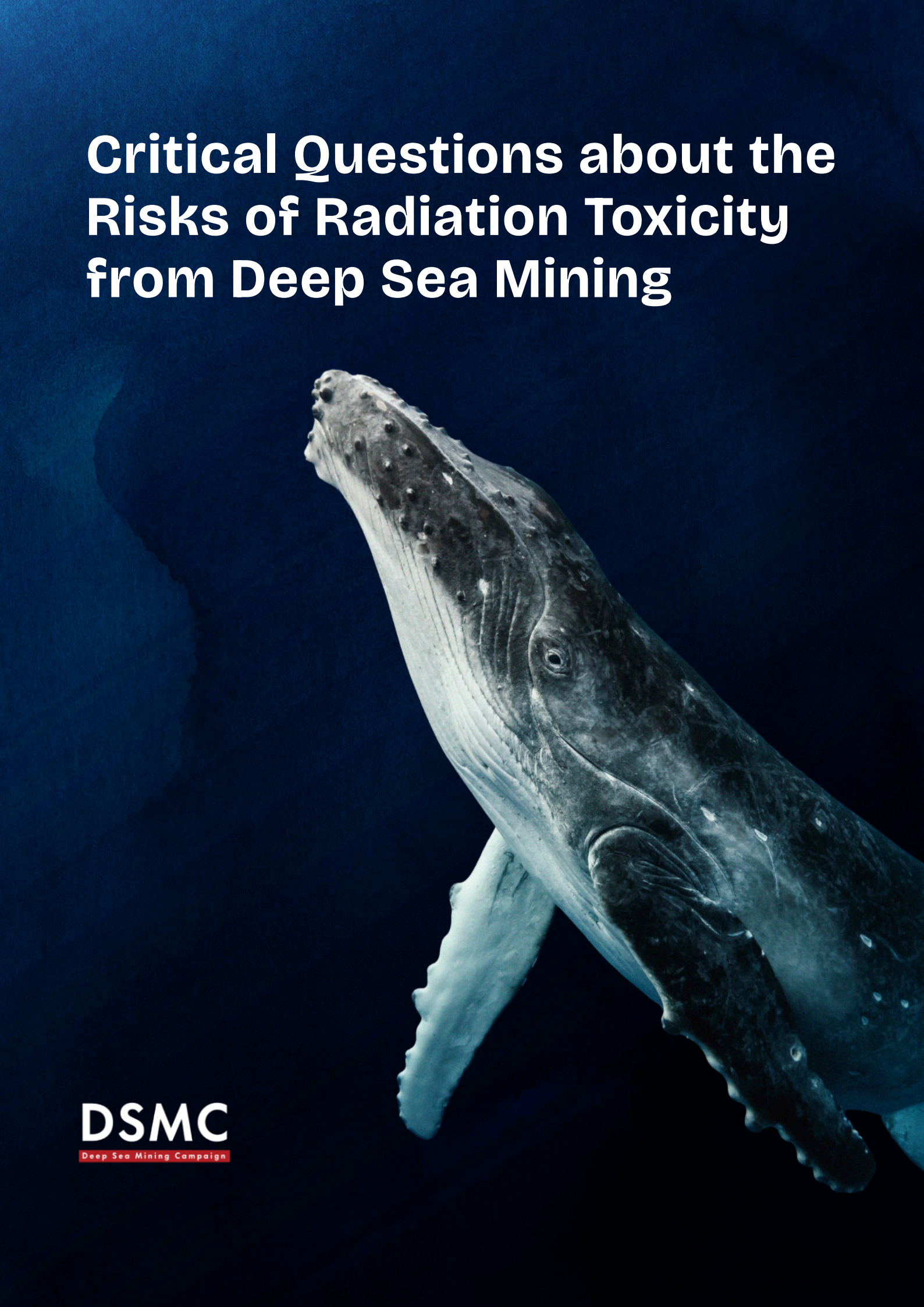
Critical Questions about the Risks of Radiation Toxicity from Deep Sea Mining



DSMC

Deep Sea Mining Campaign

Acronyms

DSM	Deep Sea Mining
IAEA	International Atomic Energy Agency
ICRP	International Commission on Radiological Protection
LET	Linear Energy Transfer
NORM	Naturally Occurring Radioactive Materials
SMS	Seafloor massive sulphides
TENORM	Technologically Enhanced NORM
TMC	The Metals Company

DSMC
Deep Sea Mining Campaign

dsm-campaign.org

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1. Introduction

The deep sea remains one of the least explored and poorly understood environments on earth (e.g., Bell et al., 2025). It's a treasure trove of biological diversity (Ramirez-Llodra et al., 2010) where surprising life forms thrive in some of the harshest conditions on the planet (e.g. Sánchez et al., 2024).

Although not yet a commercial reality, the scientific consensus suggests the impacts of deep sea mining (DSM) are severe, long-term and effectively irreversible in human time frames (Vanreusel et al., 2016; Chin and Hari, 2020; Jones et al., 2025; Thaler, 2025). Knowledge gaps remain significant and establishing critical environmental baselines which would allow managers to make responsible and accurate impact assessments will require decades at the current pace of scientific research (Amon et al., 2022).

Over the past 15 years, the Deep Sea Mining Campaign has consistently raised concerns about the risks of DSM, including metal toxicity of the sediment plumes generated on the seafloor and by the mine waste discharged back into the ocean. Recent monitoring of DSM trials has confirmed the presence of dissolved metals and the potential for metal ecotoxicity (Leandro et al., 2026; Thomson et al., 2025; Hauton et al., 2017; Sahlmann et al., 2019).

Radioactive isotopes have been documented in seawater, sediments, polymetallic nodules, and hydrothermal vent seafloor massive sulphides (SMS). They naturally concentrate on the seafloor, in SMS and on the surface of nodules by a process known as chemical scavenging. Marine and deep sea ecosystems are adapted to natural background levels of radioactive isotopes just as they are adapted to natural background levels of heavy metals.

Just as for metals, disturbing nodules, SMS, or sediments poses a toxicity risk by mobilising radioactive materials. In addition to the ecological effects that metals and radioactive isotopes may cause, a significant unknown is the potential for additive and synergistic impacts due to the simultaneous exposure of organisms to both heavy metals and radioactive isotopes.

DSM would increase the concentration and the duration of exposure through sediment disturbance, particle resuspension and the dispersion of fragments of nodules and SMS (Koppel et al., 2023). The mobilisation of radioactive isotopes by DSM could occur both near the seafloor during the mining process and in the water column (at depths of 1-2km) via the discharge of wastewater containing nodule fragments and particles from a surface vessel.

The potential health risks to workers handling and processing nodules have recently begun to receive scientific attention (Volz et al., 2023; Lüttke et al., 2025). However, no research has been published on DSM-induced radioecotoxicity in marine species and ecosystems.

Naturally occurring radioisotopes are commonly used to date materials in the marine environment and as tracers for studying the ocean's physical, chemical, and biological processes (e.g., Owens et al., 2015; O'Malley et al., 2024). This familiarity may have distracted scientific attention from the risks to marine ecosystems posed by radioactive isotopes mobilised by DSM.

Studies demonstrate that radioactive isotopes can accumulate within the tissues of marine organisms through ingestion of particles in water and consumption of prey. These isotopes can become incorporated into marine food webs via bioaccumulation (the accumulation of radionuclides within an organism) and biomagnification (the progressive increase in radionuclide concentrations up food chains), potentially reaching dangerously high levels in the bodies of top predators, including humans (Fowler and Fisher, 2005; Carvalho, et al., 2011; Fowler, 2011; Seiler and Wiemels, 2012).

While these processes have been documented to varying extents for some freshwater, coastal and ocean systems, there is a critical lack of published research on uptake, dose, and ecological effects in the deep sea under either natural or mining conditions.

The water column above the seabed hosts a wide array of marine life, ranging from microscopic plankton to whales. It provides migratory routes, including for species recognised globally as

threatened, as well as for commercially important fisheries such as tuna (Chin and Hari, 2020; Van Der Grient and Drazen, 2021; Amon et al., 2023; Thaler, 2025). In addition, many species undertake vertical migrations from deep to near surface waters and could be exposed to both the waste discharge and seabed mining plumes.

This report highlights critical knowledge gaps by examining what is known about radioactive isotopes in deep sea environments, assessing their likely ecological effects under mining conditions from available scientific evidence on uptake and toxicity, and identifying key scientific uncertainties.

We pose the question: What are the likely ecological risks and effects of radioactive isotopes released by mining polymetallic nodules and SMS, particularly in relation to impacts on marine species, ecosystems, and food webs?

Concern for ocean and human health demands comprehensive answers before marine ecosystems and our ocean commons are faced with the prospect of long-term exposure to elevated levels of unregulated radioactivity generated by an industry that is yet to acknowledge this risk. We call on the scientific community to attend to these critical knowledge gaps with urgency.

2. Research Approach

This paper is based on a review of published literature, synthesising current knowledge to identify plausible ecological impacts and key areas requiring further scientific research.

The following platforms were searched for peer reviewed papers and books: The US National Library of Medicine - National Institutes of Health database; The National Library of Medicine - National Institutes of Health Center for Biotechnology Information; Springer Nature Link; ScienceDirect; and the American Geological Institute GeoRef databases.

The AI-assisted research tool *Elicit* was used in a supplementary capacity to identify relevant research papers that may not have been discovered through database searches described above. This resulted in a further nine peer-reviewed papers being included following manual screening for authenticity and relevance. We used two slightly different search queries.

Elicit AI Query1: https://elicit.com/review/e88a782c-731b-4b85-9c43-38a5d81abd20 identified Cherry and Heyraud, 1982; Pentreath, 1984; Carvalho et al., 2011; Fowler, 2011; Koppel et al., 2023.

Elicit AI Query2: https://elicit.com/review/32fa7449-da30-43b8-a0f0-f70168f56dc3 identified Volz et al., 2023; Cherry and Heyraud, 1982 (as above); Wurz et al., 2024; Charmasson et al., 2009; Thomas & Liber, 2001 (not included in final review).

Additional papers were identified by the Elicit AI search but were not prioritised in the initial results. After manual review the following were included: Ku and Broeker, 1969; Blaylock, 1993; Fuller et al., 2015; Drazen et al., 2020; Dołhańczuk-Śródka et al., 2023; Lüttke et al 2025.

Google NotebookLM was used to generate preliminary synthesis of selected papers to support the analytical framework developed by the research team: https://notebooklm.google.com/notebook/0c186d94-c74d-463f-8e5e-a2c9606ac65a?pli=1

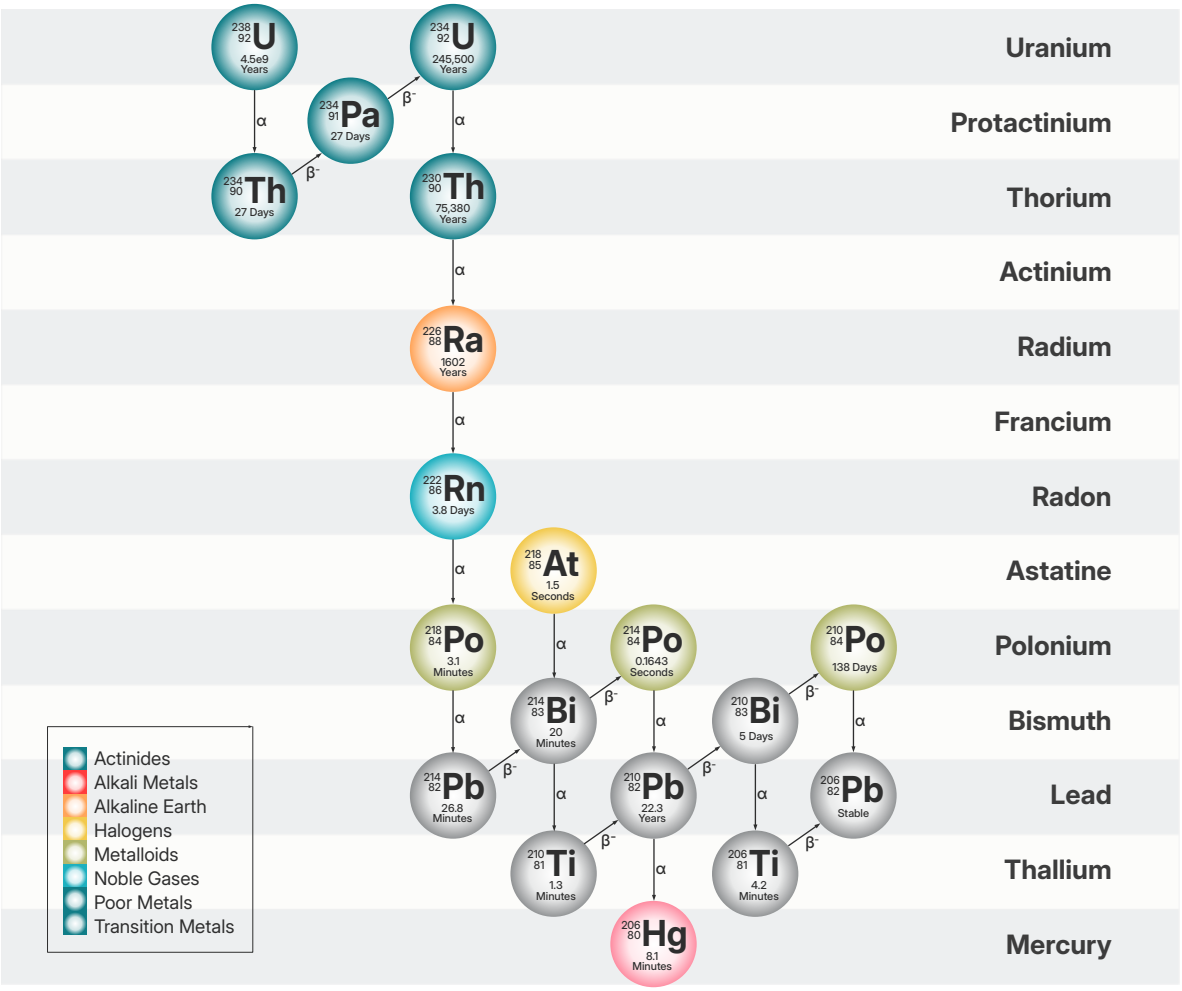
The paucity of peer-reviewed research directly relevant to our key research question (noted in the Introduction) became rapidly apparent. As a result, our source material includes some older publications than might normally be prioritised (e.g., Ku and Broecker, 1969; Huh and Ku, 1984). More recent publications that are key to this work also cite older papers due to the lack of more current relevant data (e.g., Volz et al.,2023; Kunze et al., 2024; Lüttke et al., 2025).

The terms radioactive isotopes, radioisotopes, radionuclides, and radioactive elements are used interchangeably throughout this paper.

3. The Radioactivity of Polymetallic Nodules and Seafloor Massive Sulphides

Radioactive isotopes have unstable atomic nuclei, causing them to spontaneously release energy to become more stable. This energy is released in the form of ionising radiation: alpha particles, beta particles, neutrons, or gamma rays and other forms of radiation. Known as radioactive decay, this process produces new daughter radioactive isotopes (also called radioisotopes or radionuclides), which continue to emit energy (as radiation) to become more stable, until the decay chain ultimately ends in the formation of a stable non-radioactive element. For example, uranium (U)-238 decays into a series of daughter radionuclides, many of which are highly radioactive until a stable form of lead (Pb) is produced as the final element (see Fig. 1). The length of time an isotope remains radioactive is measured by its half-life, i.e., the time required for half of the radioactive atoms present to decay. Half-lives of radionuclides can range from seconds to millions of years.

Figure 1. Uranium 238 Decay Chain showing the half-life of daughter elements and the type of radiation emitted (alpha or beta). Source: https://sites.wustl.edu/hazardouswaste/radionuclides/uranium/



The seafloor is a natural sink for radionuclides due to a process known as scavenging, whereby radioactive elements in the water column adhere to particles and phytoplankton that settle on the seabed (Fisher et al., 1991).

Polymetallic nodules and SMS contain radioactive elements, predominantly of the uranium and thorium decay series, including daughter radionuclides such as radium, polonium and lead (Douville et al., 2002; Charmasson et al., 2009; Volz et al., 2023; Dołhańczuk-Śródka et al., 2024; Lüttke et al., 2025).

Th-230 and Pa-231 and their daughter isotopes are efficiently scavenged by the iron-manganese oxides that comprise polymetallic nodules (Hayes et al., 2015). This same chemical scavenging is the process by which polymetallic nodules accumulate metal oxides over millennia. Elevated Th-230 occurs in the sediments and nodules of the Clarion-Clipperton Zone (Volz et al., 2023).

3.1 Radioactive Elements and Polymetallic Nodules

Several radioactive elements are concentrated on the surface of polymetallic nodules (within the outer 1-2mm layer) and are present there in high concentrations relative to the already enriched surrounding sediment (Volz et al., 2023; refer Table 1).

The mechanism of attachment of radionuclides to metal oxides on deep-sea nodules is still poorly understood. Current research is limited to simplified laboratory models, using synthetic manganese oxides, far removed from real-world deep-sea environments. One review found complex interactions in which oxidation could release radionuclides from manganese oxide surfaces, while, at the same time, other mechanisms enabled oxidised forms to re-attach onto the same surfaces (Szlamkowicz et al., 2023). Understanding how radionuclides bind to nodules will be a critical step towards assessing their mobilisation, bioavailability and ecotoxicity resulting from DSM.

The isotopes present in nodules are predominantly alpha-particle emitters, which are known to be highly toxic when internalised by organisms. This can occur through ingestion, respiration and transfer across membranes, all of which can readily occur in the marine environment.

During DSM we can expect the surface layer of nodules in particular to be fragmented and dispersed as debris in seawater both during the mining process (benthic plume) and through wastewater discharged at depths of 1-2 km below the sea surface following dewatering on the surface vessel (midwater plume), as proposed by companies such as The Metals Company (TMC) (TMC, 2025). Another company, Impossible Metals, plans to transport nodules to the surface in a hopper which would most likely result in sediment seepage during the ascent of the hopper producing a wash plume. All these plumes pose a potentially significant, and to date, unstudied hazard to marine life and to seafood consumers.

Radioactivity measurements in polymetallic nodules show a considerable variation due to geochemical differences between sampling locations and within nodules themselves. The surface layers of the nodules are more radioactive than their cores, with activity concentrations often peaking 1-2 mm below the surface (Volz et al., 2023).

Thorium, radium, polonium, protactinium, lead and other isotopes are efficiently scavenged by metal oxides on the surface of nodules and may be present there at 10-20 times higher concentrations than in the surrounding sediment (Volz et al., 2023). As a result, the surface of nodules show high activity concentration, meaning they contain elevated levels of radioactivity.

The radioactivity (or activity concentration) of isotopes associated with polymetallic nodules, measured in becquerels per kilogram, are shown in Table 1. Becquerels per kilogram is the standard international unit, indicating the number of atoms decaying (emitting radiation) per second for every kilogram of that material. These values indicate the relative radioactivity of the different isotopes. However, they do not indicate consequent radiation doses, as energy released during radioactive decay can vary substantially between isotopes.

A critical information gap requiring focused research attention is how to extrapolate from these activity concentrations to calculations of the doses that marine organisms would be exposed to during DSM.

Table 1. Key radioisotopes associated with polymetallic nodules and their environmental relevance.

Radioisotopes	Radiation type	Activity (Bq/kg)*	Environmental / Biological relevance	Source of Activity measurements
Uranium 238 (U-238)	Alpha	50 (avg) 9–202 (range) 1,200 (max)	Uranium-238 is the most abundant uranium isotope, has a long half-life, and decays to thorium-234. It also represents a metal toxicity risk.	Kunze et al., 2024; Dołhańczuk-Śródka et al., 2024; Volz et al., 2023 (Table S2)
Polonium 210 (Po-210)	Alpha	2,400 (avg)	Known marine radioactive environmental contaminant with a 138-day half-life. Shown to damage DNA, bioaccumulate in tissues of marine organisms and can biomagnify in marine food webs, negatively impacting marine ecosystems (Stewart et al., 2008, Fowler, 2011; Carvalho et al., 2011; Carvalho et al., 2017). Ingestion or inhalation pathways pose a significant risk of ionising radiation dose. It is extremely hazardous and has been used as a biowarfare agent.	Kunze et al., 2024
Thorium 230 (Th-230)	Alpha	2,000 (avg) 64,000 (max) Surrounding sediments: 3,200 Bq/kg	Occurs on polymetallic nodule surfaces in significantly higher concentrations than surrounding sediment and seawater. Adheres strongly to particles (particle reactive) and phytoplankton via chemical scavenging in seawater (Stewart et al., 2008).	Kunze et al., 2024; Volz et al., 2023 (Table S2); Sediment value from Volz et al., 2023
Thorium 232 (Th-232)	Alpha	50 (avg); 2,180 (max)	An abundant isotope with long half-life, decays to Radium.	Kunze et al., 2024; Volz et al., 2023 (Table S2)
Protactinium 231 (Pa-231)	Alpha Beta Gamma	120 (avg) 11,000 (max)	Part of the Uranium - Thorium decay series, long half-life, relatively high radiotoxicity due to a high dose coefficient (the conversion factor used to estimate health risks) relative to other radionuclides (Peterson et al., 2007). Adheres strongly to particles (particle reactive).	Kunze et al., 2024; Volz et al., 2023 (Table S2)
Actinium 227 (Ac-227)	Alpha Beta	50-100 (range)	Highly radioactive, 21.7-year half-life, toxicology risk due to its ability to damage DNA (NCBI Pubchem, 2026).	Lüttke et al., 2025
Radium 226 (Ra-226)	Alpha Gamma	740 (mean) 50-3,100 (range) 9,000 (max)	Can chemically substitute for calcium in biological tissues. Ingestion or inhalation poses a significant risk of ionising radiation dose to organisms but pathways differ from human to marine (Peterson et al., 2007).	Dołhańczuk-Śródka et al., 2024 (Table 3); Dołhańczuk -Śródka et al., 2024 (Table 1); Volz et al., (Table S2)
Lead 214 (Pb-214)	Beta Gamma	550 (mean) 80-2,000 (range) 3,370 (max)	Can bioaccumulate in marine food webs and is of concern as a radiotoxic contaminant in marine environments (Carvalho, 2011; Peterson et al., 2007; Oros, 2025).	Dołhańczuk-Śródka et al., 2024 (Table 3); Dołhańczuk-Śródka et al., 2024 (Table 1); Dołhańczuk-Śródka et al., (Table 3)

** Table 1. Activity values in Column 3 are rounded estimates derived from scientific literature (cited in Column 5). Values are reported in becquerel per kilogram (Bq/kg) and include averages or means (avg/mean), ranges, maximum values (max), and sediment values, where available from published datasets and cited sources.*

3.2 Radioactive elements and Seafloor Massive Sulphides

SMS are mineral deposits laid down over thousands of years around deep seafloor formations known as hydrothermal vents. Similar to geysers, the vents emit superheated hydrothermal fluids carrying a range of chemical species, metals and radioactive elements. These materials rapidly precipitate when the extremely hot fluid (over 400°Celsius) meets very cold deep seawater. This process known as high-temperature hydrothermal leaching concentrates uranium-238, thorium-232, potassium, and their decay products arising from the upper mantle. In addition, the process of scavenging further concentrates radionuclides in SMS deposits (Charmasson et al., 2009; Leybourne et al., 2022).

Although selected radionuclides have been measured in SMS for dating purposes (Kadko and Moore, 1988; Lalou et al., 1990, 1993a-b, 1998; Kadko, 1996; Münch et al., 2001; Kuznetsov et al., 2006, 2011, 2015, 2026), systematic data on radionuclide abundances and inventories in SMS deposits remain extremely limited. Elevated radionuclides (U-238, U-235, U-34, Po-210, Pb-210) have, however, been documented within polychaetes (segmented worms) collected from hydrothermal deep-sea vents (Cherry et al., 1992 and Charmasson et al., 2006, 2009, 2011). Charmasson et al. (2009) summarised:

"Hydrothermal deep-sea vent fauna is naturally exposed to a peculiar environment enriched in potentially toxic species such as sulphides, heavy metals and natural radionuclides … Though only few radionuclide measurements are available, it seems likely that hydrothermal vent communities are exposed to high natural radiation doses … Vent organisms are characterised by high U, and Po–Pb levels compared to what is generally encountered in organisms from outside hydrothermal vent ecosystems."

While vent organisms are clearly adapted to high natural radiation levels, the effects of exposing other marine organisms and ecosystems to elevated levels of radioactive isotopes mobilised by mining SMS remains unknown.

Cover image: Juvenile Whale Shark Swimming. Credit: Ollie/AdobeStock

4. The Marine EcoToxicity of Radioactive Isotopes Released by Deep Sea Mining

4.1 No safety standards protect deep sea species, marine ecosystems and human consumers from DSM elevated levels of radioisotopes

Marine organisms are adapted to normal background levels of naturally occurring radioactive materials (NORM). However, DSM would expose marine life to elevated levels of radioactive isotopes by spreading fragments of SMS and polymetallic nodules debris (especially radioactive surface layers) and sediment particles.

Given the extremely long half-lives of some isotopes present in nodules and SMS such as thorium-230 (75,380 years), protactinium-231 (32,760 years), and radium-226 (1,620 years) (Volz et al., 2023), it is possible that radiation toxicity could persist in the marine environment well beyond the decades-long operational lifespan anticipated for DSM operations. This may be particularly significant for long-lived deep-sea organisms, which could experience prolonged exposure, bioaccumulation and chronic ecological effects.

The elevation of radioactive isotopes above natural background levels, known as Technologically Enhanced NORM (TENORM), is also associated with mining on land for mineral sands, metals and coal, oil and gas production, and other anthropogenic activities. The International Atomic Energy Agency (IAEA) provides a tiered framework of safety standards as a template for national legislation for mining and other extractive industries including for managing residues and waste that contain elevated levels of natural radionuclides like thorium-232 and uranium-238, which are abundant on polymetallic nodules.

The International Commission on Radiological Protection (ICRP) and the IAEA work in a complementary manner: the ICRP provides scientifically based recommendations for radiological protection, while the IAEA translates these into international safety standards and facilitates their implementation globally. Both organisations have recognised the need to protect biodiversity and human health from TENORM sources for over 40 years.

While the understanding of health risks for humans is relatively advanced, understanding of exposure routes and effects on non-human biota remains in its infancy. For example, ICRP Committees 1 and 4 are still at an early stage in researching the effects of radiation from the subcellular to population and ecosystem levels, as well as how to apply the IAEA system of radiological protection to biota.

Furthermore, there are only three marine reference organisms for ICRP research – flatfish (*Pleuronectidae*), crab (*Cancridae*), and brown seaweed (*Fucaceae*) – none of which adequately represent the unique biology or radiosensitivity of the broad spectrum of marine life, let alone deep-sea organisms. This limitation persists despite the need for specific research on deep-sea biota that has been recognised since 1988 (IAEA, 1988, Technical Reports Series No 288).

Human safety standards are not applicable to the majority of non-human biota and especially to deep-sea species due to significant differences in physiology, radiosensitivity, ambient environmental conditions, and routes of exposure and uptake. By analogy, water quality standards can be much stricter for aquatic life than for drinking water. For example, in the European Union, the drinking water standard for mercury is 1 µg/L (EUR-Lex 2020), while the environmental quality standard (annual average) for mercury and its compounds is 0.05 µg/L (EUR-Lex 2008).

Research to safeguard the health of marine and deep sea species, ecosystems and human consumers from DSM-induced radiotoxicity is almost entirely lacking.

4.2 Ecotoxicity of elevated levels of radioactivity resulting from DSM

DSM-related hazards from TENORM would occur via the mobilisation of radioactive isotopes within the sediment plume generated by mining at the seafloor, and in mine waste discharged at 1-2 km below the surface as proposed by some companies, for example TMC (TMC, 2025). How far the midwater waste discharge and the benthic plumes would travel, and the concentrations of sediment particles and toxic contaminants, continues to be the subject of investigation (Chen et al., 2026; Haalboom et al., 2023). However, modelling studies independent of the mining industry suggest that midwater waste plumes could travel between hundreds and thousands of kilometres (Luick, 2022; Dowd et al., 2025, du Preez et al., 2025), while the benthic plumes could damage ecosystems including those in the midwater (Drazen et al., 2020).

Studies indicate that marine organisms may be affected by radioactivity via:

- Ingestion of radionuclides in contaminated water, sediments, or prey
- Internal exposure through absorption from surrounding water into the body via membranes such as gills during respiration or through an outer 'skin' layer (epidermis)
- External irradiation from radionuclides present in the surrounding environment, including beta and gamma radiation

Each of these routes of exposure and sources of radioactivity can result in different rates and pathways of uptake, bioaccumulation, and trophic transfer (i.e., biomagnification), which in turn influence radiation dose and potential ecological effects (Stewart et al., 2008). Depending on the intensity and duration of the exposure and the physical and metabolic characteristics of organisms, exposure may result in cell death, protein and DNA damage, respiratory failure, reproductive impairment or mortality (Stewart et al., 2008).

Long-term chronic impacts, particularly on early life stages and reproductive tissues, may affect population health and pose ecological risks that require careful monitoring (Seiler et al., 2012, Pradhoshini et al., 2023).

If granted, DSM exploitation licences would extend over decades. Thus, the risk to marine life of chronic exposure to radiation is likely to be significant.

Bioaccumulation is the accumulation of radionuclides within an organism, whereas biomagnification refers to the progressive increase in radionuclide concentrations across a food chain, whereby organisms at higher trophic levels accumulate greater concentrations through the consumption of contaminated prey. The level to which radioactive isotopes can accumulate in the tissues of an organism and, in some cases, be transferred and biomagnify through marine food chains depends on its chemical characteristics and the form in which they occur (speciation) in seawater and sediment, as well as biological processes such as uptake from water or diet, excretion, and metabolic transformation (Stewart et al., 2008).

Many deep-sea organisms associated with polymetallic nodules are long-lived and slow-growing with some sessile fauna living for decades to centuries (Van Reusal et al., 2016; Gollner et al., 2017; Morrison et al., 2020). Long-term exposure of such species to elevated levels of radioactivity resulting from DSM, would further increase the potential for bioaccumulation, biomagnification and chronic radiological effects.

4.3 DSM and the risk of Alpha Particle Ecotoxicity

Many radioactive isotopes present in nodules and SMS are alpha-particle emitters. When internalised, these radionuclides can be particularly damaging to biota compared to other types of radiation due to their high energy and dense ionisation. This property, known as high Linear Energy Transfer (LET), means that alpha particles can deliver highly concentrated radiation doses within a very small area of tissue (Institute of Medicine, 1995; Stewart et al., 2008; Sgouros, 2008).

While alpha particles are readily stopped by barriers like skin or paper, their dense ionisation and high LET mean they are extremely hazardous when inhaled, ingested, or absorbed internally. Radionuclides can bind to proteins and other cellular molecules and their radioactive decay

during prolonged internal exposure can cause significant biological damage for example to DNA and cells (Institute of Medicine, Basic Principles of Biology, 1995).

Radioactive isotopes of the uranium and thorium decay chains, particularly radium-226, lead-210, protactinium and polonium-210 are likely to present the greatest TENORM-related hazards associated with DSM due to their chemical behaviour in marine environments. This includes their potential for biological uptake, bioaccumulation, and trophic transfer, as well as their capacity to cause DNA damage, reproductive effects, and population-level ecological impacts (Fuller et al., 2015; Stewart et al., 2008; Pradhoshini et al., 2023).

4.4 Potential Synergistic and Cumulative Effects of Heavy Metals and Radioactive Isotopes Released by DSM

The nature of interactions between radionuclides and heavy metals in marine organisms remains a significant knowledge gap. Most studies that measure these two contaminant classes do so independently, without investigating their combined effects. Research into combined toxicology has primarily focused on co-occurring metals and findings generally indicate that cumulative, rather than synergistic effects are more likely to pose environmental risk (Cedergreen, 2014).

One of the few studies on the combined exposure of radionuclides and heavy metals examined the effect of uranium, cadmium, and copper, both individually and in combination, on freshwater crustaceans. The study found that the combined toxicological effects of uranium and copper depended non-linearly on their relative concentrations, suggesting a synergistic rather than purely additive interaction (Chen et al., 2022).

A similar study using zebrafish found uranium to have a toxicological profile comparable to that of lead, cadmium, and iron, suggesting that radionuclide impact on some marine species could be similar to that of heavy metals (Shankar et al., 2021). However, both of the above studies exposed the experimental organisms to acute, short-term, high-dosage exposures. The combined toxicological effects of chronic exposure to metals and radionuclides over longer time scales, as would likely occur under DSM, remains a major knowledge gap.

A study from the Straits of Malacca examined levels of radioactive isotopes and heavy metals in bigmouth mackerel (*Rastrelliger kanagurta*), an important food fish. While radionuclide concentrations resulting from natural and anthropogenic bioaccumulation was found to be within human consumption thresholds, concentration in seawater was substantially lower than those measured in in mackerel, demonstrating that like with heavy metals, radionuclides can bioaccumulate (Khandaker et al., 2015). The study did not investigate the effects of the combined bioaccumulation of metals and radioactive isotopes.

In another study, the bioaccumulation of radionuclides and heavy metals in fish and shellfish from the Bay of Bengal was traced to coal combustion and natural weathering of local geological deposits (Asaduzzaman et al., 2026). However, this study did not investigate the ecological impacts of combined bioaccumulation.

Thus, within the limited body of published research investigating exposure of marine life to both radionuclides and heavy metals, studies examining the combined toxicological effects are rare.

DSM will mobilise both radioactive isotopes and heavy metals with the potential to bioaccumulate within marine species, ecosystems and food webs. The combined ecotoxicological impacts over decades-long mining operations remain a significant knowledge gap.

Case Study: Radium and Polonium

Radium is one of the most widely studied naturally occurring radiotoxic elements. The radium-226 species present on nodules is chemically similar to calcium. In the marine environment it is incorporated into shells, bones, and other calcified hard parts of marine organisms. Its long half-life and relative mobility in marine systems make it a persistent environmental source of radiation and the parent radionuclide in a decay chain that produces highly radiotoxic daughter isotopes, notably polonium-210.

Although short-lived, polonium-210 is a particularly significant radionuclide in marine systems recognised for its ability to bind to proteins and bioaccumulate (accumulate in tissues) and to biomagnify through the trophic levels of marine food webs (Carvalho et al., 2011, Fowler, 2011, Seiler et al., 2012). It is known to affect phytoplankton, zooplankton, and pelagic organisms (Carvalho et al., 2017, Stewart et al. 2008, Chapter 8, pp. 272, 279–280). Polonium-210, is frequently used as a model radionuclide because it is comparatively well studied in marine systems and displays pronounced bioaccumulation and trophic transfer, making it especially useful for understanding radionuclide behaviour in marine food chains (Stewart et al., 2008).

Radiation exposure in organisms at the base of marine food webs, including microbes and invertebrates, may have disproportionate ecological consequences because these groups underpin biogeochemical cycling and trophic transfer. Pradhoshini et al. (2023) emphasise the need to investigate further the radiosensitivity of invertebrates, particularly those that form the foundation of marine food webs.

Filter-feeding organisms are particularly susceptible to radionuclide uptake due to their continuous processing of large volumes of water and suspended particulate matter, which can be enriched in radioisotopes (Stewart et al., 2008, Chapter 8). This can lead to substantial accumulation.

Should DSM proceed, additional radiological loading on marine organisms and food webs including human consumers could be anticipated. Elevated concentrations of Po-210 in marine organisms have been shown to contribute to human radiation exposure through seafood consumption, in some cases exceeding natural background exposure levels (Bulman et al., 1995; Dahlgaard, 1996; Carvalho, 2017).

Studies demonstrate that radionuclides such as polonium-210 and radium-226 can bioaccumulate and exert radiotoxic effects in marine organisms. However, no studies have clearly assessed these processes in the specific context of the deep sea or DSM. As a result, while some mechanisms of exposure and toxicity are established, the radiation doses to which organisms may be exposed, the distribution of radionuclides, and the broader ecological and food-web consequences of DSM-induced radioisotope release remain unknown.

5. Conclusion

A brittle star (Relicanthus sp.) seen in a field of manganese nodules. Image: DJ Amon & CR Smith, University of Hawai'i

Radioactive isotopes accumulate naturally on the seafloor, in seafloor massive sulphides and particularly on the surface of nodules by a process known as chemical scavenging. Polymetallic nodules and seafloor massive sulphides concentrate radioactive elements predominantly of the uranium and thorium decay series. These are largely alpha particle emitters, which are known to be highly toxic if internalised by organisms. In the marine environment this can readily occur through ingestion of particles, consumption of contaminated food sources, respiration via gills or absorption through other membranes.

During deep sea mining, the surface layer of nodules containing relatively high concentrations of alpha-particle emitters would be fragmented and dispersed as debris during operations at the seafloor and through wastewater discharged at depths of 1-2 km below the ocean surface, as proposed by some companies including The Metals Company.

The potential of these radioactive isotopes for biological uptake, bioaccumulation, and biomagnification in food chains, as well as their capacity to cause DNA and protein damage, reproductive effects, and population-level ecological impacts poses a potentially significant and to date unstudied hazard to marine life and to human seafood consumers.

The human health effects associated with processing polymetallic nodules and the biological effects of radionuclides in coastal and open-ocean systems has received some scientific attention. However, comparable research in deep-sea environments is absent, and no studies have been published on deep sea mining-induced radioecotoxicity in marine species and ecosystems.

Understanding the ecological implications of radioactive isotopes released by deep sea mining requires a holistic approach that considers the complex interrelationships within marine ecosystems and food webs. This represents a critical knowledge gap and urgently requires further research.

Despite pressure from deep sea mining companies to proceed with mining, scientific data, modelling, and analysis critical to protecting marine and deep-sea species, ecosystems and human consumers from deep sea mining-induced radiotoxicity are almost entirely lacking.

6. Recommendations

A focused investigative effort is required before marine ecosystems and our ocean commons and food sources are faced with the prospect of long-term exposures to potentially significant levels of unregulated radioactivity due to deep sea mining.

Such research should address the following questions:

- What are the chemical forms and concentrations of radionuclides released during mining of polymetallic nodules and seafloor massive sulphides?
- How would deep sea mining activities change the spatial distribution and dispersion of radionuclides?
- What radiation doses would marine organisms be exposed to as a result of deep sea mining?
- What are short and long-term impacts of such exposures on marine species, ecosystems, and food webs, including on the health of human consumers of seafood?
- Which marine species are most suitable as indicators of ecological health, and what are the natural radioisotope levels within their tissues?
- What are the bioavailabilities, uptake pathways, and trophic (food web) transfer of radionuclides within deep-sea ecosystems?
- What are the biological effects of increased radiation doses in marine organisms under chronic exposures at both high and low dose conditions, as would likely occur during deep sea mining?
- Could the ecotoxicity of radioactive isotopes, heavy metals and other contaminants mobilised by deep sea mining combine to cause even greater ecological impact? And what is the nature of those impacts on species, ecosystems and food webs?
- How do radionuclides bind to polymetallic nodules and to seafloor massive sulphides deposits, and how can this knowledge inform assessment of the radionuclide mobilisation, bioavailability, and ecotoxicity associated with deep sea mining?
- Can theoretical frameworks and computational models be developed to help address these critical knowledge gaps?

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