habitats impacted by mining, (2) speculate that there could be major ecosystem service degradation at inactive massive sulfide deposits without extensive mitigation efforts, (3) suggest minor impacts to carbon sequestration within manganese nodule fields coupled with potentially important impacts to primary production capacity, and (4) surmise that assessment of impacts to microbial ecosystem services at seamounts with ferromanganese crusts is too poorly understood to be definitive. We conclude by recommending that baseline assessments of microbial diversity, biomass, and, importantly, biogeochemical function need to be considered in environmental impact assessments of deep-sea mining.

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

Author Contribution Statement: R.M.J. constructed the maps in Fig. 1, J.J.M. developed the data set for Fig. 4 and the Supporting Information, J.A.H. contributed to Fig. 2, and B.N.O. created the remaining figures. B.N.O. wrote the manuscript with input from all authors.

With increasing demand for rare and critical metals—such as cobalt, copper, manganese, tellurium, and zinc—there is increasing interest in mining these resources from the seafloor (Hein et al. 2013; Wedding et al. 2015; Thompson et al. 2018). The primary mineral resources in the deep sea that attract attention fall into four categories (Figs. 1, 2): (1) massive sulfide deposits created at active high-temperature hydrothermal vent systems along mid-ocean ridges, back-arc spreading centers, and volcanic arcs, from the mixing of mineral-rich, advecting hydrothermal fluids with bottom seawater; (2) similar deposits at inactive hydrothermal vent sites, where fluid advection has ceased but mineral deposits remain; (3) polymetallic nodules that form on the seafloor of the open ocean

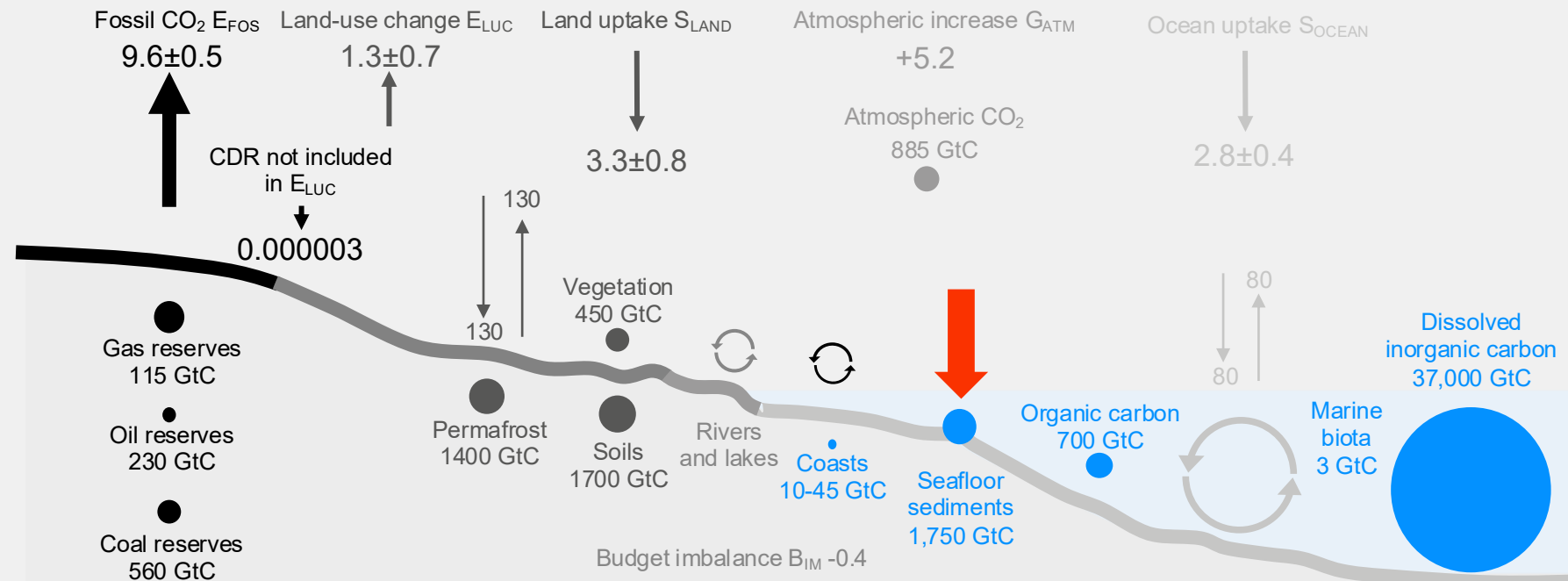
1489

Oceans are the planet's biggest carbon sink but seafloor sediments host **less than 5% of the total oceanic carbon sink.**

The global carbon cycle

Anthropogenic fluxes 2013-2022 average GtC per year

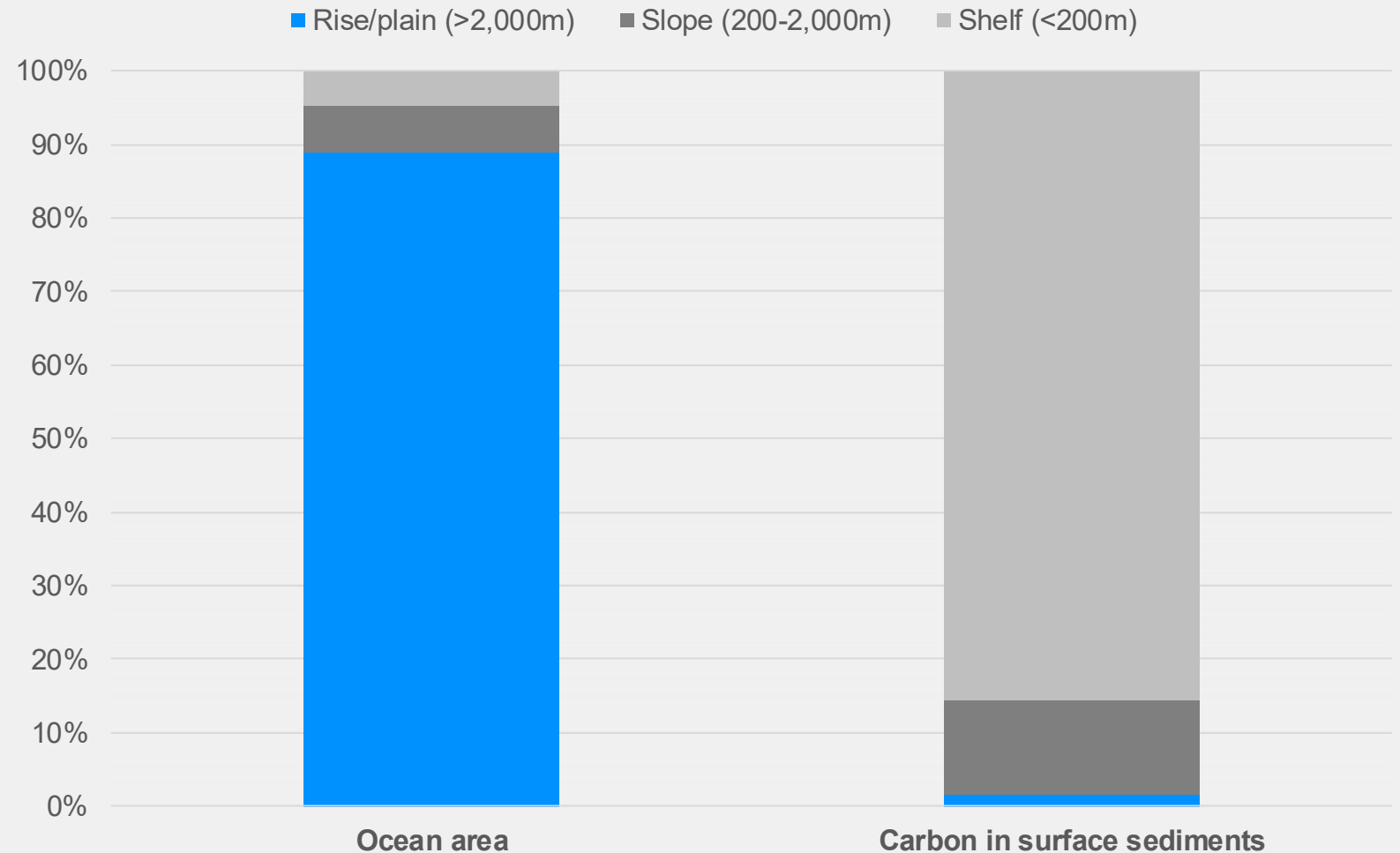
● Stocks GtC ↓ Carbon cycling GtC per year



Only 1.5% of total carbon buried in sediments are found on the abyssal plains and rises—despite them covering almost 90% of the global ocean area.

Organic carbon pools in surface sediments by depth

Percent of total ocean area by depth / Percent of total organic sedimentary carbon by depth



There are no meaningful mechanisms for carbon in abyssal floor sediments disturbed by nodule collection to reach the atmosphere.

0-200m

MESOPELAGIC

200-1000m

— 1000m

BATHYPELAGIC

1000-3000m

2000m

— 3000m

ABYSSOPELAGIC

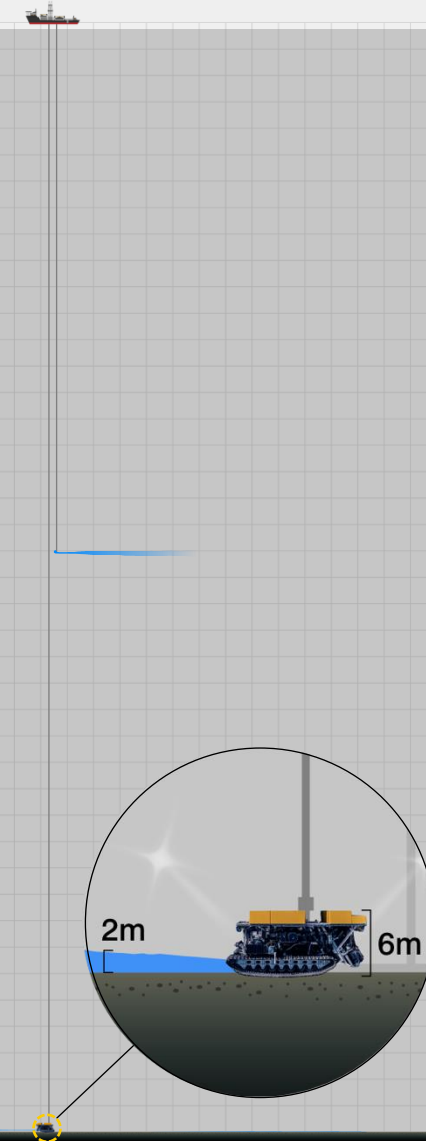
3000m+

4000m

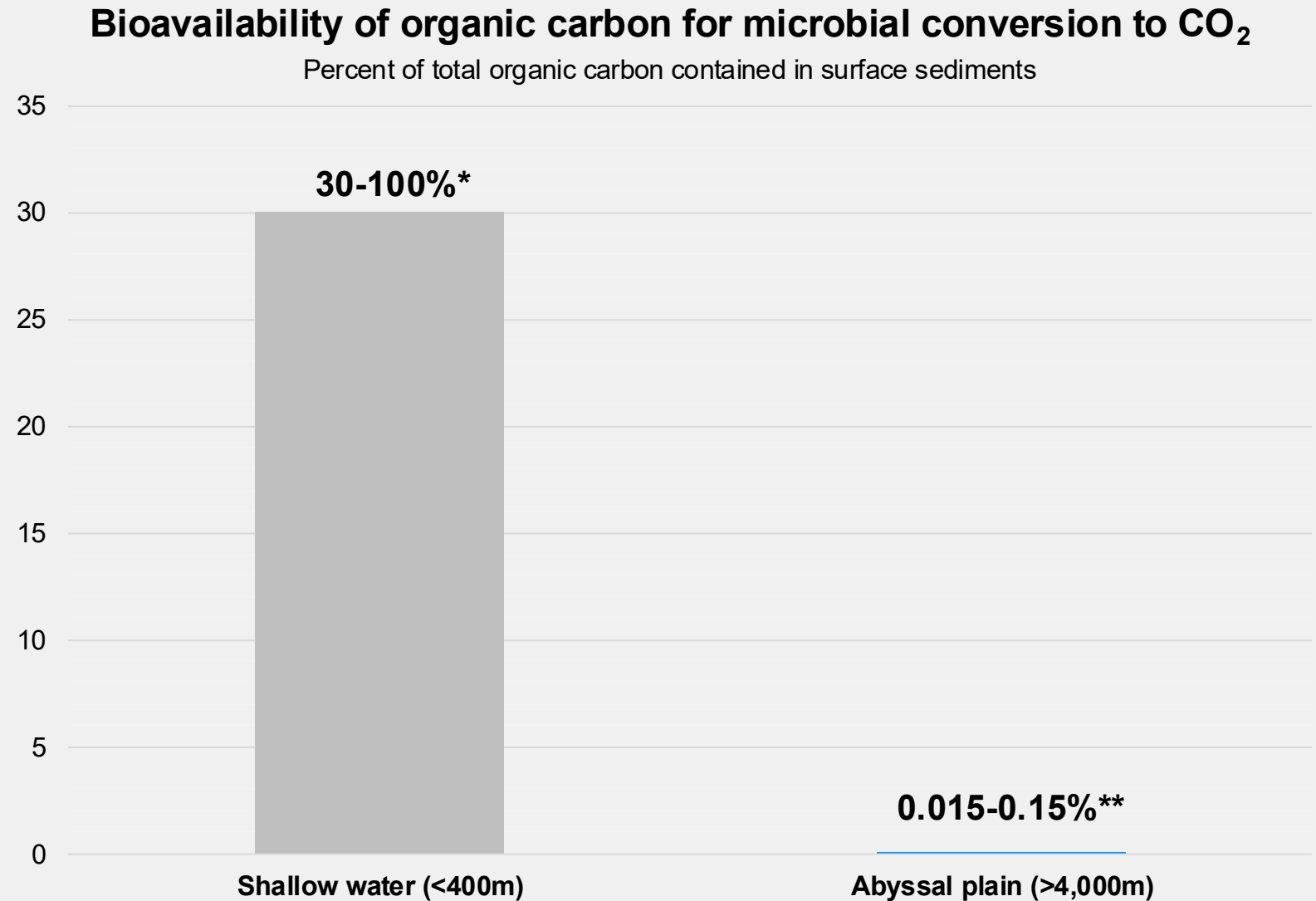
— 4200m

Observed data from in-field pilot tests show that 92-98% of mobilized sediment stays confined to below 2m above the seafloor and resettles within hours to days.

There are no known pathways for this carbon to reach the atmosphere within the short window before sediment resettles. The ocean's thermohaline circulation occurs on centuries time scale and Earth's geological cycle impacts water mass movements over tens or hundreds of millions of years.



In shallow waters, carbon in sediments disturbed by bottom-trawling is bioavailable for microbial conversion to CO₂ – this is not the case for abyssal sediments in deep water.



* Based on K value of 0.3-17 kg –yr from Atwood, T. B., A. Romanou, T. DeVries, and others. 2024. Atmospheric CO₂ emissions and ocean acidification from bottom-trawling. *Frontiers in Marine Science* **10**; Sala, E., Mayorga, J., Bradley, D. *et al.* Protecting the global ocean for biodiversity, food and climate. *Nature* **592**, 397–402 (2021). <https://doi.org/10.1038/s41586-021-03371-z>

** Based on K value of 0.00015-0.0015 kg –yr from Pika, P. A., D. Hülse, T. I. Eglinton, and S. Arndt. 2023. Regional and Global Patterns of Apparent Organic Matter Reactivity in Marine Sediments. *Global Biogeochemical Cycles* **37**: e2022GB007636. doi:10.1029/2022GB007636



Key Concern:

”Mining could irreversibly destroy ancient deep-sea habitats.”

Best mitigation is conservation: 43% of the CCZ already set aside.

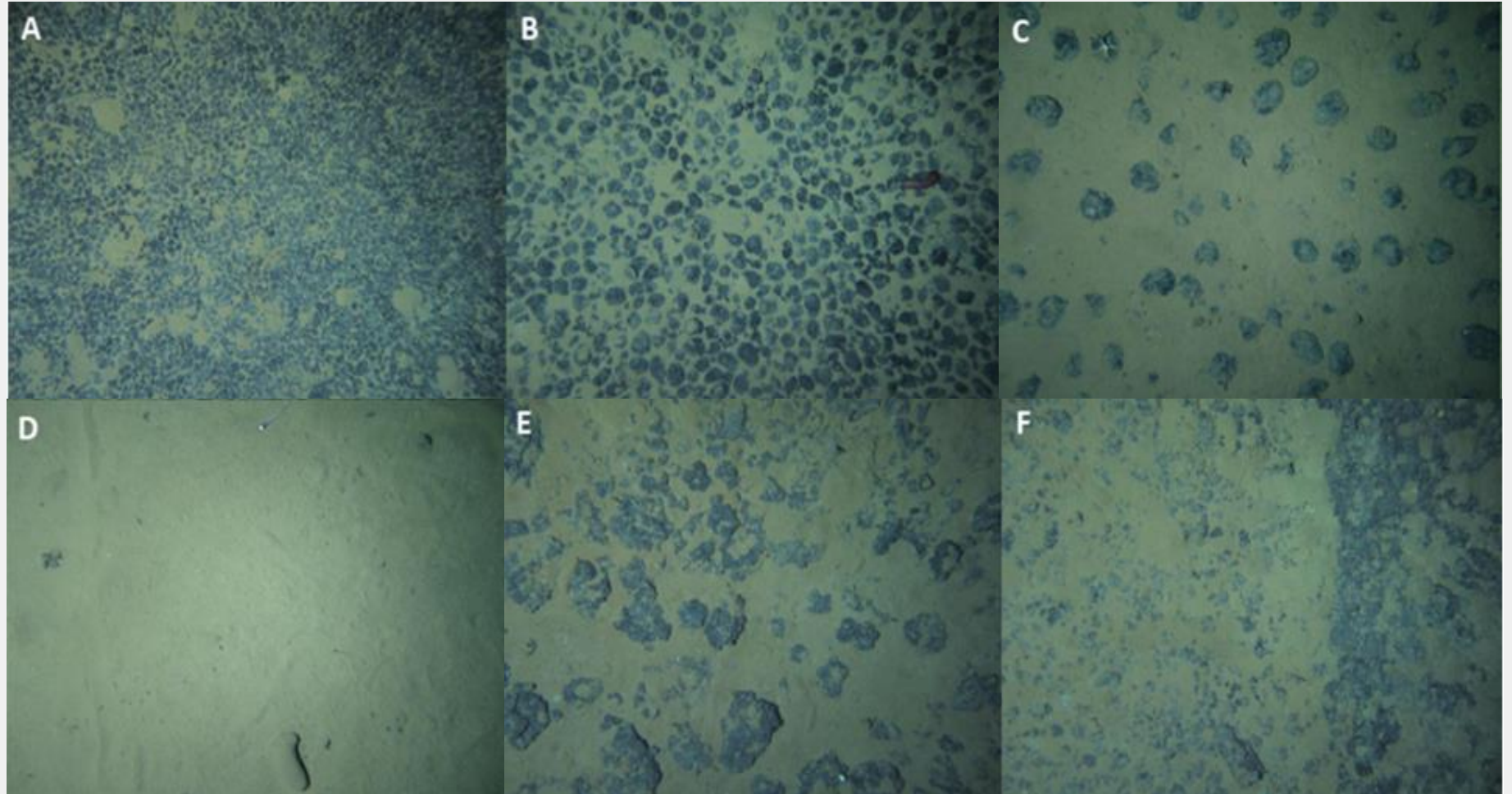
1.97m km²
under protection

1.28m km²
under exploration

The High Seas Treaty agreed in June 2023 aims to protect 30% of the oceans by 2030.



These are the different habitat types observed in seabed imagery collected across NORI-D before pilot test.



DPT : 4288.2m
ALT : 3.4m

HDG: 332.1°

E : 480284.424
N : 1141812.385

**And this is what the
seafloor looks like after
nodule collection:
it's a nodule free habitat.**

01-12-2022
UTC 05:01:04

TF-015 BC477
TMC

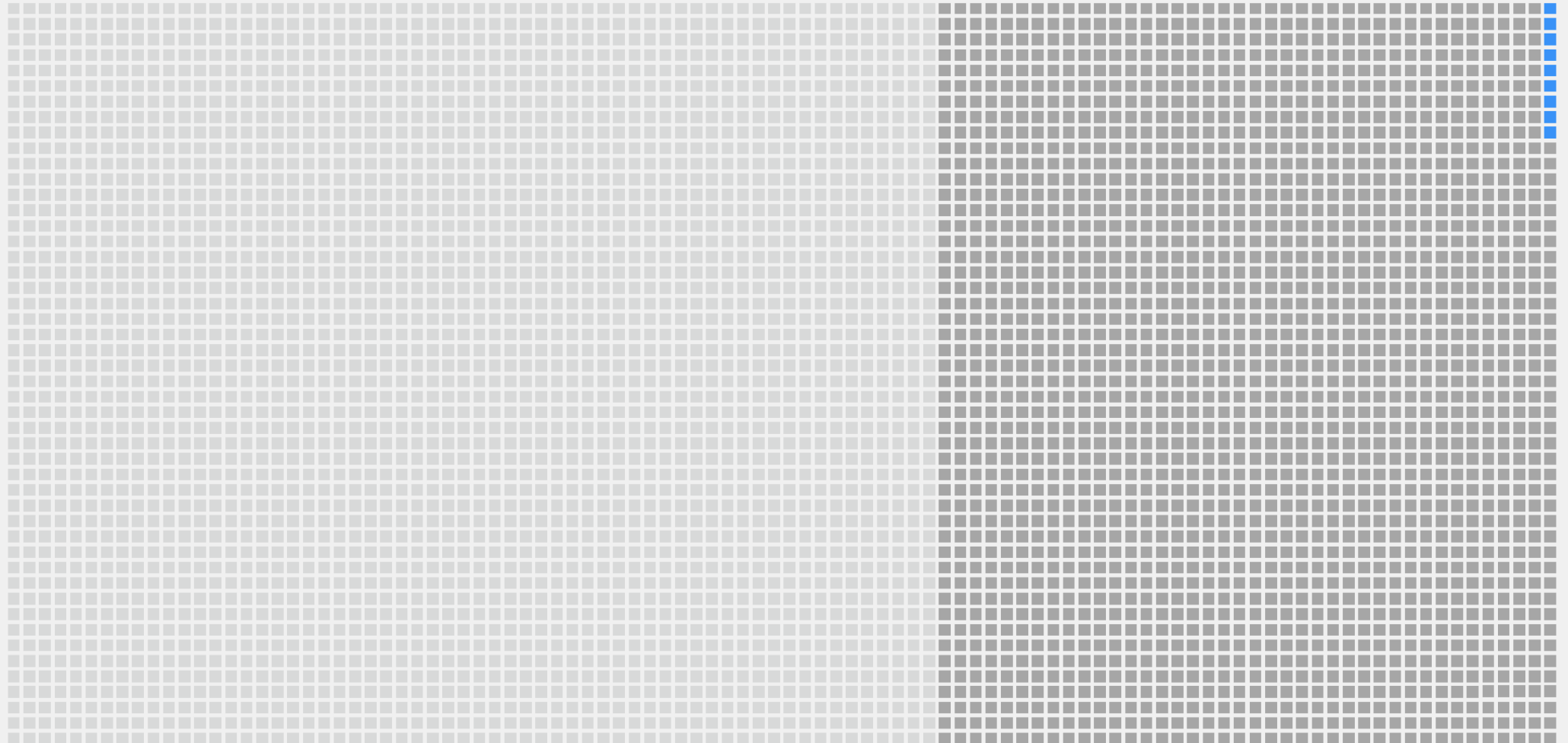
Island Pride
HD14 - Dive 464

Nodule collection could transform up to 0.18% of the seafloor from one habitat type to another.

■ Global seafloor
361m km² = 4,800 squares

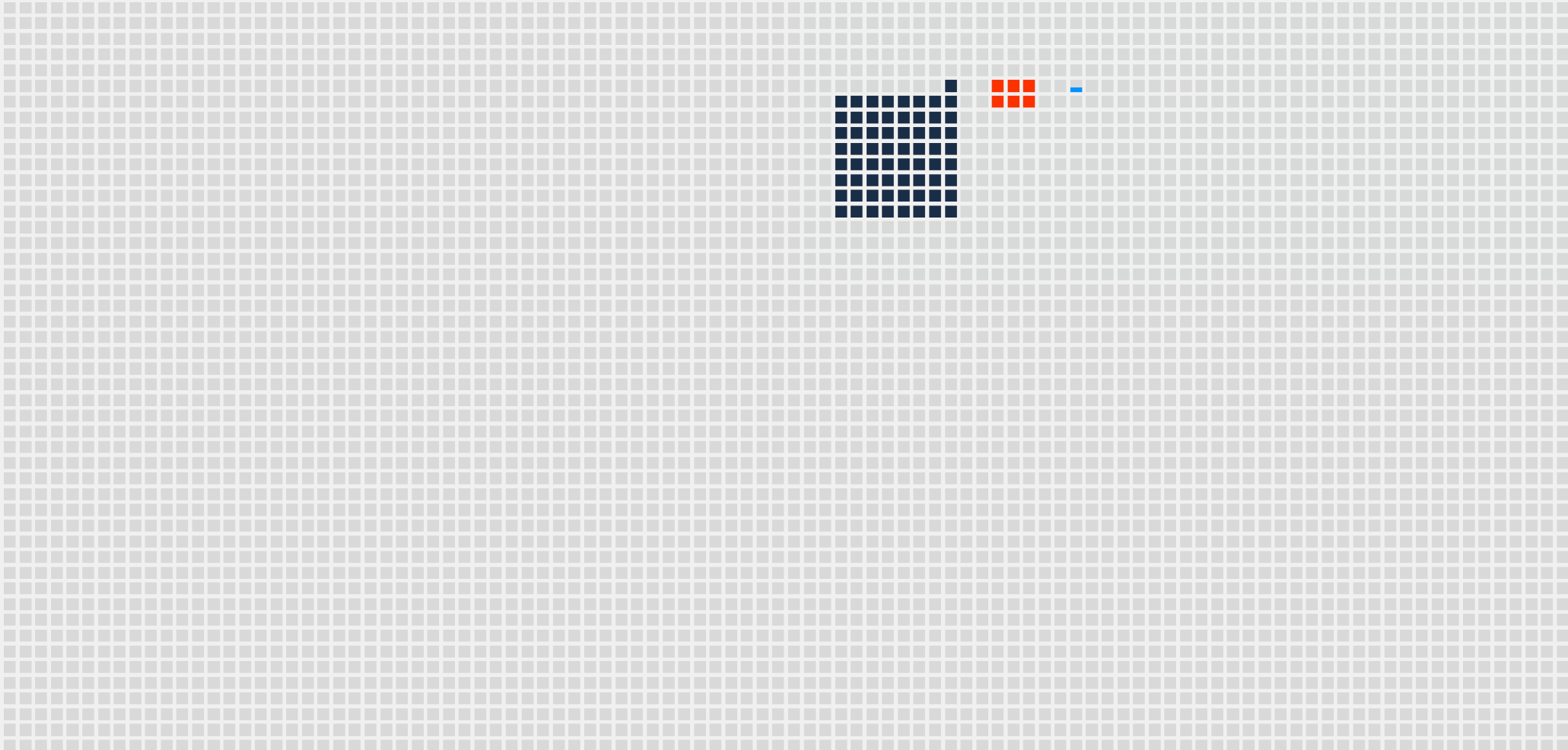
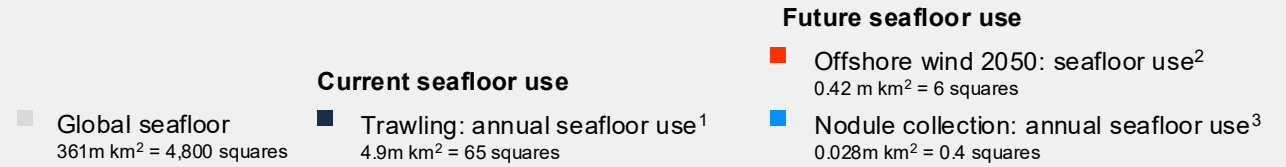
■ Abyssal plains
144 m km² = 1,915 squares

■ Nodule collection: cumulative seafloor use¹
0.64m km² = 9 squares



¹ Assuming a scenario where 50% of the 1.28 million km² of nodule exploration area in the CCZ gets exploited—an ambitious estimate given that some contractors have already stated that they believe only 20% of their exploration area is economic.

Trawling today impacts 175x more seafloor every year than nodule collection.

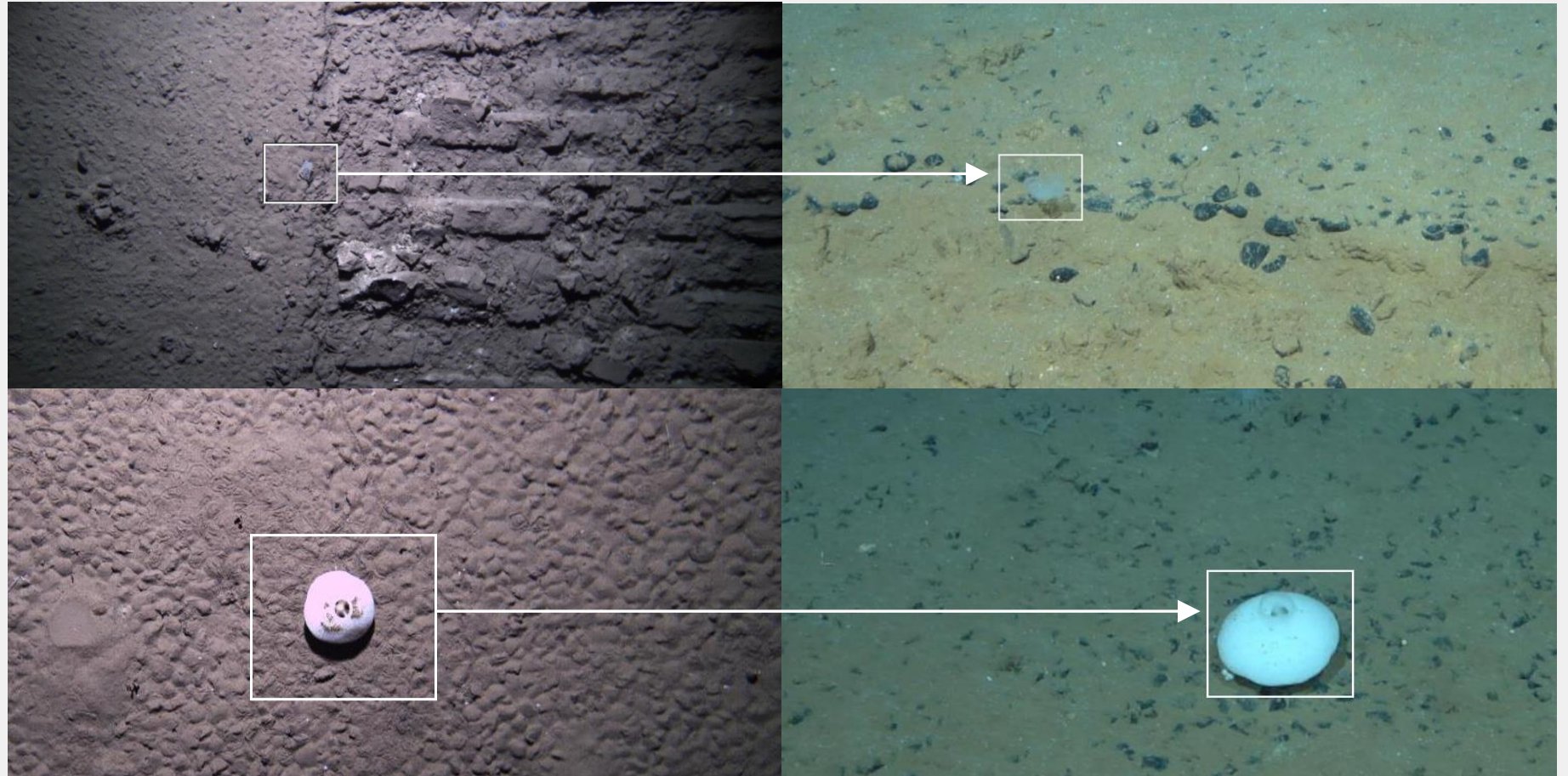


¹ Estimate provided in Sala, E., Mayorga, J., Bradley, D. *et al.* Protecting the global ocean for biodiversity, food and climate. *Nature* 592, 397–402 (2021). <https://doi.org/10.1038/s41586-021-03371-z>

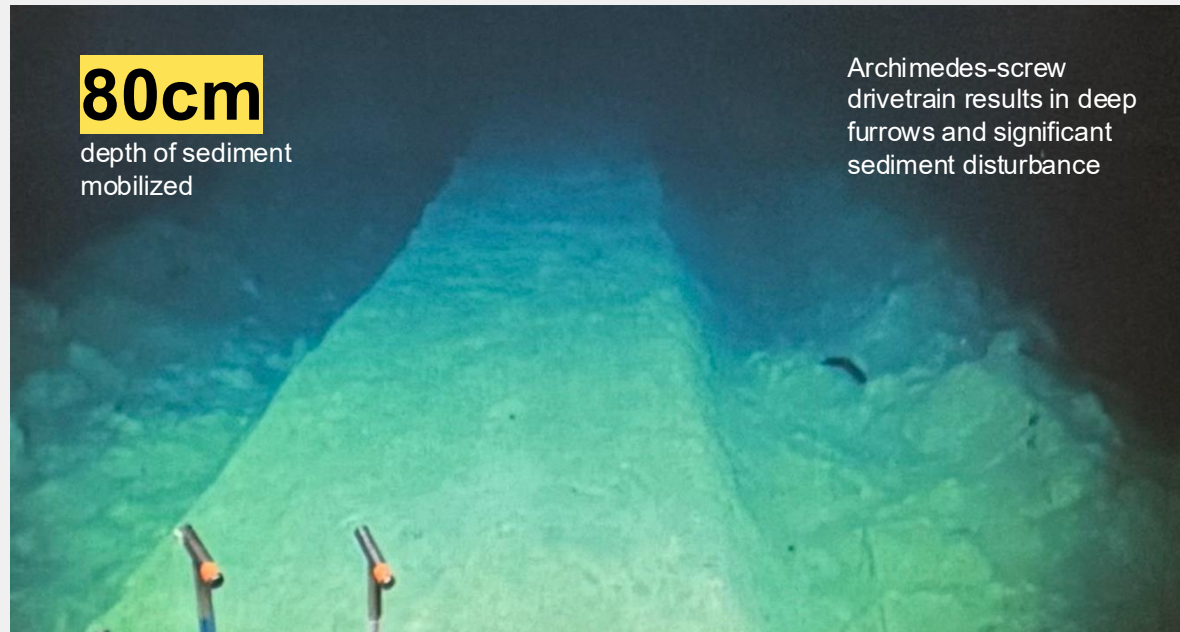
² Estimate based on IEA (2021), Net Zero by 2050, IEA, Paris <https://www.iea.org/reports/net-zero-by-2050>.

³ Assuming a scenario where 50% of the 1.68 million km² of nodule exploration area globally (international waters + EEZs) is exploited over a 30-year period, starting on the same day

Qualitative data shows individual organisms are present and alive one year following test mining, even right next to the vehicle tracks.



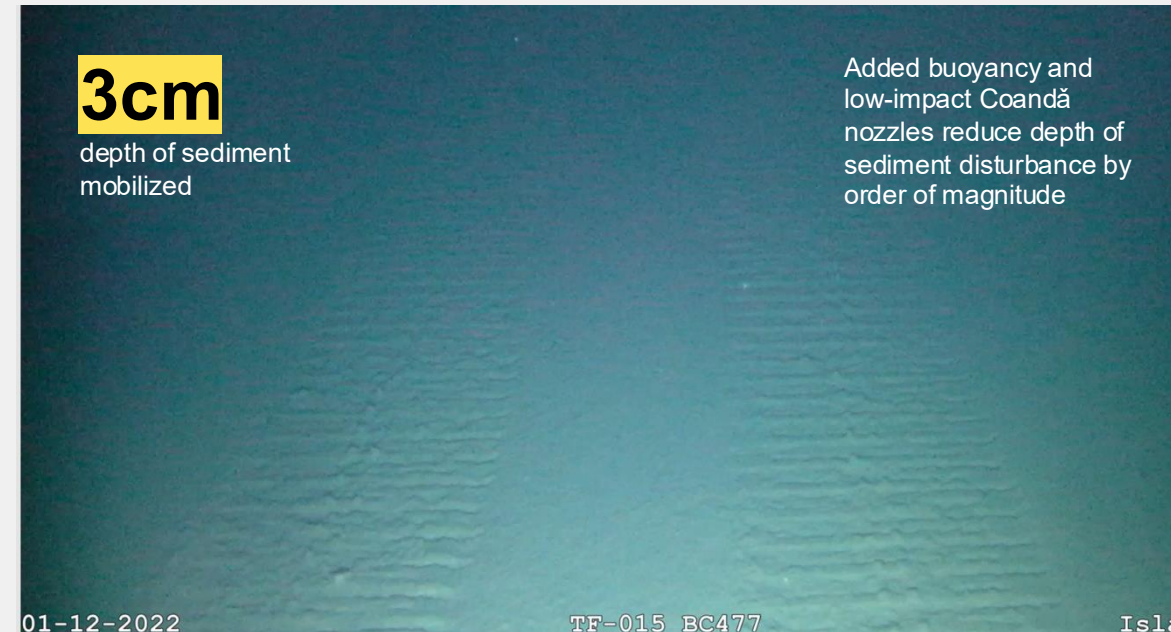
A tale of two tracks: ecosystem recovery measured after 40+ years but could be faster with our technology.



80cm

depth of sediment mobilized

Archimedes-screw drivetrain results in deep furrows and significant sediment disturbance



3cm

depth of sediment mobilized

Added buoyancy and low-impact Coandă nozzles reduce depth of sediment disturbance by order of magnitude

01-12-2022

TF-015 BC477

Isl

44 years later¹

- Full recovery of sediment macrofauna and foraminifera in tracks & plume areas
- Recolonization of xenophyophores, suggesting return of structural complexity to the ecosystem
- Sessile megafauna observed on left behind nodules, promising for mitigation through intentional retention of nodules at seafloor
- Plume had "no detectable or slightly positive biological impacts"

12 months later

- Foraminifera in tracks recovered to 30% of pre-disturbance densities & 50% of diversity²
- Differences in community composition are limited to areas of sedimentation up to 1mm (~500m from track)
- Megafauna identified 2 weeks after test mining were found present and alive in areas most affected by plume 12 months later, including right next to the collector tracks³



Extraordinary claim:

“Nodules produce oxygen through electrolysis.”

The claim that nodules produce dark oxygen has attracted a record of five rebuttals.

Questioning Dark Oxygen Production in the Deep-sea Ferromanganese Nodule Field

Kentaro Nakamura



Published: 2024-10-04

Subjects: Earth Sciences, Geochemistry, Geology, Oceanography

Previous studies have concluded that the natural process where oxygen is consumed as decomposition of organic matter that supplied from shallow waters occurs on the deep-sea floor. Sweetman et al.1 presented the surprising observation that deep-sea ferromanganese nodules generate oxygen, which they labelled as dark oxygen production. The authors claimed that oxygen was generated through the [...]

Pre-print

Critical Review of the Article: "Evidence of Dark Oxygen Production at the Abyssal Seafloor" by Sweetman et al. in Nat. Geosci. 1–3 (2024)

Lars-Kristian Lunde Trellevik, Alden Denny, Werner Svellingen



Published: 2024-08-12

Subjects: Geochemistry

UNIVERSITY OF
GOTHENBURG

This review examines the findings and methodologies presented in Sweetman et al. (2024) (hereafter referred to as 'the paper'). The paper presents findings contrasting those of all previous comparable work and has stirred international debate pertaining to deep-sea minerals. We identify significant issues in data collection, validation, and interpretation including unvalidated data collection [...]

In peer-review with Nature Geoscience

Is Abyssal Dark Oxygen Production Even Possible at All?

Angel Cuesta, Marcel Jaspars



Published: 2025-03-10

Subjects: Chemistry, Environmental Sciences, Oceanography and Atmospheric Sciences and Meteorology, Physical Sciences and Mathematics

Physical principles need to be respected when interpreting controversial findings such as the production of abyssal oxygen. Such extraordinary claims must be analysed carefully before a large [...]

Pre-print, submitted to Nature Geoscience

Contributions to the discussion of novel detection of dark oxygen production at the abyssal seafloor

Patrick Downes, Leigh Marsh, Joaquim Bento, et al.



Published: 2024-09-18

Subjects: Biogeochemistry, Earth Sciences

There is an overwhelming consensus between researchers based on a vast body of peer-reviewed literature that deep sea ecosystems constitute an oxygen sink. Specific studies on abyssal seafloor regions that contain polymetallic nodules have also confirmed this result. In contrast to this well-founded and longstanding paradigm, Sweetman et al. claim to provide evidence to support a hypothesis that [...]

Peer reviewed, pending publication in Nature Geoscience

Rebuttal of Sweetman, A.K., Smith, A.J., de Jonge, D.S.W. et al. Evidence of dark oxygen production at the abyssal seafloor. Nat. Geosci. (2024). <https://doi.org/10.1038/s41561-024-01480-8>

Anders Tengberg, Per Hall, Mikhail Kononets



Published: 2024-10-04

Subjects: Life Sciences

A rebuttal of this paper was submitted to Nature Geoscience The paper by Sweetman et al. (2024) is criticized for poor-quality lander incubation experiments, leading to faulty oxygen flux measurements. The authors misinterpret results and make unsupported speculations, raising serious concerns about the methodology, data handling, and overall conclusions of the study.

Pre-print, in preparation for submission to Nature Geoscience

Despite heavy media coverage, the five published rebuttals call for the paper to be retracted over serious concerns with the validity of its claims.

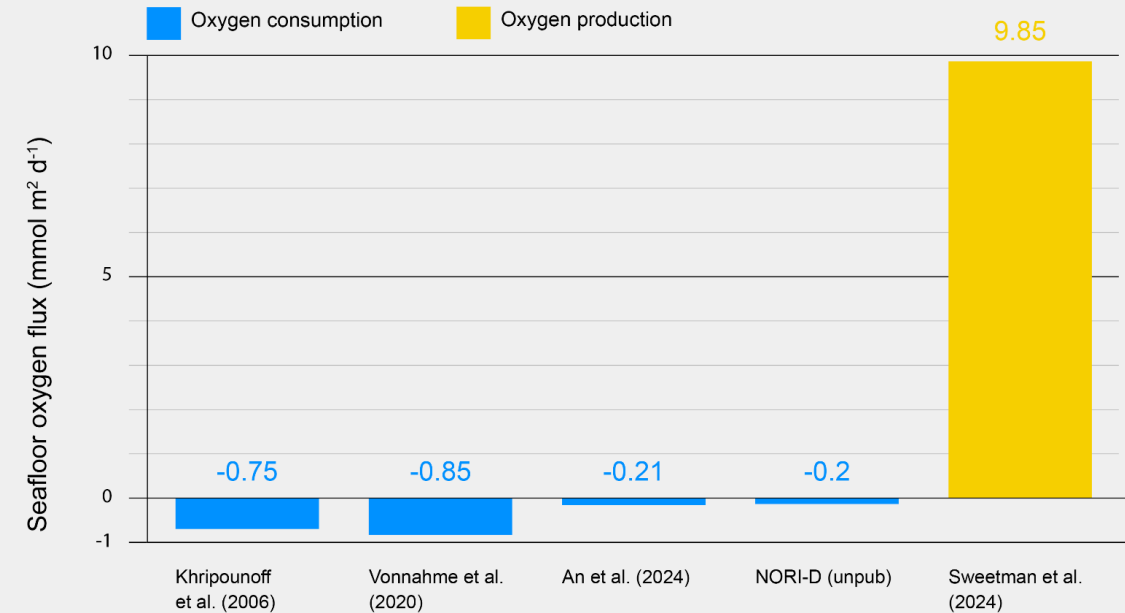
Five rebuttals are now available in pre-print, an unprecedented number for a single paper.

- **August 12:** “The level of care necessary to justify extraordinary claims with such broad implications is absent from the paper and the results are in direct opposition to all other published work.”¹ - ADEPTH
- **September 18:** selective reporting of data and omission of key evidence, including experiments that show oxygen increases without nodules, directly contradicting the authors’ claims. – TMC
- **October 4:** “Given scientific ethics, numerous methodological flaws, misinterpretations, and lack of proper quality control, it is strongly recommended that Nature Geoscience withdraws this paper.”³ – University of Gothenburg
- **October 4:** No evidence for electrolysis, and “no anomalous oxygen generation has been reported in the enormous amount of research conducted over more than half a century.”⁴ – University of Tokyo
- **March 10:** “The claimed abyssal production of dark oxygen, as proposed by Sweetman et al., is simply thermodynamically impossible... further investigation of an impossible process can negatively affect the way in which scientific findings inform the decision-making process.” – University of Aberdeen

“There is a high probability that the paper is wrong” – Kentaro Nakamura, University of Tokyo geochemist quoted in *Science*, September 18, 2024

Three prior published studies using the same techniques failed to detect oxygen production

Seafloor oxygen fluxes measured with nodules present



1) Critical Review of the Article: "Evidence of Dark Oxygen Production at the Abyssal Seafloor" by Sweetman et al. (2024). Preprint. Retrieved from <https://doi.org/10.31223/X5N98F>; 2) Downes, P., Marsh, L., Bento, J., Webber, A., & Clarke, M. (2024). Contributions to the discussion of novel detection of dark oxygen production at the abyssal seafloor. Preprint. Retrieved from <https://doi.org/10.31223/X5VW0X>; 3) Rebuttal of Sweetman, A. K., Smith, A. J., de Jonge, D. S. W., et al. (2024). Evidence of dark oxygen production at the abyssal seafloor. *Nature Geoscience*. Retrieved from <https://doi.org/10.31223/X5T708>; 4) Nakamura, K. (2024). Questioning Dark Oxygen Production in the Deep-sea Ferromanganese Nodule Field. Retrieved from <https://doi.org/10.31223/X5ph7f>; 5) Cuesta, A., and Jaspars, M. (2025). Is abyssal dark oxygen production even possible at all?. Retrieved from <https://doi.org/10.31223/X5DT6P>.

A recent peer-reviewed critique in *Frontiers in Marine Science* synthesizes all prior concerns, further questioning the validity of the dark oxygen claims.

Conclusion: *“The proposed mechanism-seawater electrolysis driven by polymetallic nodules at voltages <math><1.23V</math> lacks credible evidence and violates the First and Second Laws of Thermodynamics.*”

Specifically, the study *fails to identify a viable energy source*, demonstrate the presence of a strong oxidant, or report hydrogen production as would be expected from electrolysis.

Furthermore, *key omissions, including data from control experiments showing that the DOP signal originates from the benthic chamber lander itself-not the nodules-strongly indicates that the reported oxygen increases are experimental artefact rather than a genuine geochemical process.*”

frontiers | Frontiers in Marine Science | Sections ▾ | Articles | Research Topics | Editorial board

Extraordinary Claims Require Extraordinary Evidence: Evaluating Nodule-Associated Dark Oxygen Production Provisionally accepted

Patrick Downes^{1*}
 Angel Cuesta^{2,3}
 Alden Denny⁴
 Anders Tengberg⁵

Per O.J. Hall⁶
 Lars-Kristian Trellevik⁴
 Werner Svellingen⁴
 Marcel Jaspars²

Alexander Webber¹
 Felipe Sales de Freitas¹
 Joaquim P. Bento¹

Leigh Marsh¹
 Michael Clarke¹

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² University of Aberdeen School of Natural and Computing Sciences, Aberdeen, United Kingdom
³ Instituto de Quimica Fisica Blas Cabrera, Madrid, Spain
⁴ Adepth Minerals, Bergen, Norway
⁵ Aanderaa-Xylem, Bergen, Norway
⁶ Department of Marine Sciences, University of Gothenburg, Gothenburg, Sweden



Extraordinary claim:

“Alpha radiation from nodules is a health hazard.”

Multiple studies show **alpha radiation** from nodules is not expected to be a health hazard.

Risk assessment of the natural occurring radioactivity in polymetallic nodules



Estimations of effective doses for industrial scale handling of nodules

Thomas Lüttke, T. Kuhn, A. Vink, C. Rühlemann, C. Kunze, K. Flesch

IAF - Radioökologie GmbH
Labor für Radionuklidanalytik
Radiologische Gutachten
Consulting



2024

In response to a 2023 paper by Volz et al. claiming alpha radiation from nodules posed health risks to workers, scientists at Germany's Institute for Geosciences and Natural Resources (BGR) published two studies assessing the validity of the authors' claims.

Though Volz et al. used the correct measurements, the context and interpretation of these results was wrong.

No exceptional risk is expected from the handling of nodules with the effective dose easily limited to below 1 mSv/a. **Even in the worst-case scenario, the effective dose is well below the limit for workers of 20 mSv/a.**

Academics conclude that the paper was the cause of **much "avoidable hysteria."**

scientific reports

2025

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Article | [Open access](#) | Published: 04 September 2025

Estimations of effective doses received from naturally occurring radioactivity in polymetallic nodules from the deep sea

[Thomas Lüttke](#) , [Christian Kunze](#), [Klaus Flesch](#), [Jörg Dilling](#), [Jens Fohlmeister](#), [Holger Hummrich](#), [Robert Arndt](#), [Annegret Krzikalla](#), [Christian Lucks](#), [Thomas Kuhn](#), [Annemiek Vink](#) & [Carsten Rühlemann](#)

'In terms of health and radiation safety, we show that the radionuclide activity concentrations in nodules presented in historical and more recent datasets are not alarmingly high as postulated in conclusion by Volz et al., and that the **concerns raised therein for different parts of the nodule mining chain could not be substantiated.'**

Results are encouraging for all **six primary concerns**, and the scientific community has debunked two **extraordinary claims**.

Seafloor plumes

Status: In-field observed data shows very localized and limited seafloor plume impact, with 92-98% of sediment staying within 2 meters of seafloor.

Midwater plumes

Status: Midwater plumes rapidly dilute to natural range of background variation within 10s of km, and will not impact fisheries due to extreme vertical separation.

Noise & light

Status: Both noise and light will be constrained to a small footprint similar to other ocean industries.

Dark oxygen

Status: Unprecedented five rebuttals warn of serious methodological and ethical flaws with the study, and call for the paper to be retracted.

Carbon sequestration

Status: Carbon sequestration will not be materially impacted.

Biodiversity loss

Status: Impacts are mostly limited to nodule-dependent species, and sedimentary animals are expected to recover fully. Over 50% of CCZ will remain untouched.

Habitat destruction

Status: Mining will transform parts of the seafloor from one common habitat type to another, and life has been proven to recover quickly.

Radioactivity

Status: Peer-reviewed studies show nodules do not pose serious risks to human health.

Dr Michael Clarke
mike@metals.co

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